The Flying Electric Generator: Evaluating the claims of a largely ignored proposal for generating electricity from high-altitude winds

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Abstract

This thesis concerns the Flying Electric Generator (FEG), a technology proposed to generate electricity from winds several kilometres high in the sky. Airborne Wind Energy (the generation of electricity from high altitude winds) is an emerging field of research, with several technological approaches under development. High altitude winds are attractive for this purpose because they are generally much faster than surface level winds, and because power is a cubic function of wind velocity. Winds are fastest within the subtropical jet stream, located about 25–30 degrees north and south of the equator, at an altitude of 10–12 km.

The FEG is a device consisting of multiple rotors attached to a frame, which is tethered to the ground. The rotors work as autogyros to provide lift; additional energy extracted from the wind is converted to electricity and conducted to the ground via the tether. The FEG would operate kilometres high in the atmosphere, up to jet stream levels.

Papers about the FEG were first published in 1979, and in 2002 a company was founded to commercialise the FEG. So far, this has not happened, and many details of how the technology would operate remain uncertain, despite three decades of research literature. Only small test craft (rotors of up to 24 feet in diameter) have flown at low altitudes (up to 100 feet). Many of the claims in the literature, which are optimistic about the FEGs performance at high altitude, are experimentally untested. FEGs have never operated at the altitudes described in the corresponding literature, and the project has not been commercialised or attracted much if any recent research funding. Other, newer entrants to the Airborne Wind Energy field have seen success in research funding and commercialisation.

This thesis addresses two problems: first, it tests some of the claims in the FEG literature and second, it attempts to fill in details not provided. The particular claims concern the power density available in high altitude winds over Australia and its seasonal variation, the amount of time a hypothetical FEG setup would be
“grounded” due to insufficient wind speeds to keep it aloft, and expected capacity factors of a hypothetical FEG setup.

Claims about the magnitude of the wind power resource were tested using re-analysis data (the ERA-40 dataset was used, and was validated against Bureau of Meteorology upper air statistics). Power density and wind speeds at different altitudes above Australia were calculated and analysed. The reanalysis wind data in conjunction with a model of FEG operation (based on lifting rotor theory detailed in the FEG literature) were used to calculate downtime and capacity factors.

The results showed a clear seasonal variation in power density over Australia, which was most pronounced at 30 degrees south of the equator (although winds above Tasmania showed much less variation). Winter had the strongest winds, and summer the weakest. The highly skewed distribution of power density meant that median power densities (unreported in the FEG literature) were more appropriate than means. Downtime calculations showed that a particular FEG setup rated at 240 kW operating at a pressure level of 600 hPa would be landed for at least 20% of the year at all locations in Australia, and for at least 40% of the year north of 20° S. Annual capacity factors for the same FEG setup were calculated to vary between 0.1–0.4 over Australia, no different from conventional ground-based wind turbines. Capacity factors for the summer months were substantially lower than the annual values. These results support the main contention of the thesis, that the FEG is far more limited in its potential as source of energy from the wind than the literature claims.
Declaration

This is to certify that

(i) the thesis comprises only my original work towards the Master of Science,

(ii) due acknowledgement has been made in the text to all other material used,

(iii) the thesis is less than 50,000 words in length, exclusive of tables, maps, bibliographies and appendices.

Steven Kambouris
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Chapter 1

Introduction

1.1 Background

1.1.1 Renewable Energy

Modern economies and societies are based on the availability of cheap, reliable energy. The vast majority of this energy comes from fossil fuels. Alternative energy sources have historically played only a small role in meeting energy demand, but in the past few decades, this has been changing.

The oil crises of the 1970s boosted interest in alternatives to fossil fuels (Kandpal and Garg, 1999; Jacobsson and Johnson, 2000; Gan et al., 2007). Restrictions to the supply of oil forced governments and industries to consider other energy sources (although the intermittent “resolution” of these crises led, in most cases, to a returned reliance on oil and relative neglect of energy alternatives). More recently, concern about anthropogenic climate change has led many nations to explore alternative energy options, especially renewable energy sources, in order to reduce consumption of fossil fuels and the associated emissions of carbon dioxide and other greenhouse gases (Hoffert et al., 2002).

1.1.2 Wind Energy

Wind power (fundamentally, the conversion of kinetic energy in wind into mechanical energy and then electrical energy (Inglis, 1978, p.18)) is a well-established example of an alternative, renewable energy source (Freris and Infield, 2008, p.28). Wind turbines are in operation across the world, both as stand-alone electricity generators in remote areas and as part of an established electricity grid. Although it makes up
only a small fraction of the worldwide electricity market\textsuperscript{1} (which is dominated by fossil fuel-based electricity generation), wind power is commercially viable and its market share is growing.

Wind has some drawbacks as a source of electricity: wind is intermittent (as are many other renewable energy sources) and variable in speed (wind speeds at a fixed location vary over time), it cannot be controlled (unlike the output of a fossil fuel-based power plant), and wind speeds are difficult to predict. These factors mean electric power supply from a wind turbine will not necessarily be correlated with demand for electricity.

An additional drawback is in relation to the amount of power which can be extracted from the wind. The speed of wind directly affects the amount of kinetic energy available to be harnessed by a wind turbine. Although wind is abundant, the wind speeds typically encountered at the earth’s surface allow for only a modest electrical output from a single commercial wind turbine (with an output on the order of 1 MW), compared to a commercial-scale coal-fired power plant (with output typically on the order of 100 MW). Many large wind turbines would need to be installed to replace the capacity of a typical fossil fuel-based power plant, and even then, matching the consistency of the plant’s output would be difficult to achieve.

\subsection{1.1.3 High Altitude/Airborne Wind Energy}

These two undesirable characteristics of surface winds—low speeds and intermittency—are reduced with increased height. This is due to interactions between the earth’s surface and the atmosphere: air at the surface experiences heating and cooling as well as friction due to trees, buildings, hills, etc. Winds further away from the surface are less susceptible to these interactions. In particular, winds above this area of surface influence, the planetary boundary layer (which can extend anywhere from 100 m to a few kilometres in height), are generally strong and consistent compared to surface winds. In the troposphere (up to approximately 12–13 km in altitude), winds typically become faster with increasing altitude.

\footnote{For 2013, electricity generated from wind power was estimated to have met 3.4\% of global electricity demand (Wiser and Bolinger, 2014, p.7). The penetration of wind power into the electricity market varies widely between countries. Europe has the highest wind power penetration; in 2013 wind turbines in Denmark generated electricity equivalent to nearly 35\% of the country’s annual electricity consumption. Using the same metric, Spain, Portugal and Ireland each had a value of 20\% in 2013. (In the US, Australia, and China, this metric for 2013 was below 5\%).}
In principle, for a rotor of a given diameter, harnessing high altitude winds for electricity generation would deliver more electrical power than when using surface winds. In addition, the power output from the rotor would be far less intermittent than at the surface.

The desirable properties of high altitude winds have motivated research into different methods of extracting electrical power from these winds. The idea was considered as early as the 1930s (Williams, 2006). In 1938, Aloys van Gries patented an apparatus for lifting a wind turbine to high altitudes (an exact altitude or height was not specified) using a series of kites connected by a long tether (van Gries, 1938a,b). In 1939, Hermann Honnef described the design for an arrangement of wind turbines atop a tower approximately 300 m in height, designed to take advantage of the faster winds found at high altitudes (Honnef, 1974b,a).

Interest in high altitude wind energy grew in the 1970s and 1980s as a response to the oil crises, with small groups and individual researchers first publishing their ideas and concepts. For example, in 1977 Hermann Oberth presented a design for a “kite power plant”: a wind turbine lifted up to 12,000 m in altitude by a balloon, and secured by a long tether to the ground (Der Bote, 2011; Oberth, 1987). The design was never implemented.

However, as fossil fuel prices lowered from the crisis peaks, interest in these ideas waned over the 1980s and 1990s, with little published during this time. Since the mid 2000s, there has been a resurgence of interest and Airborne Wind Energy (AWE) has begun to emerge as its own field of research, with an association, conferences, and an academic volume published. From this new, reinvigorated community, a number of potential solutions have emerged. Each has been developed to a certain extent and a couple have reached the stage of commercialisation. A recent review article by Cherubini et al. (2015) describes a large number of different AWE systems that are under development. Cherubini et al. (2015) group the different projects by whether electricity generation occurs on the ground (with an airborne component providing mechanical energy to generator), or occurs in the air (i.e. the generator is attached to the airborne component, and transmits generated electricity to the ground via a conducting tether). The ground-based generator designs are further broken down by whether the ground generator is fixed or moves (e.g. pulled along on a track). The majority of the AWE projects make use of the crosswind flight effect outlined by Loyd (1980): in a sufficiently strong wind, a tethered aircraft can pull on and unwind its tether by tacking back and forth along an axis perpendicular
to the wind, and then alter its flight path so the tether can be retracted using less energy than the wind provided during the unwinding phase. This method of net energy extraction from the wind has been adopted and refined by different research groups, and many variations of the basic concept have been devised.

Although not all are assured of widespread adoption or commercial success, technologies which generate electricity from high altitude winds are now being considered as options in the search for alternative energy sources.

In this thesis, I focus on a particular high altitude wind energy technology, the Flying Electric Generator (FEG), which was conceived earlier than most AWE concepts (the first papers were published in 1979) and has been in development since. However, despite the pioneering work done by its inventor and his associates, the FEG design concept is not prominent in the contemporary AWE field, and despite having a “head start” on virtually all other high altitude projects, it has not enjoyed the success or attention that other, different AWE concepts have. Different from all the other high altitude energy concepts, the FEG employs rotor blades rotating at an angle to the wind at altitude, generating both lift and electricity. The electricity is transferred to the ground via a conducting tether.

1.1.4 The Flying Electric Generator

The Flying Electric Generator (FEG) is the invention of Dr Bryan W. Roberts, who has developed the concept and written multiple papers on the subject, starting in 1979. The most recent peer-reviewed journal article on the FEG was published in 2007 (Roberts et al., 2007).

The FEG has been designed to fulfil two functions: generate electricity and maintain its position high in the atmosphere. It is as much an aircraft as it is a power plant, and contains elements of both in its design. An FEG is made up of four two-blade coplanar rotors, each at least 10 metres in diameter, which are attached to a thin frame (see Figure 1.1), which is in turn attached to a conducting tether connected at the ground. The rotors and frame together are referred to as a “platform”. The plane of the rotors is set an angle of 10–45° to the horizontal (see Figure 1.2). Wind incident on the rotors causes them to rotate, which generates electricity like a conventional wind turbine, but also creates lift in a way similar to an autogyro. The rotors contra-rotate; that is, they rotate in opposite directions. This adds to the stability of the platform. Electricity is generated by generators on the platform, which is conducted through the tether to the ground, where it is
1.1. Background

Figure 1.1: A top-down view of a four-rotor FEG platform.

Figure 1.2: A side-on view of the FEG while operating at altitude in oncoming wind, $v$. The angle $\alpha_c$ represents the angle of the plane of the rotors to the horizontal, and the angle $\beta$ represents the angle the tether makes to the horizontal at the ground.

This design is as described in Roberts et al. (2007), and is one of many possible designs of FEG, all closely related. FEGs have been designed with two coplanar rotors, and also more than four rotors.

There is a similarity between the four-rotor design of the FEG and the quadcopter design commonly seen in unmanned aerial vehicles (UAVs), which have become increasingly popular in recent years (Brooks, 2012; Marris, 2013). However, UAV quadcopters are on a much smaller scale than the FEGs are envisioned to be, and need not be tethered. Detailed analysis of quadcopter dynamics seems to have come
years after the FEG rotary-wing concept was initially conceived (Hoffmann et al., 2007).

FEGs are envisaged to operate in the mid to upper troposphere; that is, at altitudes from 4 km to 12 km above the surface of the earth (Roberts et al., 2007). An FEG would ascend to its designated operating level by engaging its rotors in a helicopter-style mode, with the generators acting as motors, drawing electrical power from the ground.

The rated power output of an FEG depends on the size and number of rotors. A single commercial FEG platform could be scaled in size to produce anywhere from 3 to 30 MW. The estimated weight of a platform rated at 3.4 MW is 10,000 kg (this does not include the weight of the tether).

Despite decades of development (as evidenced through conference papers and journal articles) and the establishment in 2002 of a company, Sky WindPower Corporation, in California, and in 2011, Altitude Energy Pty Ltd in Australia, the FEG technology is not yet commercially available, and at the time of writing only small prototype crafts have been flown at low altitude for test purposes. Although starting development years before competing AWE designs, the FEG has ended up lagging behind other concepts, which have attracted more funding and the attention of the still-young AWE research community. Cherubini et al. (2015) report that Sky WindPower has gone out of business (although this could not be independently verified).

1.2 Thesis

This thesis evaluates claims about the expected performance of the FEG, essentially addressing the basic question of whether the technology is able to generate electricity as claimed. There are also a large number of issues and questions about the practicality and viability of the FEG beyond this.\(^2\) I’ve compiled a non-exhaustive list below. These are the questions and issues that would be most important to stakeholders (e.g. investors, governments, research grant councils) considering the FEG.

\(^2\)It should be noted that many of these issues are applicable to any idea proposed for generating electricity at high altitude, not just the FEG.
Safety Issues

- FEGs would need to be able to be “recalled” (i.e. be able to descend and land safely on the ground) sufficiently quickly to prevent aircraft strikes, lightning strikes, strong winds, etc.

- FEGs would need to be sufficiently spaced to prevent the possibility of tether entanglement.

- FEGs would need regularly scheduled maintenance, more akin to the maintenance schedule of an aircraft than to the maintenance schedule of conventional ground-based wind turbines.

- The FEG might crash to earth (whether due to mechanical failure, insufficient wind, loss of control, etc.) anywhere within the radius of its tether length from the ground station.

- The tether might break, meaning the FEG would crash to earth at a location much further away than the length of the tether from the ground station.

- Parts of the FEG (rotor blades, for example) might break off and fall to earth.

- At higher altitudes where the temperature is lower, ice might build up on the FEG platform and tether, adding to the weight and affecting performance (or causing a failure of some kind).

- Lightning might strike the FEG and/or tether, which would presumably cause damage to the FEG/tether and possibly affect the electricity grid.

Legal/Regulatory Issues

- Dedicated airspace would need to be declared and enforced. FEGs could not be sited near existing flight paths (or, flight paths would need to be altered).

- The land directly below and surrounding an operating FEG would presumably have land use restrictions, reducing the number of potential sites (away from urban areas, most obviously). The area of land affected would increase with the operating altitude of the FEG.
Economic Issues

- How much is the FEG likely to cost to build and maintain, given it is much closer to being an aircraft than to being a conventional ground-based wind turbine?
- Insurance costs, given the safety issues already outlined, might be prohibitive.
- Would the FEG generate enough electricity to be profitable?

Answers to these issues ought to be considered as part of any comprehensive evaluation of the technology, but they are well beyond the scope of this thesis. In particular, it is very difficult to estimate the costs of the FEG construction and maintenance, so detailed evaluation of the economic feasibility of the FEG is not attempted in this thesis\(^3\). Addressing the issues listed above can be thought of as the “next tier” of evaluation, after the more fundamental questions about how the FEG would perform have been answered, which is what this thesis attempts to do.

This thesis focuses on the FEG literature, which contains a number of statements about how the FEG will operate and perform. Since a full-scale prototype has not yet flown at the high altitudes envisioned, these statements about performance are not based on empirical evidence but instead are better characterised as claims, based on theoretical calculations, simulations, and also some experiments at a much lower altitude with small-scale models. There are three broad claims (each contains a number of more specific sub-claims) that I will focus on in this thesis:

- FEGs can generate more electricity (per unit rotor area) than conventional, ground-based wind turbines, due to the higher power density of high altitude winds.
- FEGs can be deployed across a large area (in particular, throughout a 1,000 km wide band extending from Perth to Brisbane in Australia). This means that FEGs can be strategically located to integrate with existing power networks.
- FEGs have much higher capacity factors\(^4\) than conventional ground-based wind turbines, making them a potential candidate for base load power generation.

\(^3\)Fletcher and Roberts (1979) noted the difficulty of coming up with estimates for the costs of the various components for a precursor to the FEG, given that nothing like that had been attempted before.

\(^4\)Capacity factors are introduced and discussed in Section 2.1.
I chose these three broad claims, because they are (i) fundamental to the successful operation of the FEG and thus would be of interest to stakeholders, etc., and (ii) able to be assessed using only published literature and other publicly available data, and do not require “insider” knowledge about the specific design and construction of the FEGs (information that is not publicly available).

In this thesis I review these claims, and attempt to evaluate them by calculating the performance of FEGs myself in much more detail than is presented in the literature.

I contend that the FEG is much more limited in its potential to generate electricity at altitude above Australia than claimed in the FEG literature. The calculations I have performed show that the FEG would not perform nearly as well as claimed, and these calculations could have been done at any time over the years since the FEG concept was first introduced, but were not published or included in FEG-related papers. (The calculations that I performed are indeed necessary to fully understand the performance of the FEG, because in many places the FEG literature itself stresses the importance of such calculations, but then does not provide them.)

1.3 Outline

This thesis is split into five chapters. Chapter 2 reviews the available literature on the FEG and the literature discussing high altitude wind (in particular the jet stream) as a potential energy source. Chapter 3 describes the quantitative methods I used to test the claims about the FEG, and Chapter 4 reports the results of those calculations. Chapter 5 discusses my results, and how they do not support the claims made about the FEG, followed by discussion of the failure of the FEG and inadequacies in the literature. In the conclusion (Chapter 6), I consider the future of the FEG, in light of my evaluation.
Chapter 2

Literature Review

2.1 Conventional Wind Power

At its most fundamental, “wind power” is the conversion of the kinetic energy in the wind into mechanical energy and then electrical energy via a wind turbine and generator (Inglis, 1978, p.18). Wind power is a well-established alternative to fossil fuel-based methods of electricity generation, with a long history of development and widespread commercial use (Freris and Infield, 2008, pp.15, 28). Freris and Infield (2008) name wind power as “the leading source of new renewable energy” (Freris and Infield, 2008, p.xiii).

The environmental credentials of wind power are well documented:

- The wind resource, ultimately deriving from incoming solar energy, is renewable and inexhaustible (Freris and Infield, 2008; Şahin, 2004).

- Wind is available across the entire surface of the earth (Freris and Infield, 2008, p.15).

- Wind turbines do not produce greenhouse gases or air pollution as a byproduct of electricity generation (Hossain, 2009; Randolph and Masters, 2008; Şahin, 2004; Tester et al., 2005).

- Wind turbines do not require water in order to generate electricity (cf. steam turbines used in coal power plants) (Tester et al., 2005, p.635).

Tester et al. (2005) state that considered over a complete lifetime, the carbon dioxide emissions associated with the operation of a wind power plant will be 2% of those associated with a coal power plant of a comparable size (p.636).
The amount of electricity that a turbine can generate from the wind is ultimately a function of the power density of the wind. “Power density” is a term used to refer to the energy flux density of wind: it is the amount of kinetic energy that passes through a unit area perpendicular to the wind direction per unit time. It is calculated from the wind speed and the air density using the formula

$$P_w = \frac{1}{2} \rho v^3,$$

(2.1)

where $P_w$ is the power in the wind, $A$ is the area that the wind is passing through, $\rho$ is the air density, and $v$ is the wind speed. As the equation shows, the power density in the wind varies with the cube of the wind speed. Wind patterns at surface level are highly variable over time (whether seasonal, daily, or hourly) and space (e.g. dependent on local topography), and so it is difficult to nominate a “typical” value of power density for surface-level wind (and so it is difficult to find literature that does so). Fletcher and Roberts (1979) estimated the annual average power density for ground-level winds in Australia to be about 0.2–0.4 kW m$^{-2}$. Archer and Jacobson (2005) considered sites with annual average wind speeds of 6.9 m s$^{-1}$ or higher at a height of 80 m to have good potential for low-cost electricity generation. A wind speed of 6.9 m s$^{-1}$ near ground level has a power density of 0.2 kW m$^{-2}$ (although it is important to point out that the power density of the annual mean wind speed is not the same as the annual mean power density$^1$). An atlas of high altitude wind power density (Archer and Caldeira, 2008) estimated the median annual power density at 80 m over the entire world (based on re-analysis data$^2$ for the period 1979–2006), and found that most continents and coastal waters have median power densities

---

$^1$This is because in general, the cube of the average of a number of values does not equal the average of each of those values cubed. Power density is proportional to the cube of the wind speed, and the factor of $\rho/2$ can be considered a constant for nearly all practical purposes. Consider the simple case of two values, $a$ and $b$, which have an average of $(a + b)/2$. The cubes of those values, $a^3$ and $b^3$, have an average of $(a^3 + b^3)/2$. The cube of the average of $a$ and $b$ is $((a + b)/2)^3 = (a + b)^3/8 = (a^3 + 3a^2b + 3ab^2 + b^3)/8$. This is not equal to the average of the cubed values $(a^3 + b^3)/2$, except in the trivial case $a = b = 0$. This demonstrates that the mean of the power density can’t be derived from the mean wind speed; power density needs to be calculated separately for each wind speed observation over space/time, and then averaged.

$^2$Re-analysis data is explained in more detail in Section 3.1.1. Archer and Caldeira (2008) used a re-analysis dataset from the National Centers for Environmental Prediction and Department of Energy, called the NCEP-DOE AMIP-II Reanalysis. The re-analysis incorporates actual observations of the atmosphere (e.g. wind speed, temperature, pressure, specific humidity) from radiosondes across the world into a single model of the atmosphere, and interpolates the state of the entire atmosphere onto a set of grid points in space at a series of discrete time points.
in the range of 0.01–0.50 kW m\(^{-2}\), increasing up to around 1 kW m\(^{-2}\) over the open ocean. The analysis of Archer and Caldeira (2008) at the 80 m level is (intentionally, necessarily) coarse-grained, and the calculated values of median power density at specific locations are unlikely to be accurate. For my purposes, it is sufficient to consider just the order of magnitude of the median power density.

At this point, it’s worth noting that a wind turbine can’t extract all of the energy from the wind—the effort of turning the turbine rotor slows down the wind, but the particles that make up the air don’t (and indeed, can’t) stop completely after passing through a rotor. \(C_P\), the power coefficient, represents how much power \(P\) is captured by a wind turbine as a fraction of the total power in the wind that passes through a cross-section the same size as the turbine (Simões and Farret, 2008, p.12).

\[
C_P = \frac{P}{\frac{1}{2} \rho A v^3},
\]

where \(\rho\) is the air density, \(A\) is the swept area of the rotor and \(v\) the wind speed. The Betz Limit is the theoretical maximum proportion of power that can be extracted from oncoming wind (Tester et al., 2005, pp.624–626). It is \(16/27\), or 0.593.

Ideally, electricity generation should be predictable and controllable. The biggest limitation of wind power is that the wind resource is intermittent and can’t be controlled (Tester et al., 2005, p.617). In periods of little or no wind, wind turbines won’t generate electricity at all (winds below a threshold speed, called the “cut-in” wind speed—the value of which depends on the size and design of the turbine—will not be strong enough to overcome the internal friction of the drive train and turn the rotor blades). More generally, the actual output of a wind turbine will go up and down over time, following the pattern of the fluctuating wind speed. Wind turbines have a rated power output, which is output when winds reaches particular speed (the rated wind speed). The nameplate or rated output of a wind turbine is dependent on the rated wind speed and the diameter of the rotor, the values of which are decisions made by the wind turbine designer (Tester et al., 2005, p.632). Given the typical values of power density in winds at ground level discussed above, wind turbines rated at 1–2 MW need rotors 60-100 m in diameter to generate their rated power at a reasonable wind speed (that is, other than the strongest wind speeds, which would have higher power density, but occur too rarely to rely on for electricity generation). Hence, despite wind turbines having a rated output, the actual power output of a turbine will vary over time with the actual wind speed, which may often be below the rated wind speed (and thus the turbine will be generating below the rated power).
This gap between the rated power output and the actual output of a wind turbine can be summarised by calculating its capacity factor. The capacity factor of a power plant is defined as the ratio of the actual total energy output of that power plant over one year to the amount of energy that would have been output over one year had the plant been producing power continuously at its rated output (Freris and Infield, 2008, p.71). Capacity factors are measured from actual turbine performance, or can be inferred from wind speed data (for a turbine with a known rated power, rated wind speed, rotor diameter, etc.). Tavner (2008) reports that wind turbines in the UK have capacity factors ranging from 15% to 51%, according to British Wind Energy Association data from 2006 (Tavner, 2008, p.4398). Freris and Infield (2008) claims that the average capacity factor for onshore wind turbines in the UK is about 30% (p.71). Pacala and Socolow (2004), when speculating about how much wind power would be needed to displace coal power plants by 2054, accounted for the intermittency of wind power by assuming that 3 GW of installed rated capacity would supply 1 GW of actual base load capacity, implying a capacity factor of one third, or 33%. The average capacity factor of wind power projects in the US over the period 2006–2013 was 32.1% (Wiser and Bolinger, 2014, p.38). The capacity factors of US wind power projects could vary substantially from this long-term mean, however; for the year 2013, the capacity factors for projects ranged from 5–10% all the way up to 50–55% (Wiser and Bolinger, 2014, p.41). Boccard (2009) showed that the mean capacity factor of wind turbines in Europe over the period 2003–2007 was only 20.8%, demonstrating that a widely-held assumption that wind power capacity factors were typically 30–35% were overly optimistic. Approaching the same problem from the opposite direction, Flora et al. (2014) calculated that

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3Note that the capacity factor can be calculated for any type of power plant with a rated power output (coal, nuclear, solar, hydro, gas), and is not specific to wind turbines. Even though coal is not an intermittent energy resource like the wind resource, and so coal power plants might be expected to constantly perform at their rated power output, they still need to occasionally reduce or halt power output for maintenance reasons, reduced demand, etc. Therefore, even “baseload” power plants will have capacity factors of less than (although close to, perhaps) 100%.

4Wiser and Bolinger (2014) note that although the 2006–2013 average is higher than the average capacity factor for the period 2000–2005, 30.3%, the trend of average capacity factor over time has been stagnant, despite new wind power projects employing improved technologies and installing larger turbines. The authors attribute this to three factors: purposeful curtailment of wind power generation because of various grid integration issues; inter-year variation in the wind resource caused by (for example) El Niño/La Niña patterns; and the increase of wind power projects built in areas with a lower quality wind resource (pp.38–44).
the average ratio of *unused* wind turbine capacity to the maximum possible power out for wind turbines in Europe was 0.79 for period 1998–2011. This accords with the Boccard (2009) result for Europe.

These two issues, the low power density of surface winds that necessitate building wind turbines with larger rotor diameters in order to generate more power, and the intermittent, variable nature of surface winds that leads to turbines spending much of their time generating below their capability, are what motivated Roberts to investigate the possibility of harnessing winds higher in the atmosphere. The next section reviews the available published literature on Roberts’ invention.

### 2.2 The Flying Electric Generator

In this section, I review the published literature (journal articles, conference papers, patents and technical reports) on the Flying Electric Generator. In nearly every case, Roberts is the author or a coauthor. The papers reviewed cover the period 1979–2014. I’ve reviewed every paper that I was able to obtain, but there were some papers about the FEG that I was not able to find (see Section 2.2.12). As outlined in Section 1.2, my review of the literature focuses on claims made about the higher power density enjoyed by FEGs, the wide range of locations they can be deployed, and the high capacity factors (comparable to base load power plants) that FEGs are predicted to have. To this end, then, I will particularly focus on the details provided in the literature about the following:

- Wind resources available to the FEG, which includes claims made about the power available in the wind, optimal locations and altitudes for operation, seasonality of high altitude winds, and downtime due to insufficient wind;

- FEG design and performance, which includes the weight and rotor size of the FEG platform, tether weight\(^5\), the rated power of FEG platforms, and predicted capacity factors.

\(^5\)Parameters such as platform/tether weight and rotor size are important for simulating FEG performance later.
2.2.1 The Charles Kolling Research Laboratory Technical Notes

The precursor to the FEG began with a series of technical papers written in 1979 at the Charles Kolling Research Laboratory, part of the Department of Mechanical Engineering at the University of Sydney. Despite considerable effort, I have been unable to locate copies of these reports. The titles suggest that they focused on different aspects of the “jet stream wind energy project” (the “Flying Electric Generator” concept had not been created yet): “An Economic Study of Electricity Generation from the Jet-stream” (Fletcher et al., 1979), “The Use of Australian Upper Wind Data in the Design of an Electrical Generating Platform” (Atkinson et al., 1979), “Various Engineering Concepts in the Design of an Aerodynamic Generating Platform” (Roberts, 1979b), and “Tether Design for Jet-stream Wind Energy Project” (Roberts, 1979a). I believe that these papers developed a concept different from the helicopter-like rotorcraft that Roberts developed later; this original concept was the one detailed in Fletcher and Roberts (1979), which I’ll discuss shortly.

Of these original papers, Atkinson et al. (1979) has been cited by Roberts in at least seven of his subsequent papers; the calculations of the high altitude wind resource in this paper have seemingly been used for years after. I’ve pieced together the contents of the report as best I can and reviewed it in Section 2.3.3.

2.2.2 Fletcher and Roberts (1979)

“Electricity Generation from Jet-Stream Winds” (Fletcher and Roberts, 1979) was published in the peer-reviewed Journal of Energy in the same year as the Charles Kolling Research Laboratory reports. The concept discussed in this paper is not a FEG; instead, the paper describes a tethered fixed-wing glider with two wings (similar to a biplane), which has four shrouded turbines between the wings. The wings provide the lift, and the turbines capture the power in the wind. Since any further development of this concept by Roberts ceased relatively soon after publication (in favour of the FEG concept), I won’t go further into the details of the design. However, other parts of the paper are relevant for understanding the development of the FEG.

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6The University of Sydney library catalogue indicates that the library holds the entire series of Charles Kolling Research Laboratory Technical Papers (which were written on a wide variety of different topics), but manual inspection of the stacks revealed that all the papers specific to high altitude wind power were missing from the collection.
Wind Resource

This paper makes it very clear that the authors were focused on exploiting the high wind power density of the jet stream. The authors explain their proposed energy resource in detail. In addition to a brief description of the jet stream’s underlying causes, the authors note that over Australia, the jet stream winds “blow within a few degrees of due west all the year round”\(^7\), at an approximate altitude of 10 km and average wind speed of 35 m s\(^{-1}\) with peaks above 100 m s\(^{-1}\). (Fletcher and Roberts, 1979, p.241) Further, it is mentioned that jet stream winds in the southern hemisphere are stronger than those in the northern hemisphere, and that Australia has a particularly stable jet stream pattern, since the winds arrive from the Indian Ocean and first pass over the flat terrain of Western and central Australia. The authors also state that the jet stream is located just below the tropopause.

Although the jet stream is a global phenomenon (and so there are many locations around the world that could be chosen for analysis), the authors focus on operation just over Australia. In the introductory section, the authors note the stable and strong jet stream pattern over the Australian continent as particularly favourable for FEG operation and present a contour plot of annual average power density at 250 hPa over Australia, bringing to attention a “west-east ridge of maximum power density” at about 30°S (Fletcher and Roberts, 1979, p.242). The maximum of this ridge is 18.12 kW m\(^{-2}\), and is located above Moree in NSW. The wind data used in the paper comes from Bureau of Meteorology high altitude soundings for particular sounding sites across Australia.

This paper also stands out because it mentions the seasonality of the jet stream (and thus power density and wind speed) explicitly and quantitatively. The authors presented a figure showing the annual variation of power density above Charleville, QLD. The annual average power density for Charleville at 250 hPa (about 10.7 km in altitude) was 16.04 kW m\(^{-2}\), but the monthly average power densities at this altitude ranged widely from about 5 kW m\(^{-2}\) (during November-February) to 45 kW m\(^{-2}\) in July (30 kW m\(^{-2}\) in June, 35 kW m\(^{-2}\) in August). Such a large difference in power density between months of the year would surely imply uneven electricity output over

\(^{7}\)This claim, quoted directly from Fletcher and Roberts (1979), is incorrect. It implies the jet stream wind maintains a steady west-to-east direction, with very little movement north/south. Although the jet streams do have a strong net west-to-east component when considered over long time periods like a year, the actual jet stream core meanders north and south, resulting in wind directions substantially different from due west over shorter time scales.
the year, but the authors don’t mention the consequences of such strong seasonal variation.

Design

The design of the fixed-wing concept craft is shown in Figures 2.1 and 2.2. Although the specifics of the design of this fixed-wing concept aren’t relevant to the FEG, it’s still worth looking at the tether calculations, since the same fundamental principles apply to the FEG. The tether envisioned in the paper was of a kevlar core (for tensile strength) surrounded by an aluminium sheath (to conduct the electricity). In this design, there would be two tethers attached to the craft. The authors mention that the tether diameter would vary with height, so ensure adequate tensile strength along the whole length, but this is not quantified (they mention that the variation of diameter would be small, so using a constant-diameter tether with a fixed weight per unit length in calculations is an acceptable approximation for their purposes). The tether properties for a 1 MW and a 10 MW craft were provided in the paper, which I’ve included in Table 2.1, along with imputed values for the lengths of the two tethers, using the information provided (I’ve assumed them to be equal in length).

Figure 2.1: A top-down view of the fixed-wing concept craft described in Fletcher and Roberts (1979). This diagram is based on Figure 4 of that paper.

I could not get consistent results between the lengths of the Kevlar and con-
ducting components of the tethers (I treated both as cylinders, using the diameters listed in Table 2.1 to calculate the cross-sectional areas of each component). The tether lengths imputed from the conducting component values seem to be closer to the expected result, since the authors calculated the optimum angle of the tether to the horizontal at the platform to be around 47–56 degrees. Putting this discrepancy aside, these tether values will be useful to compare to the tether parameters used for later designs.

**Capacity Factors**

Although the capacity factors for this particular design are no longer relevant, they still provide context for the capacity factors claimed by the FEG. Charleville, Woomera, Forrest and Perth were used as test locations for an economic analysis of hypothetical 10 MW and 100 MW platforms. All four of these locations lie in the west-east ridge of maximum power density mentioned above. The economic analysis listed the capital and operating costs as well as the capacity factors for a hypothetical FEG at each of the four locations. Charleville was the location offering both the highest capacity factor (0.47/0.35 for the 10 MW and 100 MW platforms, respectively). This is in contrast to Charleville being ranked third out the four locations in terms of annual average power density (Woomera and Forrest are ranked first and second with annual average power densities of 17.28 kW m\(^{-2}\) and 16.13 kW m\(^{-2}\), respectively).
Table 2.1: The properties of the tethers used on hypothetical 1 MW and 10 MW crafts from Fletcher and Roberts (1979). All values are from Fletcher and Roberts (1979), except for the values in italics. The value of the density of Aluminium was obtained from Tennent (1997) and the value of the density of Kevlar was obtained from DuPont (2000). Note that in this early platform design, each platform has two tethers.

<table>
<thead>
<tr>
<th>Item</th>
<th>1 MW Platform</th>
<th>10 MW Platform</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total platform weight (kg)</td>
<td>5790</td>
<td>42400</td>
</tr>
<tr>
<td>Total Kevlar cable weight (kg)</td>
<td>2650</td>
<td>27600</td>
</tr>
<tr>
<td>Individual Kevlar cable diameter (mm)</td>
<td>10.1</td>
<td>29.7</td>
</tr>
<tr>
<td>Total electrical conductor weight (kg)</td>
<td>2000</td>
<td>15100</td>
</tr>
<tr>
<td>Individual conductor diameter (equivalent) (mm)</td>
<td>5</td>
<td>13</td>
</tr>
<tr>
<td>Operating altitude (km)</td>
<td>11.8</td>
<td>11.8</td>
</tr>
<tr>
<td>Density of Aluminium (kg m(^{-3}))</td>
<td>2710</td>
<td>2710</td>
</tr>
<tr>
<td>Density of Kevlar (kg m(^{-3}))</td>
<td>1440</td>
<td>1440</td>
</tr>
<tr>
<td>Imputed length of conductor per tether cable (km)</td>
<td>18.8</td>
<td>21.0</td>
</tr>
<tr>
<td>Imputed length of Kevlar per tether cable (km)</td>
<td>11.5</td>
<td>13.8</td>
</tr>
</tbody>
</table>

2.2.3 Roberts and Blackler (1980)

“Various Systems for the Generation of Electricity Using Upper Atmospheric Winds” is the paper that introduces the FEG, or as it is called at this stage, the rotary-wing device/concept. The paper starts with a comparison of four different concepts for generating electricity at high altitude: the “airship” concept, the “open-rotor type turbine and biplane” concept, the “rotary wing concept with tail rotor or tailplane”, and the “ducted turbines with monoplane or biplane” concept. Except for the rotary wing concept, each is rejected for the reasons prescribed below.

The airship concept uses a balloon with rotors attached to it in some fashion. The balloon provides the lift, and the rotors work as conventional wind turbines.
Table 2.2: A calm wind summary for Forrest, WA, at 35,000 feet. (Table taken from p.71 of Roberts and Blackler (1980).)

<table>
<thead>
<tr>
<th>Stall wind speed in knots true air-speed</th>
<th>20</th>
<th>40</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of occurrences per annum below stall</td>
<td>26</td>
<td>72</td>
<td>86</td>
</tr>
<tr>
<td>On each occurrence the average period below stall - hours</td>
<td>9</td>
<td>21</td>
<td>33</td>
</tr>
<tr>
<td>Total hours per annum below stall</td>
<td>234</td>
<td>1512</td>
<td>2838</td>
</tr>
<tr>
<td>Percentage time below stall</td>
<td>2.7</td>
<td>17.2</td>
<td>32.4</td>
</tr>
</tbody>
</table>

The advantage to this approach is that a balloon can remain aloft in low wind conditions, and wouldn’t need to land due to inadequate winds. The authors reject the concept for two reasons: first, helium is expensive, and hydrogen is dangerous. Second, the balloon skin would need to be very strong to withstand the pressure differences at high altitude and in high winds.

The open-rotor turbine and biplane and ducted turbine and biplane are pretty much the same concept, just employing a different design of turbine. This is the concept that was the subject of Fletcher and Roberts (1979). The authors reject this fixed-wing approach due to the problem of having to land the craft in inadequate winds. The minimum wind speed required to remain aloft (the stall wind speed) was highlighted as a crucial performance parameter. Data was provided to show the effect of the stall speed (see Table 2.2).

Given that the fixed-wing craft would be relatively large and fragile compared to other fixed wing aircraft, having to perform multiple landings (and subsequent take-offs) was regarded as difficult and potentially risky (taking into account the possibility of tethers becoming tangled and the space required for a take-off/landing strip).

At this point, the rotary-wing concept was introduced. The authors pointed out that the two or more rotors on the device would provide lift via autorotation as well as generate power, and also had the ability to hover like a helicopter, drawing power from the ground. This is the advantage over the fixed-wing concept that the
authors press: the ability to hover means that the craft could remain aloft during times of inadequate winds, and then when it did land (during extended wind lulls, or for maintenance) take-off and landing would be much simpler and easier.

The next part of the paper describes some preliminary experiments with a rotor attached to the back of a car and then driven into the wind, followed by the construction of a two-rotor prototype which was flown in the University of Sydney’s wind tunnel. The experiment section is followed by an analysis of the efficiency of the rotors, the relationship between tether weight and tether tension, the optimal power to platform weight ratio, and then finally puts all of this analysis together by considering a theoretical craft operating at 35,000 feet above Forrest. This analysis calculated a capacity factor of 0.68 for the craft.

2.2.4 Blackler et al. (1981)

This conference paper, “Experiments with a Twin Rotor, Single Bladed Gyromill”, describes the construction of a small experimental rotorcraft (named the Gyromill at this stage) and the preliminary results of a test flight. The authors also outline the “philosophy” of the design, which is what I will focus on.

They start by mentioning that power density can be as high at 20 kW m\(^{-2}\) at jet stream levels (35,000 feet). After reviewing other concepts (balloon, fixed-wing) for generating electricity from high energy winds (essentially a brief version of Roberts and Blackler (1980)), the authors make the following comments:

The plain, fixed wing configurations all suffer from an inherent stall condition when there are insufficient winds aloft. Depending on the precise stalling speed of any configuration, it can be shown [(O’Doherty and Roberts, 1982)] that system collapse can occur for some thousands of hours per annum. To alleviate the stall, the fixed wing devices generally use circling or tacking manoeuvres in order to offset the collapse condition.

Furthermore, it should also be appreciated that the balloon and fixed wing (including hybrids) systems proposed so far are intended to remain aloft and unmaintained for periods up to 8000 hours per annum. These extended periods aloft appear to be necessary in order to avoid repeated and complex landing and take-off, or other manoeuvres, whenever the wind lulls at altitude. (Blackler et al., 1981, p.514)
2.2. The Flying Electric Generator

The authors bring up the issue of the minimum viable wind speed to remain aloft, in anticipation of presenting their solution to the issue. They (correctly) identify this wind speed as a critical design parameter of a high altitude wind power system. The mention of the expected duration of time spent aloft (8,000 hours a year, which is about 90% of the year) frames the expected “uptime” of a rotorcraft to about the same duration.

An advantage of the rotary-wing concept over the fixed-wing and balloon concepts is that the rotary-wing Gyromill can operate as a helicopter (drawing power from the ground) to (i) remain aloft during times when the wind is not strong enough to generate lift via autorotation, and (ii) land the craft easily when required (in contrast with the “complex” landing procedures necessary for fixed-wing and balloon concepts). The authors go to say that “[these] management considerations are statistically significant during the lull periods aloft, and they are considered by the current authors to be an integral and important part of the design features of a remote or tethered wind energy conversion system” (Blackler et al., 1981, p.514). It’s unclear what the comment about statistical significance refers to precisely (an unspecified wind study, presumably), but the key point, that the Gyromill can hover, aiding landing and remaining aloft, is inescapably clear.

The authors also go to considerable lengths to specify the scale of the Gyromill. They write:

The present authors wish to make it clear that the current paper is not intended to relate to operations of a tethered windmill system at the tropopause level. It acknowledges that the ultimate objective or prize might be to obtain energy conversion at this level, but it can be asserted that the strength of the tropospheric winds tend to increase in strength and persistence [(O’Doherty and Roberts, 1982)] as the altitude increases.

The current paper is intended to simply report on our present constructional work and our future tests with the gyromill concept. We are of the firm opinion that the gyromill concept needs much closer examination than simply paper studies. The system will be investigated and evaluated at a meaningful research scale by suitable experimentation and demonstration.

... The authors have opted to investigate, by analysis and experiment,
2. Literature Review

the characteristics of the gyromill concept. It is not intended at this time to investigate the high altitude performance. Therefore, considerations of the tether’s strength, weight, conductivity and insulation, etc., can be disregarded for the moment. This then focuses attention onto the layout and design of a simple, rotary-wing craft which can simultaneously remain airborne and generate electricity. In other words, we intend to work at altitudes of up to about 500 feet in winds applicable to these altitudes. (Blackler et al., 1981, pp.514–515)

This clear statement of intention is significant, because it provides a reference point for understanding subsequent research papers. In particular, we can see that the authors regard the jet stream as the ultimate goal, even though pragmatism compels them to focus on much lower altitudes for now.

The rotorcraft itself consisted of twin, single-blade rotors (8 feet in diameter) on a fuselage weighing 70 pounds. Figures 2.3 and 2.4 show the basic design of the rotorcraft. The motors and gears were all commercially available off-the-shelf parts. The rotorcraft operated with a number of tethers attached, in order to have complete manual control over its movement. The authors mentioned that automatic control would be an eventual goal, but at this early stage of experimentation the ability to manually adjust constraints was preferable. The authors reported that the craft was able to hover (drawing from mains power) without a problem.

The authors acknowledge the support of the Energy Authority of New South Wales, although no details are given of the nature of the support/grant. The National Energy Research, Development and Demonstration Council (NERDDC) grant (see next section) is not mentioned.

2.2.5 Roberts (1984)

This report, titled “Design and preliminary performance of the Gyromill Mk. 2”, is an end-of-grant report to the Australian Commonwealth Government’s National Energy Research, Development and Demonstration Council (NERDDC). The grant was specifically awarded to develop the rotary-wing concept for exploiting high altitude wind power.

As the title suggests, the report is focused on the technical details of the Gyromill Mk. 2. The Gyromill Mk. 2 looks very similar to the craft shown in Figures 2.3 and 2.4. It starts with a theoretical treatment of the rotor, to determine the operating parameters that would allow the gyromill to autorotate in 15 knot winds. The effect
2.2. The Flying Electric Generator

Figure 2.3: A top-down view of the rotorcraft described in Blackler et al. (1981). This diagram is based on Figure 1 of that paper.

Figure 2.4: A side-on view of the rotorcraft described in Blackler et al. (1981). This diagram is based on Figure 1 of that paper.
of the tether angle with the horizontal, the blade twist, rotor solidity\(^8\), and the collective pitch angle are all considered. Then, experiments using the Gyromill Mk. 2 (and its predecessor, the Gyromill Mk. 1) are described and the results compared with theory. The bulk of the report is devoted to detailing the design of the Gyromill Mk. 2, including about 100 diagrams.

The report mentions in passing that the project was awarded two research grants (not including the NERDDC grant) in 1980–81. It’s likely that two grants are those from the Energy Authority of New South Wales, and the Solar Energy Research Institute in the US.

Although the wind is not at all the focus of this report, the Preamble mentions that the winds are most powerful along an axis from Brisbane to Perth, at an altitude of 25,000 feet, with a power density of 18 kW m\(^{-2}\). It’s also noted that in Antarctica, the optimal altitude for a gyromill is 2,000 feet.

A central concern of the design of the Gyromill Mk. 2 was the disk loading. This is the ratio of the weight of the Gyromill (and tethers, etc.) to the area of the rotors, \(\frac{1}{2}mg_0/\pi r^2\) (where \(mg_0\) is the weight of the craft and \(r\) is the blade radius). The weight is halved because there are two rotors to share the load. Reducing the disk loading (by reducing the total weight, or perhaps by increasing the rotor size) was the key to lowering the wind speed at which the gyromill could autorotate. A lot of detailed analysis went in to determining the operating parameters required to autorotate at the lowest possible wind speed. It was determined that a disk loading of 0.25 pounds per square foot was required for the Gyromill Mk. 2 to be able to autorotate in 15 knot winds. The final, constructed Gyromill Mk. 2 had a disk loading of 0.29 pounds per square foot (with a rotor diameter of 12 feet). Both the Mk. 1 and Mk. 2 Gyromills had single-bladed rotors, with a counterweight.

At the time of the report, Gyromill Mk. 1 had accumulated 50 hours of flight testing, up to an altitude of 30 feet. This guided much of the testing of the Mk 2. In the experiments performed on Gyromill Mk. 2, the maximum altitude could not have been much higher than 30 feet—the Gyromill Mk. 2 was towed on a trailer by a car driving at a constant speed into the wind (if there was any). In the autorotation tests, the Gyromill Mk. 2 was reported as rising up to one foot above its resting position (while being constrained by tethers). They were actually able to generate a small amount of electricity (0.4 kW) while in tethered flight in winds of about 30

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\(^8\)Rotor solidity \(\sigma\) is the ratio of the area of the rotor blades to the swept area of the rotor (Burton et al., 2001, p.174). A rotor of radius \(R\) with \(n\) blades, each with area \(A_{\text{blade}}\), will have a rotor solidity of \(\sigma = nA_{\text{blade}}/\pi R^2\).
feet per second. Overall, the agreement of the experimental results to the theory was regarded by the author as good.

The report concluded with the simple statements that the Gyromill Mk. 2 had been constructed within budget, the experiments had gone well so far and the results agreed with theory, and that testing would continue. Given that this was the end-of-grant report, it’s unclear if any further funding came from the Commonwealth Government after this.

### 2.2.6 Roberts and Strudwicke (1997)

The conference paper “Performance and stability simulation of a flying wind generator” is a presentation of the results of Strudwicke’s thesis, on the development of a control system to maintain the positional stability of a FEG. This paper is the third published after a 10-year gap in the FEG literature between 1984–1994 (I couldn’t obtain the first and second, see Section 2.2.12). The details are quite technical and not relevant to my thesis. The paper concludes that the control system was tested via simulation, and then used on a laboratory-scale rotorcraft (the “Gyromill Mk3”). The control system was successful at reacting to perturbations to the craft's position, and adjusting the collective pitch angle of the blades to compensate. The particular craft being studied, the “Gyromill Mk3,” had two rotors with diameter 1.2 m (Strudwicke, 1995, p.5) and used three tethers. The authors give a brief background of the concept before discussing the control system details, and provide a couple of details about the operating altitude. First, “[the flying wind generator concept] is intended to be flown in the vast and powerful jet stream winds” (Roberts and Strudwicke, 1997, p.425). As a preamble to discussing the steady state performance of the craft, the authors state “[a] number of machines have been built and flown at low altitudes. For high altitudes, typically around 5 kilometres, the steady state performance has been studied mathematically” (Roberts and Strudwicke, 1997, p.425–426).

### 2.2.7 Roberts (2000)

This conference paper, “Flying Electric Generator to Harness Jetstream Energy,” was presented a couple of years before Sky WindPower (see Section 2.2.13) was founded. It is the first paper to use the term “Flying Electric Generator”, and although it is used in the title of the paper, it is not used in the body of the text (a generic “craft” or “machine” is referred to). This paper makes reference to a
confidential commercial proposal made to NorthPower, a New Zealand based power company which operates in Australia, in 1998. Other notable things in this paper are a detailed description of a theoretical FEG design, with most parameters specified, and a declaration that FEGs operating at an altitude of 4 km offer the best return on investment.

Like the previous papers, this paper begins by outlining the high power density in jet stream winds, at a latitude of 30–40° in both hemispheres. The contrast with power density at the ground (50 to 100 times greater) is made, and the figure of an annual average power density of up to 20 kW m$^{-2}$ is quoted. The two wind studies (Atkinson et al. (1979) and O’Doherty and Roberts (1982)) are cited in connection with the maximum annual mean power density at jet stream levels over the US (17 kW m$^{-2}$) and Australia (19 kW m$^{-2}$). All of this very similar to previous papers. Something not seen before is the statement that a study of high altitude wind over China is underway, although no details are given (and this study is never mentioned again).

In a section of the paper specifically focused on the jet stream, the physical cause of the jet stream is described, along with a mention that the jet stream meanders north and south, “washing” a single location. As noted above, this paper goes on to nominate 4 km as the operating altitude that provides the best return on investment, but even so, no information about the expected power density or wind speeds at that altitude are provided.

The craft described in this paper is a two-rotor design, with three tethers (a conceptual design is shown in Figures 2.5 and 2.6). The angle the plane of the rotors makes with the wind can be up to 40°. The advantage of being able to function as a helicopter in low winds (by drawing power from the ground) is mentioned. It’s suggested that periods of insufficient winds could be taken advantage of to perform maintenance on the craft while landed. At this point, an interesting claim is made: the landed periods would not unduly affect the generating potential. This is quantified by stating “[averaged] over a year, it has been shown that at the best Australian and US sites landings due to lulls would be necessary for around 30 hours every seven days. Landings would be more common in summer than winter” (Roberts, 2000, p.2).

The discussion of the flight performance mentions that the best power coefficient values occur when the control axis angle is at around 55°, and the tip speed ratio is about 0.075. This leads to a consideration of the best operating parameters for
Figure 2.5: A top-down view of the two-rotor (with twin blades) craft described in Roberts (2000).

Figure 2.6: A side-on view of the two-rotor (with twin blades) craft described in Roberts (2000).
autorotating in low wind, where the work of Jabbarzadeh Khoei (1993) is referenced
(see Section 2.2.16). The angle the tether makes to the horizontal, $\beta$, was assigned a
“reasonable” value of 40°. The control axis angle and tip speed ratio for autorotating
were 24° and 0.10, respectively. The work by Ho (1992) and Strudwicke (1995) on
the control and stability of the craft is briefly reviewed in a dedicated section, too.

The paper also devotes a section to describing the parameters of a theoretical
3.1 MW craft. The details are provided in Tables 2.3–2.5. There is also a description
of the operating modes of a craft, applicable to all models of the rotary-wing type:

- Mode A: Operating at rated power output, in winds above the rated speed.
- Mode B: Operating at rated power output, at the rated speed (the lowest
  speed that the rated power can be produced).
- Mode C: Operating at below rated power output, in wind speeds below the
  rated speed.
- Mode D: Operating in autorotation (with zero power output), at the minimum
  possible autorotation speed.

Even though it is not mentioned in the paper, one could also add a “Mode E”, which
would be operating as a helicopter. It’s implied that over these different modes of
operation (including within the same mode), the control axis angle and tip speed
ratio will change. It’s also (more obliquely) implied that the tether angle to the
horizontal would change with operating conditions: “Finally it has been arbitrarily
assumed that the total cable length is no more than twice the operating altitude.
This criterion can be reduced, as required, if this length is considered to be excessive
in Mode D” (Roberts, 2000, p.5, author’s emphasis). This is also supported in Table
2.4, in the row “Tether angle $\beta$ implied by length.”

In Table 2.4, there is inconsistency among the values supplied for the tethers.
The values of the tether lengths reported do not match the lengths derived from
dividing the tether weights by the tether weight per unit length (set at 0.229 kg m$^{-1}$
in the paper). It is possible that the tether weights had been increased by a factor
to ensure the calculation results were conservative, but there is nothing in the paper
to indicate this.

The location applicable to the analysis in Table 2.5 is not mentioned anywhere
in the paper. Because of this omission, it’s not clear if these results are supposed to
Table 2.3: The properties of the craft described in Roberts (2000).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power (MW)</td>
<td>3.1</td>
</tr>
<tr>
<td>Rated operating altitude (km)</td>
<td>4.57</td>
</tr>
<tr>
<td>Number of rotors</td>
<td>2</td>
</tr>
<tr>
<td>Rotor diameter (m)</td>
<td>35</td>
</tr>
<tr>
<td>Rotor solidity</td>
<td>0.05</td>
</tr>
<tr>
<td>Craft weight (kg)</td>
<td>3135</td>
</tr>
<tr>
<td>Tether weight per unit length (kg m(^{-1}))</td>
<td>0.229</td>
</tr>
</tbody>
</table>

be optimal, or just typical. It is nonetheless helpful in that it provides a benchmark for further analyses.

The paper makes another specific claim, about the operating altitude of the craft:

Finally, the author has made a careful study of the Australian situation and it can be shown that the *best return on investment* from the sale of jetstream electricity is at an operating altitude of about 4 km. At lower altitudes the wind resource begins to wane excessively while at higher altitudes, adjacent to the jetstream core, the cost associated with higher transmission voltages become less beneficial. This optimal altitude concept is an important driver in the commercialisation of this technology. (Roberts, 2000, p.5, author’s emphasis)

The “careful study” referred to is actually a confidential commercial proposal made to a power company, NorthPower, in 1998. No details are provided. This quote also acknowledges that winds at this level are below the jet stream “core”, at 10–12 km. Despite this, no quantitative details of the wind resources at 4 km are provided in the paper.

In the conclusion of the paper, it is briefly mentioned that a number of small craft have been tested, the largest having two rotors with diameters of 12 feet and a rated power of 5 kW. This 5 kW craft was tested at low altitudes, and the results were described in Roberts and Pan (1999), a paper published in Chinese that I was unable to obtain. Finally, it’s mentioned that a 50 kW craft is in the planning stage, although no other details are given.
Table 2.4: The performance of the craft described in Roberts (2000) during its different operating modes. The rows marked with a double asterisk (**) have been calculated by me. The value for the tether length in Mode A, 3.32 km, has been marked with an asterisk (*) because I believe it is a typo—the tether length cannot be shorter than the operating altitude. This also means that the tether angle cannot be calculated.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mode A</th>
<th>Mode B</th>
<th>Mode C</th>
<th>Mode D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Output (MW)</td>
<td>3.13</td>
<td>3.13</td>
<td>1.26</td>
<td>0</td>
</tr>
<tr>
<td>Control axis angle $\alpha_c$ (°)</td>
<td>27.4</td>
<td>47.0</td>
<td>49.4</td>
<td>26.0</td>
</tr>
<tr>
<td>Wind speed (m s$^{-1}$)</td>
<td>36.6</td>
<td>25.8</td>
<td>18.3</td>
<td>10.2</td>
</tr>
<tr>
<td>Hours per annum at or above wind speed</td>
<td>570</td>
<td>2280</td>
<td>4330</td>
<td>6950</td>
</tr>
<tr>
<td>Maximum tension on each side cable (kN)</td>
<td>148.9</td>
<td>149.8</td>
<td>115.8</td>
<td>30.3</td>
</tr>
<tr>
<td>Range of each cable (km)</td>
<td>3.32*</td>
<td>7.04</td>
<td>8.45</td>
<td>8.69</td>
</tr>
<tr>
<td>Tether angle $\beta$ implied by length** (°)</td>
<td>*</td>
<td>40.5</td>
<td>32.4</td>
<td>31.7</td>
</tr>
<tr>
<td>Mass of each side cable (kg)</td>
<td>1296</td>
<td>1923</td>
<td>2201</td>
<td>2310</td>
</tr>
<tr>
<td>Total tether length implied by weight** (km)</td>
<td>5.76</td>
<td>8.40</td>
<td>9.61</td>
<td>10.09</td>
</tr>
</tbody>
</table>

2.2.8 Roberts and Shepard (2003)

“Unmanned Rotorcraft to Generate Electricity Using Upper Atmospheric Winds” was the first paper co-authored by Bryan Roberts and David Shepard. This paper was presented in 2003, the year after Sky WindPower had been founded. In terms of its structure, the paper is very similar to Roberts (2000). However, a couple of changes in the proposed design of the craft have occurred since 2000:

- The craft may have two, four, or more rotors per unit.
- The craft would use a single tether, made from an aluminium-Spectra composite.

Also gone is the endorsement of 4 km as an optimal operating altitude. In fact, no operating altitudes were explicitly mentioned in the paper, except for when calculat-
Table 2.5: The output of the craft described in Roberts (2000) for two operating altitudes.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>At 15,000 feet</th>
<th>At 30,000 feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak power output (MW)</td>
<td>3.13</td>
<td>3.13</td>
</tr>
<tr>
<td>Annual capacity factor (%)</td>
<td>48</td>
<td>67</td>
</tr>
<tr>
<td>Annual energy output (GWh)</td>
<td>13.3</td>
<td>18.2</td>
</tr>
<tr>
<td>Approx. value of energy ($/annum)</td>
<td>$1.3 \times 10^6$</td>
<td>$1.8 \times 10^6$</td>
</tr>
<tr>
<td>Annual energy output per m$^2$ of rotor area (kWh m$^{-2}$)</td>
<td>6910</td>
<td>9480</td>
</tr>
<tr>
<td>Percentage of time landed (%)</td>
<td>20.3</td>
<td>16.7</td>
</tr>
</tbody>
</table>

The performance of a theoretical 2.81 MW twin rotor FEG (with rotor diameter 30.4 m): performance was calculated at 29,000 feet and 15,000 feet. Over a variety of US sites, the average capacity factor at 29,000 feet was 80%, while at 15,000 feet, the average was 60%. Now, this might have indicated a return to focusing on jet stream altitudes, but it is difficult to tell, because the summary of performance was immediately followed by this paragraph, a re-worked version of the same one in Roberts (2000):

Finally, there is some merit in the view that the best return on investment in jet stream energy will be dependent on the optimal, operating altitude. At low altitudes the average wind velocity wanes, while at higher altitudes, adjacent to the jet stream core, the costs produce a less than beneficial return, because of the need for a higher transmission voltage as the altitude increases. Thus it will be necessary to closely examine the best return from an investment as a function of the maximum operating altitude. Such an analysis would be site specific. Nevertheless the above figures give some idea of the situation. (Roberts and Shepard, 2003, p.7)

The paper describes a 50 kW demonstration craft that was in the final stages of design and construction (weighing 140 kg, with two 9.1 m diameter rotors). A figure showing the relationship between the control axis angle of the FEG and the wind speed states that the air density used for calculations was 1.23 kg m$^{-3}$, implying the
demonstration craft would be operating a low altitude, near the surface. The authors stated that they had FAA approval in the US and CASA approval in Australia to perform testing of the demonstration craft.9

2.2.9 Roberts et al. (2007)

“Harnessing High-Altitude Wind Power” (Roberts et al., 2007) is the only paper written by Roberts and his collaborators on the subject of FEGs that has been published in a peer-reviewed academic journal. This article in some ways represents a peak for the FEG: after many years of development, the FEG was on the cusp of being commercialised, and it was published in a prominent journal. The paper follows on well from Roberts (2000) and Roberts and Shepard (2003), in that parts of it are a restatement of some of those existing conference papers.

The central point of the article is that the FEG is technically feasible and economical. There are a lot of auxiliary claims/predictions (based on calculations) that get made along the way (specific power density values, capacity factors, etc.). The paper provides no direct experimental evidence of the feasibility of the FEG; the evidence is in the form of calculations showing the expected performance.

Importantly, Section VII provides details of a Demonstration Craft, which was specifically designed to attempt to show that the FEG concept is commercially viable (Roberts et al., 2007, p.141). I use these details as the basis for calculating the expected performance of the Demonstration Craft.

The article begins in the same fashion as the previous papers: the jet stream is introduced as a source of highly concentrated energy, with power density one to two orders of magnitude greater than available at ground level. The annual average power densities of 19 kW m\(^{-2}\) over Australia and 17 kW m\(^{-2}\) over the US are quoted and attributed to Atkinson et al. (1979) and O’Doherty and Roberts (1982), respectively, although this time, a there is also reference to calculations available on the Sky WindPower website. This new reference shows that the high altitude wind resource has been investigated more recently than 1982: the authors used wind speed data from the ERA-15 reanalysis data set to calculate the seasonal mean power density for all altitudes and latitudes (the means were calculated along lines of longitude). These calculations showed that the mean seasonal power density could exceed 10 kW m\(^{-2}\) “at the jet stream’s typical latitudes and altitudes” (Roberts et al., 2007, p.141). I use these details as the basis for calculating the expected performance of the Demonstration Craft.

Any results from these test flights, if they occurred, are not published in Roberts et al. (2007), Roberts (2011), or anywhere else I could find.
Mean seasonal power densities of non-jet stream winds (of any altitude or location) were not mentioned.

Alternative solutions (balloons, fixed-wing craft, and kites) are mentioned in a single sentence, before the authors declare their preference for the rotorcraft concept. The low altitude experiments of Roberts and Blackler (1980) and the four-rotor design presented in Roberts and Shepard (2003) are mentioned in a lead up to the article’s central premise:

Commercialization of the quadrotor technology could significantly contribute to greenhouse gas reductions.

Tethered rotorcraft, with four or more rotors in each unit, could harness the powerful, persistent jet streams, and should be able to compete effectively with all other energy-production methods. (Roberts et al., 2007, p.137)

The authors go on to acknowledge two drawbacks: the need for dedicated airspace that would not disrupt other aircraft, and the need to operate FEGs well away from populated areas (at least until the technology could be demonstrated to be safe). As first mentioned in Roberts and Shepard (2003), the authors envisioned a single tether. The ability of the FEG to hover during winds lulls and/or land easily is mentioned.

The article reveals the scale of commercial FEG operation envisioned by the authors: groups of FEGs, individually rated at 3–30 MW, would be clustered in a high altitude wind farm, ideally as close to centres of high electricity demand as possible. The energy loss over the length of the tether is predicted to be as high as 20%. This was by design, since energy loss to heat was deemed beneficial (although the reason was not explicitly mentioned, presumably to prevent the tether from icing).

The authors make a similar collection of claims about the performance of FEGs as was presented in Roberts and Shepard (2003): Over the period October 2000–September 2001, the average capacity factor of a FEG (of unspecified design) at 10,000 m over the US was 80% (with examples of 77% above San Diego and

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10 As alluded to in the paper, this analysis is available on the Sky WindPower website, and shows that 10 kW m⁻² is only exceeded during winter months (June–August in the southern hemisphere, and December–February in the northern hemisphere) at an altitude of around 10–12 km and a latitude of about 30° N/S. For the remainder of the year, average seasonal power density barely exceeded 5 kW m⁻², at any altitude or latitude, and was often, far, far lower.

11 Roberts et al. (2007) mentions that these capacity factor calculations are available on the Sky
90% above Detroit). This was compared to a capacity factor of 35%, presented as a typical value for ground-based wind turbines. The capacity factor calculations account for time spent grounded due to wind lulls or storms.

As was claimed in previous papers, it’s claimed that controlling the FEG via collective pitch rather than cyclic pitch will reduce maintenance requirements on the rotors, but this is accompanied by a new claim: the flexibility of the tether means that FEG rotors are better able to withstand wind gusts compared to rotors fixed on static, ground-based towers, reducing the fatigue on components due to gusts by an order of magnitude.

Another set of claims similar to those found in Roberts (2000) and Roberts and Shepard (2003) are the best operating parameters for (i) maximising the power coefficient \( C_P \) and (ii) autorotating in the lowest possible wind speed. The equilibrium performance studies by Ho (1992) and Jabbarzadeh Khoei (1993) are referenced. The best operating conditions for a maximum \( C_P \) of 0.4 occurs when the tip speed ratio \( \mu \) is 0.075 and the control axis angle \( \alpha_c \) is 50°. The FEG will autorotate at the lowest possible wind speed when \( \alpha_c \) is 24° and \( \mu \) is 0.10. Once again, the minimum wind speed required for autorotation is emphasised as a fundamental parameter for the FEG. Unlike previous papers, the authors add an example: “A typical minimum wind speed for autorotation is around 10 m/s at an operating altitude of 15000 ft (4600 m).” (Roberts et al., 2007, p.139).

Although much of the details in the article are very similar to previous papers, the authors do include concepts that were not given much coverage in previous papers: the use of GPS and gyroscopes to control the position of FEGs during operation, integration with the existing electricity grid, and integration with “dispatchable” power resources. I won’t dwell on the details of these sections, but the inclusion of the second two indicates an advancement of the project from merely being concerned with the FEG itself to how it fits in the wider picture.

The use of differential GPS, with a feasible accuracy of a few metres, is suggested as a way to monitor the pitch, roll and heading of the FEG in real time. Three or more GPS receivers/antennas fixed at the ends of the FEG platform would be one way to do this. Using onboard gyroscopes would be another way to monitor the angle of the FEG to the horizontal.

Regarding the integration of FEGs with the electricity grid, the authors envision

WindPower website (www.skywindpower.com), which they are, but I could not find on the website any details of the FEG configuration used for these calculations.
the tethers conducting electricity at 11–25 kV AC, although even higher voltages were possible with emerging technologies. The authors also claim that the high capacity factors (around 85%) of the FEG make dispatchable power sources economical (to cover the relatively rare times when the FEG cannot generate electricity). These options are not economical for ground-based wind power with capacity factors of 30%. Pumped water storage (hydroelectric dams), compressed air energy storage, and hydrogen gas creation are suggested as possible partner energy solutions that could work in tandem with a farm of FEGs, providing electricity when the FEGs were grounded (and having their stores replenished when the FEGs were operating). Apart from this general overview, these ideas are not worked out in any detail.

Both the grid integration and energy storage sections of the article mention the seasonality of the jet stream, an issue which has only been discussed very briefly in previous papers, when mentioning downtime. Although it is only relatively briefly mentioned in this article, the implications of the solutions to address seasonality demand attention. In particular, it is the north-south meander of the position of the jet stream over the course of the year that is addressed. The authors envision a number of prepared operating sites, which a mobile FEG could migrate through each year, following the location of the jet stream. These sites could be connected by a single high voltage line, to maintain continuous grid integration, and the FEG would simply “plug in” to the optimal site. It’s also tacitly conceded that tracking the jet stream might not be enough, and so energy storage could supply electricity in the off months for FEG operation. The example of Patiala, India is given, where the poor performance of a FEG (operating at 10.7 km) in summer (capacity factor 37%) could be offset by using hydrogen to generate electricity, which could be replenished using electricity from the FEG operating in the winter, when winds are strongest (capacity factor 90%).

Another section not seen before is dedicated to describing a Demonstration Craft, which “will demonstrate the commercial viability, or otherwise, of the flying generator concept” (Roberts et al., 2007, p.141). The section provides values for a number of parameters, which I’ve summarised in Table 2.6. The design of the craft is shown in Figure 2.7.

The Demonstration Craft was designed to operate at 15,000 feet (4,600 m), and it is in this section of the article that the authors include the paragraph about optimal height that was included in Roberts (2000) and Roberts and Shepard (2003):

Finally, there is some merit in the view that the best return on in-
Table 2.6: The parameters of the demonstration craft described in Roberts et al. (2007).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power (kW)</td>
<td>240</td>
</tr>
<tr>
<td>Rated operating altitude (km)</td>
<td>4.6</td>
</tr>
<tr>
<td>Number of rotors</td>
<td>4</td>
</tr>
<tr>
<td>Number of blades per rotor</td>
<td>2</td>
</tr>
<tr>
<td>Blade twist, $\theta_0$ (°)</td>
<td>0</td>
</tr>
<tr>
<td>Rotor diameter (m)</td>
<td>10.7</td>
</tr>
<tr>
<td>Rotor solidity</td>
<td>0.05</td>
</tr>
<tr>
<td>Craft weight (kg)</td>
<td>520</td>
</tr>
<tr>
<td>Tether weight per unit length (kg m$^{-1}$)</td>
<td>0.115</td>
</tr>
<tr>
<td>Tether diameter (mm)</td>
<td>10</td>
</tr>
<tr>
<td>Rated wind speed (m s$^{-1}$)</td>
<td>18.4</td>
</tr>
<tr>
<td>Autorotation wind speed (m s$^{-1}$)</td>
<td>11.5</td>
</tr>
<tr>
<td>Range of control axis angle, $\alpha_c$ (°)</td>
<td>10–45</td>
</tr>
<tr>
<td>Range of rotor speed (RPM)</td>
<td>130–300</td>
</tr>
<tr>
<td>Electrical transmission efficiency of tether (%)</td>
<td>90</td>
</tr>
<tr>
<td>Power consumption when hovering at rated altitude (kW)</td>
<td>75</td>
</tr>
<tr>
<td>Tether DC transmission voltage (kV)</td>
<td>15</td>
</tr>
</tbody>
</table>
Figure 2.7: A top-down view of the Demonstration Craft design described in Roberts et al. (2007). This diagram is based on the artist’s impression of the FEG shown in Figure 2 of Roberts et al. (2007), and on Figure 11 in Roberts (2011).

Investment of these crafts will be dependent on an optimal, operating altitude. At low altitudes, the average wind velocity wanes, while at higher altitudes, adjacent to the jet stream core, the costs produce a less than beneficial return, because of the need for a higher transmission voltage as the altitude increases. Thus, it will be necessary to find the best return from an investment as a function of the maximum operating altitude. This aspect will be developed and confirmed over 12 months of flights planned during the demonstration program. (Roberts et al., 2007, p.141)

Although this Demonstration Craft would operate at about 4 km, the explicit endorsement of that altitude as offering the best return on investment that was seen in Roberts (2000) is gone, as it was similarly missing in Roberts and Shepard (2003). There is no evidence that the Demonstration Craft was built, let alone tested at altitude. The authors intended to test the FEG in the southern parts of the USA, or outback Australia.

This Demonstration Craft is the most detailed description of a FEG provided in the literature. As such, I will use it as the basis for my own calculations on FEG performance in Chapters 3 and 4.

One of the main contentions of this article is that FEGs are economical, and to show this, the authors calculate the predicted cost of energy (COE) for a hypothet-
ical four-rotor FEG rated at 3.4 MW. The authors envisioned a cluster of 30 FEGs, creating a farm rated at about 100 MW. The rotor size was not specified, but each 3.4 MW FEG was estimated to weigh 9,500 kg (unclear if this includes the tether, but I don’t think so).

To determine running costs, the authors considered the FEGs operating at altitudes up to $9 \text{ km}$, at three US sites: Topeka, Detroit, and San Diego. Wind speed data for the period October 2000–September 2001 was used to calculate the capacity factors for the 100 MW FEG farms at each of these three locations, resulting in the following estimates: 91% for Topeka, 90% for Detroit, and 70% for San Diego. Downtime of 10% was assumed (for maintenance and storms), and tether losses of 20% were assumed.\textsuperscript{13}

### 2.2.10 Roberts (2011)

“Rotorcraft to capture high altitude energy” is the most recent paper on the FEG presented by Roberts at an academic conference (it was presented at the Future of Rotorcraft conference, hosted by the Royal Aeronautical Society in June 2011). This paper is similar in style to Roberts (2000); Roberts is the sole author, and Sky WindPower is not mentioned (I believe Roberts had moved on from day-to-day involvement with Sky WindPower by this time).

The paper starts out like almost all of the previous papers, with a description and explanation of the jet stream, before moving on to discussing the potential of the wind “resource”. The description of the wind resource includes many familiar elements (citing the annual means from Atkinson et al. (1979) and O’Doherty and Roberts (1982), for instance), but this time there is particular emphasis on modelling the cumulative distribution $P(V)$ of wind speed $V$ at a location using the Weibull

\textsuperscript{12}The authors refer to a “range” of altitudes, and supply a simple formula to calculate the rated wind speed ($V$, in $\text{m s}^{-1}$) for the 3.4 MW FEG given the operating altitude ($H$, in m):

\[ V = 14 + 5.7 \times \frac{H}{10000} . \]

This strongly implies that the authors performed this analysis assuming that the FEGs would adjust operating altitudes to generate the maximum amount of electricity possible.

\textsuperscript{13}In terms of costs (assumed to be in 2007 US dollars), the initial capital cost of a 100 MW farm was estimated to be $71$ million, maintenance was estimated at $82,000$ per year per 3.4 MW FEG, and the replacement cost of a FEG was estimated to be 80% of the initial capital cost (unspecified “life limited” components were estimated to require replacement at 10-year intervals, and “tether longevity is a risk”, but no further details were provided). All up, the COE for a 100 MW FEG farm was estimated to be 1.94c per kWh at Topeka, 1.96c per kWh at Detroit, and 2.49c per kWh at San Diego.
model, which has not been mentioned before outside of O’Doherty and Roberts (1982):

\[ P(V) = 1 - \exp \left( -\left(\frac{V}{V_0}\right)^n \right) \text{ for } V_0 > 0, \]

(2.3)

where \( V_0 \) and \( n \) are constants chosen to best fit the data (this was the technique used in O’Doherty and Roberts (1982)). There is a comparison of the amount of downtime between Oakland, CA with Albany, NY, for winds at 300 hPa and a threshold velocity of 10 m s\(^{-1}\): 1226 hours per annum below the threshold at Oakland, versus only 655 hours per annum at Albany. It’s not clear why this particular value of threshold wind speed (or operating pressure level) is chosen. Lulls of one day every 1.5 weeks is reported as “more or less typical of the US wind resource at altitude” (Roberts, 2011, p.3).

Another unique property of this paper is a detailed, chronological history of the experimental testing of the FEG, including the Gyromill Mk 1 and Mk 2, covering the period up to the mid 1980s. This account says that the Gyromill Mk 2 flew briefly at an altitude of 50 feet. This history leads into a description of the current four-rotor FEG design, which again is very similar to previous papers (e.g. aluminium-Kevlar tethers, 3-30 MW FEGs envisioned, restricted airspace required, angles of up to 50° to the wind, higher capacity factors than ground-based wind turbines, citing values of 71–90% over the US mentioned in Roberts et al. (2007), collective not cyclic pitch reduces maintenance, tethered FEG better withstands wind gusts). However, DC tether transmission at about 15 kV is now preferred, and there is no discussion of grid integration. Despite this omission of grid integration, it is concluded that FEGs “can be classed as baseload generators if the above capacity factors [71–90%] were to be demonstrated” (Roberts, 2011, p.6).

The treatment of the equilibrium flight performance is the same as previous papers, but in this paper, more attention is paid to the autorotation wind speed and operating parameters. In particular, the angle of the tether to the horizontal, \( \beta \), is allowed to vary to find the optimal value (35° is suggested as reasonable, different from the value of 40° used in Jabbarzadeh Khoei (1993), Roberts (2000), and Roberts and Shepard (2003)). A figure is included to show the affect of tether angle on the ability of the FEG to generate sufficient life to sustain autorotation, and from this, an “extremely important” conclusion is drawn:

*If a high altitude craft, with 5% solidity, were to have a straight, massless tether arranged at an angle of say 35 degrees to the horizontal, then for the craft to stay aloft the craft’s weight disk loading to dynamic*
pressure ratio cannot exceed 0.69. If we wish to have it in autorotation at 15,000 feet in say a 10 m/s wind, then the weight disk loading must be at or less than \((0.69 \times 38.5)\) Pa, or 0.553 lb/ft². In other words, the craft’s weight disk loading must be low by rotorcraft standards, and it must not exceed 0.553 lb/ft² to achieve an autorotation speed of 10 m/s at the nominated 35 degree cable angle.

In making the above statement it is realized that the tether has been assumed to be weightless. Of course, a change in the autorotation speed quoted above will be in proportion to the square root of any change in the weight disk loading, all other factors remaining the same. In practice it is estimated that the total tether weight, for say 15,000 feet operation, will be more or less equal to the craft’s weight. If we were to take all of the tether weight to be concentrated on the vehicle, then the maximum allowable weight disk loading is limited to not more than about 0.28 lb/ft², in order to achieve autorotation at the nominated 35 degree cable angle and 10 m/s. (Roberts, 2011, pp.9–10, author’s emphasis)

This simplified model of incorporating tether weight (which does not take into account the aerodynamic drag on the tether and the drag on the fuselage) is used to calculate the expected performance of a 3.1 MW FEG operating at 15,000 feet (4.6 km). This 3.1 MW hypothetical FEG is almost identical to the FEG considered in Roberts (2000). The FEG’s performance in the four operating modes, A–D, first outlined in Roberts (2000), are tabulated for Moree in NSW (it’s claimed that the wind profile at Moree is almost identical to the wind profile for Albany, NY). The capacity factor for this FEG is calculated to be 48%, with an annual energy output of 13.3 GWh. The downtime of the craft (at a threshold wind speed of 10.2 m s⁻¹) was calculated to be 20.3% of the year.

In addition to the calculations, it is for the first time made explicit that the angle the tether makes with the horizontal changes with the operating mode. In mode A, in a wind speed of 36.6 m s⁻¹, the angle is as large as 56°, while in mode D, in autorotation, the tether angle drops to between 30–35°. This means that the length of the tether changes with operating mode. I have included the imputed tether angles for each mode in Table 2.8; these calculations assume the tether is straight, and not in a catenary shape.

The paper includes a brief discussion of the stability and control of the craft, very similar to the section in Roberts (2000), before concluding. In the conclusion,
Table 2.7: The parameters of the hypothetical craft described in Roberts (2011).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power (MW)</td>
<td>3.1</td>
</tr>
<tr>
<td>Rated operating altitude (km)</td>
<td>4.6</td>
</tr>
<tr>
<td>Number of rotors</td>
<td>4</td>
</tr>
<tr>
<td>Number of blades per rotor</td>
<td>2</td>
</tr>
<tr>
<td>Blade twist, $\theta_0$ ($^\circ$)</td>
<td>Unspecified</td>
</tr>
<tr>
<td>Rotor diameter (m)</td>
<td>24.7</td>
</tr>
<tr>
<td>Rotor solidity</td>
<td>0.05</td>
</tr>
<tr>
<td>Craft weight (kg)</td>
<td>3140</td>
</tr>
<tr>
<td>Tether weight per unit length (kg m$^{-1}$)</td>
<td>0.46</td>
</tr>
<tr>
<td>Tether diameter (mm)</td>
<td>15</td>
</tr>
<tr>
<td>Rated wind speed (m s$^{-1}$)</td>
<td>25.8</td>
</tr>
<tr>
<td>Autorotation wind speed (m s$^{-1}$)</td>
<td>10.2</td>
</tr>
<tr>
<td>Range of control axis angle, $\alpha_c$ ($^\circ$)</td>
<td>10–50</td>
</tr>
<tr>
<td>Range of rotor speed (RPM)</td>
<td>Unspecified</td>
</tr>
<tr>
<td>Electrical transmission efficiency of tether (%)</td>
<td>90</td>
</tr>
<tr>
<td>Power consumption when hovering at rated altitude (kW)</td>
<td>Unspecified</td>
</tr>
<tr>
<td>Tether DC transmission voltage (kV)</td>
<td>15</td>
</tr>
</tbody>
</table>
the paper compares the performance of the 3.1 MW FEG with a typical ground-based wind turbine rated at 3.6 MW. It’s noted that the FEG requires less material, comparing the weight of the FEG (3.14 tonnes) to the weight of a wind turbine and tower (about 39 tonnes), has a higher capacity factor (48% for the FEG compared to 28% for the turbine), and has a higher value of energy produced per year per unit rotor area (6.91 MWh m\(^{-2}\) for the FEG versus 0.91 MWh m\(^{-2}\) for the turbine).

Although the vision of large, 3–30 MW FEGs providing baseload power has already been outlined in this paper, the conclusion contains, for the first time, a brief mention of the possibility of FEGs on a smaller scale: “smaller scale units could be constructed for surveillance duties, where a small electrical output may be used to power on-board avionics and sensors over long periods” (Roberts, 2011, p.12). No details are given of the size or rating of such FEGs, but it is the first acknowledgement that FEGs may have other applications than providing baseload power.

However, in another first, the rest of the conclusion addresses the “pressing difficulty” of developing generators/motors that are both (i) sufficiently light weight,
and (ii) high power output and high voltage. It’s noted that for the 3.1 MW FEG design, about 50% of the FEG’s 3.14 tonnes was taken up by the generators, with the remaining 50% being made up of the rotors, fuselage, control electronics, etc. The power-to-weight ratio of the generators has a direct impact on the performance of the craft, in particular the minimum wind speed required for autorotation. Again, for the 3.1 MW FEG, a power-to-weight ratio of 0.9 kW per lb is required to keep the autorotation wind speed at about 10 m s\(^{-1}\). If such a high ratio isn’t possible, the autorotation wind speed would rise. It is noted that commercially available auxiliary power units, such as those used on Boeing 747s have power-to-weight ratios in the right range, although they are not designed to deliver such high voltages. On this point, the paper concludes with a problem that remains to be solved:

Therefore, at this time the most difficult issue in achieving large-scale generating units at altitude is the design and production of low specific weight, special purpose, electrical machines. (Roberts, 2011, p.12)

Overall, there are four things striking about this paper, which set it apart from the rest:

- It’s not clear what altitude FEGs are envisioned flying at: downtime is investigated at 300 hPa, capacity factors are quoted that were calculated at 10 km, but all other examples in the paper use an altitude of 15,000 feet (4.66 km). There is no decisive statement about an optimal altitude.

- Roberts has a strong preference for designing FEGs around a minimum autorotation speed of 10 m s\(^{-1}\), whether at 300 hPa or lower (15,000 feet, between 500-600 hPa).

- The change of the tether angle to the horizontal with different modes of FEG operation, and the theoretical treatment of the tether weight as a point mass added to the FEG platform weight are outlined explicitly, for the first time.

- A technical (and perhaps economic) problem, namely the challenge of getting generators/motors with sufficiently high power-to-weight ratios, is mentioned as a problem to be solved, in contrast to the more optimistic conclusions of previous papers, which suggested that suitable components were already available commercially.
2. Literature Review

2.2.11 Papers Since 2011

Since the publication of Roberts (2011), there has been little research activity from Roberts. The few papers that have been written have been more general summaries of the FEG concept, rather than papers providing technical details or new results. Roberts has made submissions to state and federal government inquiries on renewable energy (Roberts, 2012b, 2013; Roberts and Roberts, 2014), and presented a paper to Future Directions International, an Australian independent research institute based in Perth (Roberts, 2012a). Most recently, Roberts presented an overview of the concept via video link to the 2015 Airborne Wind Energy Conference held in Delft in The Netherlands (Roberts, 2015).

Roberts (2012a) does contain details of a small four-rotor craft (termed an Electrical Generating Rotorcraft, or EGR): four rotors, 2 meters in diameter, will produce 4 kW of power in winds 12.9 m s\(^{-1}\) or higher, total craft weight of about 20 kg, tether weight of 25 kg km\(^{-1}\), operating at an altitude of about 500 m. The plan would be to scale up to a craft rated at 20 MW, operating at an altitude of 4 km. Capacity factors are claimed to be about 70–80%, high enough to be regarded as a baseload generator.

2.2.12 Literature Not Obtained

In addition to the Charles Kolling Research Laboratory papers that I’ve already mentioned, I could not obtain the following FEG-related papers:

- “The stability of a tethered gyromill” (Rye et al., 1981)
- “A report on initial flight trials with a tethered wind energy conversion system known as a gyromill” (Roberts, 1982b)
- “A report on hovering trials with a wind energy conversion system known as a gyromill” (Roberts, 1982a)
- “Hovering tests on a flying windmill known as gyromill” (Blackler and Roberts, 1983)
- “A new form of wind driven, electric generator” (Roberts, 1994)
- “Tethered rotorcraft as a means of electricity generation at high altitude” (Roberts, 1996)
2.2. The Flying Electric Generator


Although of course I cannot be certain, I think it unlikely that these papers contain crucial information or results that cannot be found in the literature I do have access to. These papers were only referenced once, and/or only in student theses—I’m assuming their obscurity reflects their relative importance.

2.2.13 Sky WindPower and Altitude Energy

Sky WindPower Corporation was founded in California in 2002 by inventor David H. Shepard (it is unclear if Bryan Roberts was also a founder) to commercialise the rotorcraft, known by this stage as a Flying Electric Generator. Shepard had been working on his own invention to exploit high energy winds since the 1980s. Roberts and Shepard presented at a conference in 2003 (Roberts and Shepard, 2003) and were co-authors on Roberts et al. (2007). I believe “Flying Electric Generator” is the name of the patented invention owned by Sky WindPower. Sky WindPower maintains a website (www.skywindpower.com) and has published at least two Executive Summaries (Sky WindPower, 2012, 2013) describing the current status of their FEG development. In their AWE review article, Cherubini et al. (2015) reported that Sky WindPower had gone out of business.

In 2011 in Australia, Bryan Roberts founded a limited liability company, Altitude Energy, Ltd. I believe this company owns the invention of the “Electrical Generating Rotorcraft”, patented by Bryan Roberts in 2011. The only activity of Altitude Energy that I have found are the papers written by Roberts over 2012–2014 (Roberts, 2012b,a, 2013; Roberts and Roberts, 2014).

2.2.14 Patents

The patenting of the rotorcraft/Gyromill/FEG/EGR came relatively late in the history of its development, in the early 2000s, around the same time that Roberts and Shepard started their attempt to commercialise the idea. The details of the patents are not particularly illuminating, although Roberts and Shepard (2007) contains some useful guidelines about the tether not elsewhere published in the literature: the FEG can be altered to output DC or AC. If DC, then two tethers are required. If AC, then three tethers are required. However, a single tether with the conductors integrated into it is also feasible. The authors suggest aluminium
Table 2.9: Australian patents related to FEGs.

<table>
<thead>
<tr>
<th>Title</th>
<th>Inventor</th>
<th>Date Granted</th>
<th>Patent Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windmill kite</td>
<td>Bryan Roberts</td>
<td>07/11/2001</td>
<td>2001PR8712</td>
</tr>
<tr>
<td>Control system for a windmill kite</td>
<td>Bryan Roberts</td>
<td>09/04/2009</td>
<td>2009238195</td>
</tr>
<tr>
<td>Electrical generating rotorcraft</td>
<td>Bryan Roberts</td>
<td>17/08/2011</td>
<td>2011293078</td>
</tr>
</tbody>
</table>

Table 2.10: US patents related to FEGs.

<table>
<thead>
<tr>
<th>Title</th>
<th>Inventor</th>
<th>Date Granted</th>
<th>Patent Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apparatus for extracting energy from winds at high altitudes</td>
<td>David H. Shepard</td>
<td>25/02/1986</td>
<td>US4572962 A</td>
</tr>
<tr>
<td>Power generation from high altitude winds</td>
<td>David H. Shepard</td>
<td>21/04/1987</td>
<td>US4659940 A</td>
</tr>
</tbody>
</table>

conductors, insulated to 10 kV each, integrated into a Vectran fibre tether cable. They claim that a per-tether weight of about 0.4 lbs/kW/1000 feet (0.6 kg/kW/km) is required, although if the single integrated tether is preferred, then the tether weight can be up to 0.8 lbs/kW/1000 feet (1.2 kg/kW/km). The patents filed by Roberts and Shepard are shown in Tables 2.9 and 2.10. In addition, there have been a number of FEG-related patents filed by other employees of Sky WindPower since 2007, building on the original FEG concept.

### 2.2.15 Student Theses

Roberts has supervised a number of research projects which investigate aspects of the FEG in detail, which Roberts has then cited in his published work. The theses describe the methods and assumptions behind FEG performance calculations in much greater detail than Roberts is able to provide in space-limited conference papers or journal articles. Some of the theses concentrated on particular technical problems: Rye (1986), Ho (1992), and Strudwicke (1995) focused on the stability and control of the FEG in flight. Murthy (2000) concentrated on tether dynamics.
The specific problems and how they were solved don’t matter for the purposes of this thesis. However, two theses (Jabbarzadeh Khoei (1993) and Welch (1999)) address issues that I am concerned with in this thesis, and so I’ll go over these in more detail.

2.2.16 Jabbarzadeh Khoei (1993)

Jabbarzadeh Khoei (1993), in his thesis titled “The Optimum Twist for Windmilling Operation of a Tethered Rotorcraft,” analysed the effect of rotor blade twist on FEG performance. Rotor blade twist refers to a gradual change in the cross-sectional shape of the blade from the root of the blade to the tip (in particular, a change in the angle that the leading edge of the rotor blade makes with the underside of the blade—the angle becomes more acute with distance from the root of the blade). Untwisted blades have the same cross-sectional shape along the entire length of the blade. Jabbarzadeh Khoei looked at the effect of blade twist on four metrics of FEG performance: windmill power coefficient, windmill lift coefficient, windmill torque coefficient, and the minimum wind speed for remaining aloft via autorotation. The conclusions of this thesis (the optimal amount of blade twist is either $2^\circ$, $7^\circ$, $8^\circ$, $13^\circ$ or $14^\circ$, depending on what performance criteria you wish to prioritise) are not as important as the method that Jabbarzadeh Khoei used to determine the different performance metrics of the FEG. This method has informed my own analysis of FEG performance.

The aerodynamics of rotors is complex, and I won’t go into the details. Jabbarzadeh Khoei based his analysis on the extended theory of lifting rotors developed by Gessow and Crim (1952). For my purposes, the important thing is this: using the code from Appendix B of Jabbarzadeh Khoei (1993) (see Appendix C of this thesis for the code itself), the following parameters can be estimated for a given rotor blade design and tip speed ratio: the windmill thrust coefficient, the windmill lift coefficient, the windmill power coefficient.

The tip speed ratio $\mu$ is defined as the ratio of the wind speed normal to the plane of the rotor, divided by the speed of the tip of the rotor blade:

$$\mu = \frac{v \cos \alpha_c}{\Omega R},$$

where $v$ is the wind speed, $\alpha_c$ is the control axis angle of the rotor (i.e. the angle the rotor is inclined into the wind from the horizontal), $\Omega$ is the rotational speed of the rotor, and $R$ is the length of the rotor blade from the hub to the tip (which is the radius of the rotor).
The windmill thrust coefficient $C_{TW}$ is the ratio of the thrust force that the wind imparts to the rotor, divided by the total force in the wind over the area of the rotor:

$$C_{TW} = \frac{T}{\frac{1}{2} \rho A v^2},$$

(2.5)

where $\rho$ is the air density and $A$ is the area swept by the rotor. The vertical component of the thrust force is lift, and we can calculate the windmill lift coefficient $C_{LW}$ by taking into account the angle that the rotor plane is inclined from the horizontal:

$$C_{LW} = C_{TW} \cos (\alpha_c + a_1),$$

(2.6)

where $a_1$ is the rotor backward tilt angle (the rotor blades can tilt slightly relative to the axis of the rotation). The coefficient of lift tells us how much lift a rotor will generate, given incident wind of a given speed and air density. In the context of a FEG, this helps tell us how much wind is required for a FEG (of a given mass) to generate enough lift to overcome gravity and remain aloft. Jabbarzadeh Khoei simplified the relationship between wind, lift and FEG weight $m$, taking into account the fact that the FEG is tethered at an angle $\beta$ to the ground, too:

$$C_{LW}(1 - \tan (\alpha_c + a_1) \tan \beta) = \frac{m g_0}{\frac{1}{2} \rho v^2}.$$

(2.7)

Jabbarzadeh Khoei coined the coefficient $C_{LWOP} = C_{LW}(1 - \tan (\alpha_c + a_1) \tan \beta)$ as a shorthand (for a given $\alpha_c$, $a_1$, and $\beta$). As I will show later, $C_{LWOP}$ is critical for determining the minimum wind speed required for a FEG to remain aloft.

As defined earlier, the windmill power coefficient $C_{PW}$ is the ratio of the power $P$ generated by a rotor divided by the power in the wind for an area the size of the rotor:

$$C_{PW} = \frac{P}{\frac{1}{2} \rho A v^3}.$$

(2.8)

The code used by Jabbarzadeh Khoei in his thesis calculates $C_{PW}$, $C_{TW}$, $C_{LW}$, and $C_{LWOP}$ for values of $\mu$, $\alpha_c$, $a_1$, $\beta$, collective blade pitch $\theta_0$ and blade twist $\theta_1$. From this, Jabbarzadeh Khoei was able to see the effect of varying blade pitch on the performance of $C_{PW}$ and $C_{LWOP}$. This approach can be used more generally to find the operating conditions (primarily $\mu$ and $\alpha_c$) that optimise $C_{PW}$ and $C_{LWOP}$. This is what I will use it for in Chapter 3.
2.2.17 Welch (1999)

Welch (1999) focused on the characteristics of high altitude wind over Australia in the thesis “A Statistical Analysis of Upper Atmospheric Winds”. This thesis was heavily influenced by Roberts’ own past wind analyses (Atkinson et al., 1979; O’Doherty and Roberts, 1982). Those reports were referenced and discussed by Welch, and their analysis methods were used by Welch.

Welch analysed wind speed measurements made by the Bureau of Meteorology at Moree, NSW, at the 850 hPa and 900 hPa pressure levels, corresponding to an operating altitude of approximately 1,000–2,000 m. Moree was chosen due to its location beneath the jet stream:

“This thesis is concerned with the stream running almost parallel and on top of latitude 30°. This stream meanders north and south more or less over the city of Moree, latitude 29°28’S, longitude 149°51’E. This is the location from which the wind measurements have been taken, and is the site at which it is intended to fly the craft.” (p.4)

Relatively low altitudes (compared to the location of the jet stream) were specifically chosen for analysis in order to prove the operation of a FEG at low levels. This choice was contrasted with the high altitudes analysed by Atkinson et al. (1979), who looked at 200 hPa and 250 hPa pressure levels, corresponding to 10,000–12,000 m in altitude.

Welch’s analysis involved fitting Weibull distribution parameters to the probability distribution of the wind speed above Moree. From the data, Welch calculated the long term average wind speed above Moree as well as its variation by month.

The concept of a minimum wind speed required for autorotation was acknowledged and discussed in the thesis, although no specific threshold values were mentioned. This study seems to have been performed without a particular FEG specification in mind.

Following the approach in O’Doherty and Roberts (1982), Welch analysed wind lulls and derived plots of wind speed vs the number of occasions per year at or below that wind speed, and plots of wind speed vs the average period (in hours) of lulls below that wind speed. These plots serve as a lookup graph for a threshold wind speed of choice, further indicating that these results were intended to be independent of FEG specification.

The one exception is when a wind speed of 15 m s$^{-1}$ was chosen in order to perform a month-by-month/seasonal analysis of the number of wind lulls and the
average length of those wind lulls. This is the same wind speed value that O’Doherty and Roberts (1982) used for their month-by-month wind lull analysis, and may have been the motivation for Welch’s choice.

One notable conclusion that Welch draws from his analysis is that some months, particularly January and February, will be unsuitable for operating a FEG at Moree, due to low average wind speeds and a large amount of inconsistency (frequent wind lulls).

2.2.18 Responses to Roberts’ Work

Fletcher, who had been co-author with Roberts on the 1979 paper, published two papers in the *Journal of Energy* in 1983. The first, “Aerodynamic Platform Comparison for Jet-Stream Electricity Generation” (Fletcher et al., 1983), performs an in-depth economic comparison of different high altitude wind energy generation concepts, including the rotary wing concept. The other three concepts analysed were variations on the fixed-wing concept outlined in Fletcher and Roberts (1979), and I won’t discuss them. Fletcher et al. (1983) identifies a number of issues with the rotary wing concept that increase its cost of generating electricity compared with the fixed-wing concepts:

- For all concepts (rotary wing and fixed-wing alike), the replacement and maintenance costs are higher compared to conventional aircraft. This is because to be competitive, electricity generating platforms would need to operate for at least 7,000 hours per year, while commercial aircraft might operate for about 700 hours per year, typically. This means that components will be worn out at a rate ten times faster than for conventional aircraft. While this might apply to fixed-wing and rotary wing concepts equally, the authors point out that conventional rotary wing aircraft typically have double the maintenance cost of conventional fixed-wing aircraft. In particular, the rotor, hub, and gearbox of the rotary-wing concept are relatively short-life components, indicating regular replacement would be necessary.

- The rotary wing concept is inclined at an angle to the wind, which means that there is a component of the oncoming wind that is in the plane of the rotor (as well as perpendicular to the plane of the rotor, which is what provides the thrust, etc.). It’s claimed that the component of wind in the same plane as the rotor induces an oscillatory load on the rotor, which leads to vibrations
that reduce the life of the generating components due to fatigue, and that vibration is a major cause of unscheduled maintenance on conventional rotary wing aircraft.

Overall, while Fletcher et al. (1983) found that the four concepts compared had similar rated wind speeds and stall speeds at 11.8 km, and also all had very similar capacity factors (calculated to be 0.45–0.46), the cost of energy for the rotary wing concept was 16.0 c/kWh (in 1983 Australian dollars), compared with a cost of 4.9–5.4 c/kWh for the other three concepts.

Another issue was raised in the paper, about the tether configuration for the rotary wing concept, and this argument was expanded in a second paper in same issue of the Journal of Energy, “On the Rotary Wing Concept for Jet Stream Electricity Generation” (Fletcher, 1983). The authors claim that there is a fundamental incompatibility between the range of control axis angle $\alpha$ of the rotors required for optimal electricity generation, and the limitations of the tether. This is because it is claimed that angle $\beta$ that the tether makes with the horizontal at the rotor varies with the ratio of excess lift $\Delta L$ (i.e. the lift that the rotor generates in excess of that required to balance the craft and tether weight) to drag $D$ (i.e. the horizontal component of the rotor thrust that pushes the craft in the direction of the wind, which is balanced by the horizontal component of the tension in the tether).

If the ratio $\Delta L/D$ is small, then the tether angle will be small, and the tether will be very long. At some critical angle (which would vary with materials and design), the tether would be so long (and therefore heavy) that it would break under its own weight. This is associated with a rotor angled at a large incline to the oncoming wind: more of the oncoming wind can be used for generation, and so one can get a large output for a given rotor size.\footnote{Fletcher et al. (1983) points out that if the tether was infinitely strong, the ideal angle of the rotors to the horizontal would be large, allowing more electricity to be generated per unit area of rotor, and the angle of the tether to the horizontal would be small, and hence the tether would be very long (with no fear of breaking). Then, all one would need to do would be to increase the rotor size so that enough lift could be generated to keep the whole thing aloft.}

Conversely, if the ratio $\Delta L/D$ is large, then the tether angle will be large, and so the tether would be shorter. However, in this situation, the angle the rotor makes with the horizontal is smaller, which means a lower amount of power generated per unit rotor area. This means a larger rotor is required to generate a particular rated power, which in turn means the tension in the tether would become larger, and so the tether diameter would need to increase to avoid breaking. The extra weight
caused by the increased thickness of the tether once again reaches a critical point where the tether breaks under its own weight.

The authors identify the range of 45–65° as the best tether angle to the horizontal, because outside this range required tether weights rise dramatically, increasing the chance of a tether break. Corresponding to this, it’s claimed that the rotor angle of incidence is constrained to between \( \alpha_c = 35° \) when \( \beta = 45° \) and then falls linearly to \( \alpha_c = 20° \) when \( \beta = 65° \). If the maximum allowable angle of rotor incidence is \( \alpha_c = 35° \), then the rotary wing concept would be confined to lower values of \( C_P \), as Jabbarzadeh Khoei (1993) showed in his thesis, and as is claimed in Roberts et al. (2007) (that is, the highest values of \( C_P \) are associated with \( \alpha_c \approx 50° \)).

As far as I can tell, none of these issues have been addressed or acknowledged anywhere else in the FEG literature.

2.2.19 Media

As might be expected for a project as novel as this, the Flying Electric Generator has attracted media attention. The FEG (in its various stages) appeared in *Engineers Australia* in 1982 ("Electricity generated by flying windmill" (Arbouw, 1982)) and again in 1994 ("Flying wind generator proposed" (Engineers Australia, 1994)). Media coverage picked up in the 2000s, as interest in renewable energy began to increase: “Reach for the Sky” (Torok, 2000) appeared in *New Scientist*, “Windmills in the Sky” (Behar, 2005) in *Popular Science* are early examples, along with “Plan B for Energy” (Gibbs, 2006) in *Scientific American*, which looked at a number of speculative energy technologies.

In 2007, the publication of Roberts et al. (2007) received a number of mentions in the media (Dasey, 2007; Davidson, 2007; The Economist, 2007; McKenna, 2007), including in *New Scientist* again and *The Economist*. In 2009 there was an article in *Nature*, “High Hopes”, about the burgeoning airborne wind energy industry (Vance, 2009). The articles typically struck a balance between optimism and scepticism when describing the inventions and repeating the claims made by the inventors. Claims were not rigorously scrutinised, although for balance some articles quoted other scientists expressing doubt about the viability of the project. In 2008, the FEG was named by TIME Magazine as one of the top 50 inventions of the year, and in 2011 it became the cover of *Popular Mechanics*, which contained an article about different high altitude wind power projects (Vlahos, 2011).

Not all reception has been positive; Mike Barnard, who was a Senior Fellow
(with a particular focus on wind energy) at the Energy and Policy Institute based in Washington DC between March and November 2014, wrote articles critical of the FEG on the site cleantechnica.com, raising a large number of issues that the FEG is likely to face (Barnard, 2014a,b). These include: the challenge of constructing lifting rotorcraft that would be larger than any helicopter built today, and for a lower price; the land- and air-space restrictions FEG operation would require; the fact that current helicopters are not powerful enough to lift the expected tether weights; the need to drastically improve the maintenance to flight-time ratio currently used for rotorcraft; the (likely) years of stringent safety testing that would be required before commercial operation would be allowed; and the likely possibility that winter would be unsuitable for operation due to icing. Barnard argues that none of these issues have been adequately addressed in the FEG/Sky WindPower literature available to him, and concludes that the concept simply isn’t feasible at altitudes higher than 2,000 feet (and even below that, many of the same challenges remain, making the FEG an unlikely solution to high altitude wind exploitation). Barnard is not an engineer (his career is in IT, and he primarily contributed to debates about wind power through writing blogs, rather than academic peer-review literature), so these criticisms cannot be construed as criticisms from peers or the AWE community.

2.3 High Altitude Wind and the Jet Stream

2.3.1 High Altitude Wind

In this thesis, “high altitude” refers to altitudes ranging from approximately 2–12 km. This definition is primarily based on the range of expected operating altitudes reported in the FEG literature, but also takes into account the structure of the atmosphere.

High altitude winds have distinct advantages over surface winds for the purposes of electricity generation:

- They are generally faster than surface winds, and typically increase in speed with increasing altitude.

- They are generally less variable over short time periods (on the order of hours) compared to surface winds.

The differences between surface winds and high altitude winds are explained by the structure of the atmosphere and the physical principles governing the motion of air
through the atmosphere. The details are described in Peixoto and Oort (1992) and Seinfeld and Pandis (2006).

The innermost layer of the atmosphere, the troposphere, is divided into two sublayers: the planetary boundary layer, and the “free” atmosphere. The planetary boundary layer is the innermost sublayer, and can be anywhere from about 1–2 km in thickness to a few tens of metres. Its height varies with topography, surface coverage, heat advection to/from the surface, among other factors (Peixoto and Oort, 1992, p.222). Above the planetary boundary layer, the free atmosphere begins, which is where the high altitude winds reside.

The differences between the planetary boundary layer and the free atmosphere explain the differences between surface winds and high altitude winds. In the planetary boundary layer, wind is slowed by frictional drag against the earth’s surface (McIlveen, 1992, p.205), and disrupted by surface features such as trees, hills and buildings (Seinfeld and Pandis, 2006, p.742). Additionally, the viscosity of the moving air leads to turbulent flow (Peixoto and Oort, 1992, p.222). As a result, surface winds are turbulent and inconsistent (Rohatgi and Nelson, 1994, p.118).

In contrast, in the free atmosphere surface friction effects are minimal and the viscosity of the air can be neglected. Air movement may be approximated by considering only horizontal pressure gradients, and the Coriolis force (Peixoto and Oort, 1992, p.39). Air moving from a high pressure region to a low pressure region at a different longitude is deflected by the rotation of the earth. The result of this deflection is that the wind ultimately ends up travelling perpendicular to the pressure gradient, and hence blowing along lines of constant pressure. Such motion is called geostrophic wind (Seinfeld and Pandis, 2006, p.987). In the free atmosphere, geostrophic winds are largely in a west-to-east direction (Peixoto and Oort, 1992, p.152).

At any given point in time, the troposphere will contain many horizontal temperature gradients, primarily extending from the warm equator towards the cooler poles (Peixoto and Oort, 1992, p.137). This is to be expected as the atmosphere is heated differentially by the sun, with air at the equator heated more than air at the poles. The effect of horizontal temperature gradients on geostrophic wind in the free atmosphere is described by the thermal wind relation (Peixoto and Oort, 1992, p.155). The thermal wind relation holds that a horizontal temperature gradient will coincide with a wind speed gradient in the vertical direction along the lines of constant pressure. Thus, the westerly component of geostrophic wind speed, in
the presence of a horizontal temperature gradient (where the cooler temperature is towards the pole), will increase with height. The thermal wind relation, along with the absence of surface friction effects, are the primary reasons why high altitude wind speeds will, in general, be higher than surface wind speeds.

High altitude winds are more consistent than surface winds because of the difference in scale of their dynamics. In general, the free atmosphere is dominated by synoptic-scale weather events. The dynamic processes which result in geostrophic winds predominantly occur on the synoptic scale. Synoptic-scale motion occurs on a length scale on the order of thousands of kilometres, and on a time scale of days (McIlveen, 1992, p.192). Near the surface, mesoscale and microscale atmospheric motions also contribute to the specific wind pattern experienced at a wind turbine site (although synoptic scale motions are still highly relevant). Mesoscale processes have a length scale on the order of 1–100 km and a time scale on the order of minutes to days; the microscale has a length scale of less than 1 km and a time scale of seconds to minutes (Rohatgi and Nelson, 1994, p.11). A smaller scale means wind speeds will change much more rapidly over time (and space), leading to greater variability over a given time period or area, compared to larger scale winds.

2.3.2 Jet Streams

Jet streams are long, narrow currents of wind located high in the troposphere at a pressure level of around 200–300 hPa (9–18 km, depending on latitude) (Seinfeld and Pandis, 2006, p.995). They are thousands of kilometres long, hundreds of kilometres wide and are about one kilometre high (Reiter, 1996). They sit approximately horizontally in the troposphere (that is, they do not significantly change in altitude along their length or width). Jet streams are a consequence of the thermal wind relation (Seinfeld and Pandis, 2006, p.995) and so their shape and extent are a reflection of the horizontal temperature gradients below them (that is, long and narrow) (Reiter, 1996). Given the connection to thermal (and therefore geostrophic) winds, jet streams are approximately zonal (parallel to lines of latitude) in their orientation, although they meander north and south along their length (Krishnamurti, 1961; Koch et al., 2006).

Wind speeds within a jet stream are higher than in the surrounding air, resulting in high vertical and lateral wind shears (5–10 m s$^{-1}$ per km, and 5 m s$^{-1}$ per 100 km, respectively) surrounding the jet stream core (Reiter, 1996). On average, the fastest winds in the troposphere are associated with jet streams (McIlveen, 1992, p.87). A
minimum wind speed of 30 m s\(^{-1}\) is widely used when determining the extent of a jet stream (Reiter, 1996; Seinfeld and Pandis, 2006; Koch et al., 2006), although 50 knots (26 m s\(^{-1}\)) is also used (Glickman, 2000).

Jet streams are associated with discontinuities in the height of the tropopause (Bluestein, 1993, p.387; Palmén and Newton, 1969, p.105), and are also associated with the boundaries between meridional circulation cells in the troposphere.

Two jet streams of interest to this thesis are the polar front jet stream and the subtropical jet stream.

**Polar Front Jet Stream**

The polar front jet stream occurs in the midlatitudes (30–60\(^\circ\)) of both hemispheres (Seinfeld and Pandis, 2006, p.995). It is associated with the polar front, which is the boundary between the cold polar air mass and warmer midlatitude air mass (Seinfeld and Pandis, 2006, p.995; Palmén and Newton, 1969, p.107). There is a sharp horizontal temperature gradient across the polar front at surface level, which is what causes high speed winds above it (according to the thermal wind relation) (Bluestein, 1993, p.378).

The core of the polar front jet stream is found at 250–300 hPa, although strong vertical wind shear below the core is evident much lower to the surface (Koch et al., 2006, p.296–297; Bluestein, 1993, p.378; McIlveen, 1992, p.92). The mean latitude of the polar front jet stream migrates poleward and equatorward with the seasons. This follows the seasonal migration of the polar front. In the winter months of each hemisphere, the polar front jet stream will move closer to the equator to around 30\(^\circ\). In the summer months, the jet stream will move poleward to about 50–60\(^\circ\). The location of the polar front jet stream differs between hemispheres. Like the polar front, the polar front jet stream is not a continuous flow encircling the entire globe. It is highly transitory over time and location.

Wind speeds in the polar front jet stream can be as high as 75 m s\(^{-1}\) (Bluestein, 1993, p.378; McIlveen, 1992, p.383). Since the polar front jet stream generally follows the polar front (Palmén and Newton, 1969, p.201), which meanders north and south in a sinusoidal pattern zonally, the jet stream wind may be northwesterly or southwesterly in direction, in addition to the general westerly direction expected of geostrophic flow (Bluestein, 1993, p.378). Mean wind speeds in the polar front jet stream differ between seasons and hemispheres. The polar front jet stream is stronger in the southern hemisphere summer than it is in the northern hemisphere.
summer (Bluestein, 1993, p.383).

**Subtropical Jet Stream**

The subtropical jet stream occurs at latitudes much closer to the equator (25–35°). This jet stream is a consequence of the Hadley cell circulation. Warm tropical air at the equator rises up to the tropopause and then moves toward the poles. As the warm air moves towards the poles, it is deflected by the Coriolis force and gains angular momentum, resulting in an increase in speed. The subtropical jet stream forms at the poleward edge of the Hadley cell, where the tropical air starts to sink again.

### 2.3.3 High Altitude Wind Studies

There are few published studies of high altitude wind statistics which focus on the potential for power generation. Although there is considerable literature on high altitude climate dynamics and the jet stream in climatology and meteorology, such studies do not report the statistics directly relevant to wind power researchers.

In most cases, wind power research requires straightforward statistics, including wind speed means, variances, percentiles and perhaps extreme values, and similar statistics for power density. These statistics are readily calculated from climate and/or meteorological data.

In this section, I review the (scant) literature which has studied the power generation potential of high altitude winds. In each case, I note the data sources used, the sorts of statistics calculated and the results found, along with the implications of each study for high altitude wind power as reported by the authors.

**Atkinson et al. (1979)**

The earliest study I could find that was devoted exclusively to calculating the power in high altitude winds was a technical report written by Roberts and colleagues in the Department of Mechanical Engineering at the University of Sydney (Atkinson et al., 1979). As noted in Section 2.2.12, I was unable to obtain the actual report, but some of its results are reported in the papers that reference it.

Fletcher and Roberts (1979) draws heavily on the results of Atkinson et al. (1979) when discussing the high altitude wind resource. According to Fletcher and Roberts (1979), the data used for analysis in Atkinson et al. (1979) was from the Bureau
of Meteorology. The data was in the form of 6-hourly radiosonde soundings from selected locations, and published monthly wind statistics (Maher and Lee, 1977). Figure 1 in Fletcher and Roberts (1979) is taken directly from Atkinson et al. (1979), and shows a contour plot of the annual average power density over Australia at the 250hPa pressure level. The plot shows the calculated average power density at 25 locations across Australia; these locations match the locations used by the Bureau of Meteorology for high altitude wind measurements (Maher and Lee, 1977). According to the plot, annual average power density is highest (about 18 kW m$^{-2}$) at a latitude of 30$^\circ$S and between longitudes 130$^\circ$E and 150$^\circ$E at 250 hPa over Australia.

Fletcher and Roberts (1979) hint at the methodology used by Atkinson et al. (1979) for calculating the available energy in the wind; wind speed observations were placed in bins 10 m s$^{-1}$ wide over a range of 0–100 m s$^{-1}$. This would have provided information about the distribution of wind speeds over a specific period of time, and allow weighted averages and probabilities to be calculated.

There is further evidence that Atkinson et al. (1979) examined monthly breakdowns of power density at specific locations for different pressure levels, and also calculated wind lulls, i.e. the number of occasions wind speeds fell below a threshold value, and the average duration of lulls.

**O’Doherty and Roberts (1982)**


O’Doherty and Roberts (1982) analysed data supplied by the National Center for Atmospheric Research (NCAR). The data supplied were high altitude wind speed and temperature measurements from balloon soundings released every twelve hours. The data covered a seven year period (the start and end dates were not specified). Nine pressure levels were analysed (between 900 hPa and 200 hPa) at 54 locations across the US, including Alaska and Hawaii. The large number of locations covered the continental US densely and evenly.

For each of the 54 locations, O’Doherty and Roberts (1982) calculated the annual average wind speed and annual average power density at each of the nine pressure levels. The authors also calculated the annual cumulative distribution of wind velocity for each location.

For five locations, O’Doherty and Roberts (1982) performed a calm wind analysis:
this analysis counted the number of occasions per year that the wind speed dropped below a specified threshold windspeed, and calculated the annual average period (in hours) that the wind speed remained below that threshold speed. For one particular location (Portland, Maine), monthly average wind speeds and power densities were reported, as well as monthly calm wind analyses.

Finally, O’Doherty and Roberts (1982) reported the annual count of thunderstorm days across the continental US, as an indicator of the probability of lightning strikes at particular locations.

O’Doherty and Roberts (1982) found that power density was highest at the 300 hPa pressure level, with power density reaching up to 16 kW m$^{-2}$ (the location with the highest power density is New York, NY: 16.2 kW m$^{-2}$ at 300 hPa). At this level, 30% of the continental US has annual average power density between 10–16 kW m$^{-2}$. The locations with these high power densities are concentrated in the north and north-east of the continent. From the calm wind analysis, the authors concluded that “at a typical U.S. site the wind lulls approximately below 20 m/s weekly. In addition, the annual average time below 20 m/s is always greater than 30 hours, regardless of the altitude or site location” (O’Doherty and Roberts, 1982, p.16). The thunderstorm days analysis showed that Florida (with 90 thunderstorm days per year) and the southwestern states centred around New Mexico (with 70 thunderstorm days per year) have the highest indicators of lightning strikes in the continental US.

O’Doherty and Roberts (1982) concluded that the US was a favourable site for high altitude wind power. In particular, Portland, Maine was suggested as an “optimistic” site (O’Doherty and Roberts, 1982, p.19), which was the rationale for presenting an extended analysis of that location.

**Bryukhan and Diab (1995)**

Bryukhan and Diab (1995) analysed wind power potential at high altitude over southern Africa in their article, “Wind Energy Resource Estimation of the Upper Atmosphere over Southern Africa”. They used reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF).\(^\text{15}\) The latitude and longitude domains were restricted to southern Africa (0–50°S, 0–45°E) and analysis was restricted to the 1000, 850, 700, 500, 300, 200, and 100 hPa pressure levels. The

\(^{15}\text{The specific reanalysis dataset is not specified in the paper, although it is likely that it was the ERA-15 reanalysis.}\)
reanalysis data covered the period 1982–1989, although the authors analysed the
daily data (1200 UTC) for only four months (January, April, July, October) of each
year. Daily data was considered sufficient due to the minimal diurnal wind changes
in the free atmosphere, and annual means were estimated from the data for the four
months.

Bryukhan and Diab (1995) calculated the mean monthly power density (kW m\(^{-2}\))
over the entire region for each pressure level and month (over the full period of the
data), and found that power density was greatest at the 300 hPa pressure level (ap-
approximately 10 km) for all four months, and that winter months were higher than
summer months by about 25–30%. The maximum mean monthly power density
at 300 hPa was for July (over 7 kW m\(^{-2}\)); minimum was for April (approximately
5 kW m\(^{-2}\)), although January was very similar in magnitude. (Throughout this
study, only monthly means were reported; no variances were reported in the re-
results.)

Focusing on the most favourable locations for high power density at 300 hPa,
Bryukhan and Diab (1995) identified the southernmost tip of the African continent
as the most favourable. This was due to the trend of increased power density with in-
creased latitude, which was applicable to all months and longitudes. Mean monthly
power density at 300 hPa above the southernmost tip of Africa (about 35\(^{\circ}\)S) reached
a maximum of 12–13 kW m\(^{-2}\) in July and had a minimum of at least 6 kW m\(^{-2}\) in
January and April. Power density declined quickly with decreased latitude; at lati-
ditudes below 20\(^{\circ}\)S mean monthly power density was typically 2 kW m\(^{-2}\) or less at the
300 hPa pressure level for all months except July, when power densities increased
to 4 kW m\(^{-2}\) at 20\(^{\circ}\)S (though still quickly declined with decreasing latitude from there).

Bryukhan and Diab (1995) concluded that in general, power density at 300 hPa
is at least an order of magnitude greater than power density at surface level, and
that there is a noticeable seasonal meridional shift in power density, with power
density being higher in winter months than in summer months for a given latitude.

**Archer and Caldeira (2008) and Archer and Caldeira (2009)**

The most comprehensive study is the Atlas of High Altitude Wind Power (Archer
and Caldeira, 2008) (accompanied by a journal article summarising the results of
the atlas, “Global Assessment of High-Altitude Wind Power” (Archer and Caldeira,
2009)). Authors Archer and Caldeira surveyed the entire globe using data from the
NCEP reanalysis for the period 1979–2006. The atlas is in three sections: first, a survey of power density at sixteen altitudes (80, 500, 750, 1,000, 1,500, 2,000, 3,000, 4,000, 5,000, 6,000, 7,000, 8,000, 9,000, 10,000, 11,000, and 12,000 metres); second, an analysis of optimal heights for power generation (the height at which the highest power density occurs for each point on the earth’s surface); and third, an investigation of wind intermittency above five large cities around the world (Tokyo, Seoul, Mexico City, New York, and Sao Paulo).

In contrast to previous studies, Archer and Caldeira (2008) do not calculate the mean or variance of power density. Instead, they calculate three percentiles of the power density distribution (50th/median, 68th and 95th) at each height. The percentiles are calculated over the entire length of the dataset used (1979–2006) to arrive at an “annual” result, and are also calculated for each “season” (four groups of three consecutive months: DJF, MAM, JJA, SON). This method is used for the first and second sections.

Archer and Caldeira (2009) explained the decision to calculate percentiles instead of means as follows:

> The amount of energy in high altitude winds, and its intermittency, depend on the frequency distribution of wind power density. Because wind power density is proportional to the third power of wind speed ..., fluctuations of wind speed greatly affect wind power output. Furthermore, turbines often cannot capture energy in either the strongest or the weakest winds. Hence, we do not focus on mean values, but rather on a few percentiles (50th or median, 68th, and 95th), which indicate the wind power density that is exceeded on 50%, 68%, and 95% of the time during 1979–2006. (Archer and Caldeira, 2009, p.309)

Although not explicitly stated, the values of the percentiles reported (50th, 68th, 95th) were presumably on the basis that for a normally distributed variable, the 68th percentile corresponds with a value one standard deviation away from the mean, and the 95th percentile corresponds with a value two standard deviations away from the mean (the median is the same as the mean for the normal distribution).

**Archer (2013)**

Archer’s book chapter in Ahrens et al. (2013a) is a general introduction to meteorology written to be especially applicable to airborne wind energy. In keeping with
the rest of the book, Archer focuses on altitudes well below the jet stream, typically looking at heights of 400–2,000 m. Archer introduces the governing equations of atmospheric circulation (continuity equation, thermodynamic equation, momentum equation, equation of state) and mentions the difference between winds above and below the boundary layer (noting that wind above the boundary layer can be considered as geostrophic, to a good approximation). Archer reproduces maps of power density (at 80 m, 500 m, 750 m, and 1,500 m) from Archer and Caldeira (2009). One particularly useful point that Archer includes is the advice that “a proxy for wind power reliability is the 95th percentile of wind power density.” (Archer, 2013, p.92) This makes sense as it’s easy to calculate and represent, and gives a conservative estimate of the wind power potential of areas and altitudes.

**Archer et al. (2014)**

Archer et al. (2014) is perhaps less relevant to FEGs and jet stream level winds, because Archer has decided to focus on the location and persistence of low-level jet streams (below 3,000 m). Archer does acknowledge at the start of this paper that the jet stream cores do have the highest wind speeds/power densities in the atmosphere, but then immediately disregards them due to the practical difficulty of reaching them (due to tether lengths, potential damage to systems caught in extreme wind speeds) and states that most airborne wind energy systems are utilising winds between 200 and 3000 m in height. Archer says that the upper limit of 3,000 m is not based on any meteorological features or limits, but rather the limitations of tether length (and therefore weight), given that tethers will be typically at an angle of 30°, and so be twice as long as the operating height. A tether of 5–6 km can weigh over a ton, according to Archer. Archer used a recent reanalysis dataset, NCAR Climate Four Dimensional Data Assimilation, which has very fine horizontal resolution (40 km) and a time resolution of one hour. This fine resolution is important for lower level jets, since they are influenced by diurnal cycles and local geographic features to a much greater extent than the winds in the mid-troposphere and higher.

**2.3.4 Limits on Kinetic Energy Extraction from the Jet Stream**

There is an ongoing discussion in the literature about how much kinetic energy can actually be extracted from atmospheric winds, both at the jet stream level and
at surface level, and the effects of wide-scale energy extraction by wind turbines on atmospheric circulation. The limit on the amount of kinetic energy that can be extracted from wind is an important factor when considering widespread wind turbine deployment to meet a large proportion of global electricity demand. Estimates of this limit have varied widely, with different implications for any potential global-scale wind turbine projects.

Archer and Caldeira (2009) considered the climate effects of a large-scale deployment of high-altitude wind power devices distributed uniformly throughout the entire atmosphere. A climate model (the Community Climate System Model, CCSM3) simulated the effects of wind power extraction for three different densities of turbine surface area per volume of atmosphere: 1 m$^2$ km$^{-3}$, 100 m$^2$ km$^{-3}$, and 10,000 m$^2$ km$^{-3}$. The authors noted that a density of 1 m$^2$ km$^{-3}$ was approximately the density of devices in the atmosphere required to meet global electricity demand. The climate model showed that at a density of 1 m$^2$ km$^{-3}$ the impact to the climate would be small: mean surface temperature would decline by 0.04°C, sea ice cover would increase by 0.45%, and total precipitation would decrease by 0.12%. The higher densities had a much larger impact: for example, at 100 m$^2$ km$^{-3}$, mean surface temperature would decrease by 2.17°C, sea ice cover increase by 17.09%, and precipitation decrease by 6.53% (at 10,000 m$^2$ km$^{-3}$, sea ice cover would increase by 195.19%). Archer and Caldeira (2009) concluded that high-altitude wind power devices extracting power from the wind would not substantially affect the climate (unless devices were to be employed on a massive scale, many times the current global demand for power).

Miller et al. (2011) calculated a much lower limit on the amount of power that could be sustainably extracted from the jet stream. This study was in part motivated by a claim made in Archer and Caldeira (2009), that “the total wind energy in the jet streams is roughly 100 times the global energy demand” (p.307–308). Archer and Caldeira (2009) did not quantify this any further in their article, so Miller et al. (2011) used an estimate of 17 TW for global energy demand to infer that the total energy in the jet stream was 1,700 TW, according to Archer and Caldeira (2009). They note that this estimate is larger than the amount of power in all winds in the atmosphere (which they estimate to be $\approx 900$ TW)$^{16}$.

$^{16}$Archer and Caldeira (2009) cite Roberts et al. (2007) for their claim, but appear to have misinterpreted the statistic from the earlier paper. The relevant paragraph from Roberts et al. (2007) reads:
Miller et al. (2011) criticised previous studies estimating global wind power potential for relying only on the instantaneous power in the wind \(\frac{\rho v^3}{2}\), and not taking into account the rate of kinetic energy generation in the atmosphere, that ultimately limits how much power can be extracted from the jet stream. The authors considered an ideal situation of a jet stream flow in geostrophic balance, where the pressure gradient force was balanced by the Coriolis force. Associated with the flow are kinetic energy generation and dispersion rates (since kinetic energy is dispersed at the edges of the jet stream flow), which maintain the jet stream flow. If additional drag is introduced (for example, a wind turbine) into the jet stream flow, the geostrophic balance of the jet stream is interrupted, resulting in higher north-south wind velocities, which decreases the pressure gradient force. Increasing the drag reduces the jet stream wind speed further and further. Importantly, the authors found that the instantaneous power density of the wind within the jet stream was not an adequate indicator of how much power could be sustainably removed from the jet stream.

Miller et al. (2011) calculated the limit of sustainable kinetic energy extraction from the jet stream by running simulations of a general circulation model. They found a maximum sustainable extraction rate of 7.5 TW, but after taking into account the Betz limit, the actual usable power would be 4.5 TW. At this peak rate of extraction, jet stream winds in the east-west direction were two thirds of no-extraction control scenario, and there was substantially more north-south wind movement. A consequence of this was more heat moved towards the poles at high altitude, reducing north-south pressure gradients and further reducing the atmosphere’s capacity for generating kinetic energy.

Jacobson and Archer (2012) proposed “saturation wind power potential” (SWPP) as a metric for measuring the limit of global wind power potential. SWPP is defined as high power densities would be uninteresting if only a small amount of total power were available. However, wind power is roughly 100 times the power used by all human civilization. Total power dissipated in winds is about \(10^{15}\) W. Total human thermal power consumption is about \(10^{13}\) W. Removing 1% of high-altitude winds’ available energy is not expected to have adverse environmental consequences.

The comparison being made here is to the total power in all winds in the atmosphere (Peixoto and Oort (1992) is cited as the source of the \(10^{15}\) W value), not just the power in jet stream winds. (This value is similar to the estimate of \(\approx 900\) TW provided by Miller et al. (2011) for the total power in all winds.) Since the rest of Roberts et al. (2007) refers to high altitude and jet stream winds exclusively, the authors of Archer and Caldeira (2009) may have interpreted this claim to also refer to the jet stream only, rather than to the entire atmosphere.
as the maximum amount of power that can be extracted by wind turbines from the atmosphere; once enough wind turbines had been deployed to reach SWPP, deploying greater numbers of turbines would not increase the total amount of power extracted further. The atmospheric model used by the authors returned the heat generated from the use of electrical power coming from the turbines back into the atmosphere. The model also used the power curve of a 5 MW, 126 m diameter wind turbine to calculate the specific momentum sink of turbines based on the instantaneous wind speed at each point in space for each time step in the model. Additionally, the model was run for two scenarios: one with wind turbines deployed around the globe at a hub height of 100 m, and one with wind turbines deployed at 10 km.

Jacobson and Archer (2012) calculated a limit of 80 TW for turbines distributed uniformly over the entire land area (and off-shore along coastlines) of Earth at a height of 100 m above the surface. The limit for turbines distributed over the entire surface of the Earth, including oceans, at the same height of 100 m was 253 TW. The limit for turbines uniformly deployed at 10 km between 10° and 70° in both hemispheres was calculated to be 378 TW. The authors noted that previous estimates of wind power availability ranged from 450–3,800 TW which were much higher than the results presented in their paper, although they noted that none of the previous estimates modelled extraction at a specific height only; extraction throughout the entire atmosphere was assumed.

Marvel et al. (2013) varied a parameter called the “effective extraction area per unit volume” in order to find a geophysical limit to how much power could be taken from global winds. The effective extraction area per unit volume refers to the total swept area of wind turbines that exists in a unit volume of the atmosphere. The authors calculated the limit of the kinetic energy extraction rate from the atmosphere to be at least 428 TW (for surface winds) and at least 1,873 TW for the entire atmosphere (from the surface up to beyond the jet stream level).

The effects on the climate varied between the surface-only and whole-atmosphere scenarios. When kinetic energy was extracted at the rate of 428 TW at the surface, global temperatures were calculated to rise slightly on average. For the whole-atmosphere extraction rate of 1,873 TW, temperatures were calculated to fall by at least 0.5 K. Zonal wind speeds (particularly at the jet stream level) were calculated to decrease in the whole-atmosphere scenario. The authors noted that since the extraction rate required to meet present electricity demand of approximately 18 TW
would be far, far lower than these geophysical limits, climate effects would be smaller. Marvel et al. (2013) concluded that technical, economic, and political constraints would limit global wind power extraction long before the geophysical limits (as calculated in the article) would.

Miller et al. (2015) used two different methods to calculate a maximum rate of sustainable kinetic energy extraction from wind at the surface, for an area in Kansas covered in wind turbines. Using a regional weather forecasting model, the authors found that a rate of 1.1 W of electricity generation per square meter of wind farm was the maximum sustainable (the density of wind turbine capacity installed on the wind farm that corresponded to this maximum generation rate was 10 MW km\(^{-2}\)). An alternative method, based on the rate of vertical kinetic energy flux (that is, the rate that kinetic energy flows from winds above down to the wind farm turbine level, where wind speeds are assumed to have been already slowed by wind turbines upwind of a given point), estimated the maximum rate to be 0.64 W m\(^{-2}\) (for the same wind farm density as the first method).

Although slightly discrepant from each other, these two estimates were shown by the authors to be similar to (if not slightly higher than) the results from Adams and Keith (2013), as well as the surface-level results from Jacobson and Archer (2012) (whose results were translated into the comparable units of W m\(^{-2}\)). The limit of 1.1 W m\(^{-2}\) found in Miller et al. (2015) agrees closely with the results of Adams and Keith (2013), who calculated a limit of 1 W m\(^{-2}\) for ground-based wind farms covering a total area of 100 km\(^2\) or more using a mesoscale atmospheric model for a region covering Texas/Oklahoma.

This ongoing discussion about the limits on kinetic energy extraction from winds (both surface and high-altitude) shows that wide-scale energy solutions based on wind are not as straightforward as simply building more turbines, whether at ground level or in the jet stream, to match demand. There is still substantial variation in the calculated estimates of limits to wind power extraction, and a number of different methods and models have been employed. Exploring how such a limit might affect the wide-scale deployment of the FEG is beyond the scope of this thesis. However, it seems reasonable to assume that a single FEG or small number of FEGs deployed in a specific region (such as over Australia) would have a negligible impact on atmospheric circulation, and so in this case considering the instantaneous power density of jet stream winds ($\frac{1}{2} \rho v^3$) would be valid for calculating FEG performance, as will be outlined in Chapter 3.
Chapter 3

Method

3.1 Wind Statistics

3.1.1 Data

All claims about the suitability of upper troposphere winds for electricity generation ultimately rely upon measurements of the wind speed and other relevant atmospheric variables. Observations of the wind speed kilometres above the ground are made by radiosondes, aircraft and satellites, among other methods (Uppala et al., 2005). It would be preferable to be able to infer the state of the atmosphere at any point in time and space, rather than be restricted to the locations and times where observations were made. An analysis is an estimate of the state of the atmosphere at a series of points in time, based on an atmospheric forecast model supplemented by data from actual observations (Uppala et al., 2005, p.2962). One approach to analysis, called four dimensional data assimilation, allows a forecast model to evolve in time according to its governing equations. The output of this model is “updated” with observed values for atmospheric variables, which are then used to inform the next time step of the model. In this fashion, a description of the atmosphere is built, informed by observed data in some places which diffuse out into other parts of the model providing a credible estimate of the state of the atmosphere in locations and at times not directly observed. Projects which use up-to-date atmospheric models informed by vast stores of weather observations going back for decades are called re-analyses. Re-analyses are considered one of the best estimates of the whole atmosphere available.

Re-analyses are not without problems; one problem is that some regions of the earth, particularly in the southern hemisphere, are sparsely covered by weather
observation stations. In these areas, the specific estimated state of the atmosphere may be more an artifact of the model, rather than an unbiased interpolation of nearby observed data points. If the model happens to have any biases, these may be reflected in the estimated state in those areas. In general, this problem is more pronounced for older observations rather than for more recent data, since satellites provide spatially-dense observations over these areas.

Preliminary wind analysis for ground-based wind power projects commonly requires 30 years of wind data to be confident of identifying long-term trends in wind patterns. Ground-based wind analysis has the advantage of using cheap, simple anemometers to compile wind speed data on short time scales at a specific geographic location. High altitude wind analysis is more difficult and expensive to perform, and the sampling rate over time and space is much lower (however, a useful description of high altitude winds is still achievable).

For the purposes of this thesis, I will make use of re-analysis data from the ERA-40 project to estimate the typical behaviour of high altitude winds. This is to test claims made by Roberts about this energy resource as well as provide a richer description of the resource than Roberts offers.

The ERA-40 Project

ERA-40 is a re-analysis project administered by the ECMWF. The project has produced a dataset of a large number of climate variables covering the entire atmosphere over a period of forty-five years (1st September 1957–31st August 2002).

The dataset available from the ECMWF public servers has a temporal resolution of six hours over the entire forty-five year period, and a spatial resolution of 2.5° in the horizontal spatial dimensions (latitude/longitude) and has twenty-three distinct pressure levels (the resolution varies with altitude) in the vertical dimension. The dimensions of the dataset are summarised in Table 3.1.

At each point in space and time, the ERA-40 dataset contains interpolated values for a large number of atmospheric parameters. The parameters applicable to the atmosphere above the surface (termed “upper air” parameters) contained within the ERA-40 dataset are listed in Table 3.2.

Of the parameters listed in Table 3.2, the ones relevant to this thesis are geopotential, temperature, and the $U$ and $V$ wind velocities.

In 2011, the ECMWF published a new reanalysis project, ERA-Interim, designed to replace ERA-40 (Dee et al., 2011). ERA-Interim improved on ERA-40, in partic-
Table 3.1: Summary of the spatial and temporal dimensions of the ERA-40 dataset, specifying the domain and resolution of each. In the case of the vertical spatial dimension (altitude), the resolution varies over the domain.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Resolution</th>
<th>Domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitude</td>
<td>2.5°</td>
<td>[0°E, 357.5°E]</td>
</tr>
<tr>
<td>Latitude</td>
<td>2.5°</td>
<td>[−90°N, 90°N]</td>
</tr>
<tr>
<td>Altitude</td>
<td>Varies (23 levels)</td>
<td>[1000 hPa, 1 hPa]</td>
</tr>
<tr>
<td>Time</td>
<td>6h</td>
<td>[12:00 a.m. 01/09/1957, 6:00 p.m. 31/08/2002]</td>
</tr>
</tbody>
</table>

Table 3.2: Summary of the upper air parameters included in the ERA-40 dataset relevant to this thesis, along with the units of each.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geopotential</td>
<td>m² s⁻²</td>
</tr>
<tr>
<td>Temperature</td>
<td>K</td>
</tr>
<tr>
<td>Eastward wind component (U velocity)</td>
<td>m s⁻¹</td>
</tr>
<tr>
<td>Northward wind component (V velocity)</td>
<td>m s⁻¹</td>
</tr>
</tbody>
</table>

ular in its models for precipitation and stratospheric circulation, and in correcting for bias in the climate observations input into the model. Although ERA-Interim is the latest reanalysis and would be preferred over ERA-40 in climatological research performed today, this thesis began using ERA-40 before ERA-Interim was available, and the differences between the two reanalyses are unlikely to result in substantial differences for results like mean geopotential height, wind speed, or air density (as outlined in the coming sections).

Climate Parameters for Analysis

The ERA-40 parameters mentioned in the previous section are not directly applicable to the task of determining the suitability of high altitude winds for electricity generation. Instead, these parameters are used to derive other properties of the atmosphere not covered in the ERA-40 dataset. In this section I shall describe each of these derived properties and their constituent ERA-40 parameters, outline their
importance to this thesis and give their derivation from the ERA-40 parameters.

**Geopotential Height**

As mentioned before, the ERA-40 dataset describes the vertical extent of the atmosphere in terms of specific pressure levels. In contrast, the FEG literature describes the operating altitudes of FEGs in terms of feet, metres and kilometres. If these operating altitudes represent the elevation above mean sea level, then the FEG literature is reporting the expected *geometric* height of an airborne FEG.

In order to compare wind speed at the geometric heights reported by the FEG literature with wind speeds at the prescribed pressure levels of the ERA-40 data, we need a way of measuring the geometric height of a pressure level.

It is not practical to directly measure the geometric height of a point high in the atmosphere. However, geopotential can be measured and manipulated to obtain an alternative measure of height that is accurate and reliable.

For a unit mass elevated to a geometric height \( z \) above mean sea level, the gravitational potential energy of the mass, or geopotential, \( \Phi \) is given by

\[
\Phi = \int_0^z g \, dz \tag{3.1}
\]

where \( g \) is the acceleration due to gravity for that particular point above the earth. The ERA-40 dataset includes values for geopotential for each space/time point in the domain. Geopotential height \( Z \) is defined as the geopotential divided by the standard acceleration due to gravity, \( g_0 = 9.80665 \text{ m s}^{-2} \),

\[
Z = \frac{\Phi}{g_0} \tag{3.2}
\]

The units of geopotential height are the same as the units of geometric height, i.e. metres. It must be noted that geopotential height so defined will be less than the actual geometric height in regions where \( g \) is greater than the standard value, and greater than the geometric height where \( g \) is less than the standard value. If the local value of \( g \) equals the standard value, geopotential height and geometric height will be equal. In the troposphere, the difference between geopotential and geometric height is, even in extreme cases, in the order of tens of metres. Since this discrepancy is very small compared to the height scale the FEG literature invokes (which is in the order of thousands of metres), it is reasonable to compare geopotential heights directly to geometric height for the purposes of evaluating claims in the FEG literature.
Wind Speed

The ERA-40 dataset stores wind velocity as two separate components: a zonal (west-east) component $U$ and a meridional (north-south) component $V$. Both components are measured in units of metres per second (m s$^{-1}$). The wind speed $v$ is the magnitude of the wind velocity vector described by $U$ and $V$:

$$v = \sqrt{U^2 + V^2}. \quad (3.3)$$

The wind speed is also in units of m s$^{-1}$. The direction of the wind can also be calculated from the wind velocity components, but I shall ignore wind direction and only consider the (scalar) wind speed. This makes the reasonable assumption that the ability of a FEG to harness wind is independent of wind direction, which greatly simplifies analyses of wind suitability for power generation. The same assumption is made (tacitly) in the FEG literature. (It is also the case that the subtropical and polar jet streams are in general approximately westerly in direction, and so winds at or near jet stream latitudes and altitudes will tend to be westerly.)

Air Density

Air density at a particular pressure and temperature can be calculated approximately using an equation of state based on the ideal gas law:

$$\rho = \frac{pM_a}{ZRT} \left[ 1 - x_V \left( 1 - \frac{M_V}{M_a} \right) \right] \quad (3.4)$$

where $\rho$ is the air density, $p$ is the air pressure, $M_a$ is the molar mass of dry air, $Z$ is compressibility factor, $R$ is the gas constant, $T$ is the air temperature, $x_V$ is the molar fraction of water vapour, and $M_V$ is the molar mass of water.

This equation can be simplified by calculating the density of dry air ($x_V = 0$), and assuming that dry air behaves as an ideal gas ($Z = 1$):

$$\rho = \frac{pM_a}{RT} \quad (3.5)$$

Substituting the values $R = 8.3143 \text{ J mol}^{-1} \text{ K}^{-1}$ and $M_a = 2.8966 \times 10^{-2} \text{ kg mol}^{-1}$, the equation becomes:

$$\rho = \frac{p}{287.04T} \quad (3.6)$$

Equation (3.6) is used to calculate the approximate air density at an ERA-40 grid point. Since pressure levels are pre-defined in the ERA-40 data set, calculating the air density simply requires the value of the chosen pressure level (in Pa) and the
value of the temperature parameter (in K) at the chosen grid point. Using these units, the resulting air density value is in units of kg m$^{-3}$.

The method of calculating the air density shown at Equation (3.6) is simplified, and does not take into account the effect water vapour would have on the value. However, this approximation should be sufficient for the purposes of this thesis. It is superior to relying on the density values from the standard atmosphere, since local temperature is taken into account.

Air density values are required primarily for the calculation of the power density of the wind, as the next section shows.

**Power Density**

Already introduced in the previous chapter, power density is the most important property of wind for the purposes of electricity generation, as it represents how much kinetic energy there is in the wind (per second, per unit area). Wind turbines convert a proportion of that kinetic energy into electrical energy. The power density $P$ of the wind is calculated at each grid point using the previously-calculated air density and wind speed:

$$ P = \frac{1}{2} \rho v^3. \tag{3.7} $$

At high altitudes, units of kW m$^{-2}$ are the most convenient to use for power density, so all values of power density are expressed in these units.

**3.1.2 Analysis**

All quantitative analysis was performed using the R Language (R Core Team, 2014). R code used in this thesis can be found in Appendix D. All plots were created using ggplot2 (Wickham, 2009), except for the contour plots over Australia, which were created using GrADS (Doty, 2011).

**Summary Statistics**

Summary statistics for the ERA-40 variables were calculated over the time domain only, and so relate to a specific point in space. All observations in the time dimension were equally weighted. In general, statistics were calculated for ranges of sequential time observations corresponding to all observations in a particular month, season or year in the dataset.
Mean

The mean $\bar{x}$ of a variable $x$ from a sample of $N$ observations $\{x_1, x_2, \ldots, x_N\}$ was calculated as

$$\bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i$$  \hspace{1cm} (3.8)

Standard Deviation

The sample standard deviation $s$ of a variable $x$ from a sample of $N$ observations was calculated as

$$s = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (x_i - \bar{x})^2}$$  \hspace{1cm} (3.9)

where $\bar{x}$ is the sample mean.

Median

The sample median of a variable $x$ from a sample of $N$ observations (where the observations $x_i$ have been ordered from smallest to largest) was calculated as

$$\text{median}(x) = \begin{cases} 
\frac{x_j + x_{j+1}}{2} & \text{if } N = 2j \\
x_{j+1} & \text{if } N = 2j + 1
\end{cases}$$  \hspace{1cm} (3.10)

where $j \in \mathbb{N}$ and $x_j$ is the $j$th term in the ordered set of observations. This means that if $N$ is odd, then the median is the $((N+1)/2)$th term in the ordered set of observations, and if $N$ is even, then the median is the mean of the $(N/2)$th and $(N/2 + 1)$th terms in the ordered set of observations.

Quantiles

To calculate any sample quantile (e.g. the 75th percentile, or the 99th percentile), the definition of the median was generalised to allow for an arbitrary quantile $p$ (where $0 < p < 1$) (Hyndman and Fan, 1996). Once again, the sample of $N$ observations have been ordered from smallest to largest.

$$Q_p(x) = \begin{cases} 
\frac{x_j + x_{j+1}}{2} & \text{if } pN = j \\
x_{j+1} & \text{if } pN \neq j
\end{cases}$$  \hspace{1cm} (3.11)

where $j = \lfloor pN \rfloor$, and hence $j \in \mathbb{N}$, and $x_j$ is the $j$th term in the ordered set of observations. This definition of a quantile becomes the same as the definition of the median when $p = 0.5$. 

Down-time

One important set of statistics concern FEG “down-time”, which occurs when wind speed is below a threshold speed.

For a given time series of wind speed observations \( v = \{v_t, t \in T\} \) at a single location, with \( N \) observations made at times \( T = \{t_1, \ldots, t_N\} \), the following down-time statistics can be calculated.

The proportion \( q_{v<v_0} \) of time that the wind speed is less than a threshold speed \( v_0 \) is calculated as

\[
q_{v<v_0} = \frac{\left| \{v_t : t \in T, v_t < v_0\} \right|}{N},
\]

(3.12)

where \( \left| \{v_t : t \in T, v_t < v_0\} \right| \) is the count of wind speed observations in the time series that meet the condition \( v_t < v_0 \).

In order for \( q_{v<v_0} \) to be interpreted as a proportion of the total time interval covered by \( T \), this method assumes that the wind speed remains constant over each time interval between observations. Observations in the ERA-40 time dimension are spaced equally at intervals of 6 hours, so a 30 day month contains a total of \( N = 120 \) observations, and a 365 day year contains \( N = 1460 \) observations.

A distinct down-time event occurs when observed wind speed is less than the threshold wind speed for one or more consecutive observations in the time series. The down-time event ends once the observed wind speed increases to become equal to or greater than the threshold wind speed. The number \( n_{v<v_0} \) of distinct down-time events in the time series \( v \) is calculated as

\[
n_{v<v_0} = \left| \{t : t = t_1, v_t < v_0\} \cup \{t : t \in T, (v_{t-1} \geq v_0) \land (v_t < v_0)\} \right| \]

(3.13)

This method counts the number of instances where consecutive wind speed observations transition from being equal to or above the threshold to below the threshold. These instances indicate the beginning of each down-time event in the time series (if the first observation in the time series happens to be less than the threshold, then that observation is considered to be the start of the first down-time event).

The duration of each down-time event is calculated as the number of observations that the wind speed remains less than the threshold multiplied by the length of the time interval between observations.

\[
\{t : t \in T, (t \geq t_i) \land (t < t_{i+1}) \land (v_t < v_0)\}
\]

(3.14)
Distributions

The distribution of wind speed over a period of time on the order of a year is well known to be described by the Weibull distribution (Hennessey, 1977). The Weibull distribution is a family of distributions which differ according to two parameters, shape and scale. Shape is the important parameter for our purposes.

I randomly drew 10,000 Weibull-distributed values for each of the following shape parameters: 1.5, 2, 3 (the scale parameter was held constant at 1). A Weibull distribution with a shape parameter of 2 is also known as a Rayleigh distribution. The density of the three Weibull distributions is shown in Figure 3.1. These could plausibly be distributions of wind speed.

![Weibull distributions with shape parameters 1.5, 2, and 3.](image)

Figure 3.1: Weibull distributions with shape parameters 1.5, 2, and 3.

Power density is proportional to the cube of the wind speed. The distribution of the cube of the wind speed will be highly skewed, with a very, very long tail, as Figure 3.2 shows. This is the distribution of the randomly generated Weibull values, when each value has been cubed. Because the long tail makes the details difficult to see, a “zoomed in” plot of the lower end of the distribution is in Figure 3.3. Although it can’t be seen from the figures, the density in the long tail of each distribution continues to decrease as the value increases. (Since Figures 3.2 and 3.3 are based
on samples of 10,000 randomly drawn values, rather than continuous probability distribution functions, the actual density along the $x$-axis for values greater than 10 will most often be zero.

![Graph showing distribution of the cube of the Weibull-distributed values with shape parameters 1.5, 2, and 3.](image)

Figure 3.2: Distribution of the cube of the Weibull-distributed values with shape parameters 1.5, 2, and 3.

This exercise shows that power density, as the cubed of the wind speed, will have a highly skewed distribution with a long tail, and so a summary statistic like the mean will be strongly influenced by the extreme values in the tail. In such a situation, percentiles are a more intuitive and useful way to summarise the data (see Section 4.4.2 for further explanation in context, when actual results are reported).
Figure 3.3: A closer look at the lower end of the distributions of the cube of the Weibull-distributed values with shape parameters 1.5, 2, and 3.
3. Method

Locations

I restricted the ERA-40 dataset to latitudes between 10° S and 45° S, and longitudes between 110° E and 155° E, which reduced the spatial domain to include only Australia and its immediate surroundings. All pressure levels between 1,000 hPa and 100 hPa were retained, along with the full time domain 1957–2002.

I chose fifteen locations across Australia to analyse (see Table 3.3 and Figure 3.4). These specific locations were chosen because (i) data at many of these were analysed in Fletcher and Roberts (1979) and Roberts and Blackler (1980), and so my analyses can be directly compared with those papers’ results, (ii) they are locations of Bureau of Meteorology weather stations which make high altitude wind measurements, and so the accuracy of the ERA-40 data can be checked, and (iii) these locations are spread approximately evenly across Australia, so to capture much of the spatial variation in high altitude wind above Australia. The details of the weather stations were obtained from the Bureau of Meteorology Data Services website.

Table 3.3: The fifteen Australian locations used in the analysis.

<table>
<thead>
<tr>
<th>Location Name</th>
<th>Bureau Weather Station (Number)</th>
<th>Latitude (° N)</th>
<th>Longitude (° E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albany, WA</td>
<td>Albany Airport Comparison (9741)</td>
<td>-34.9414</td>
<td>117.8022</td>
</tr>
<tr>
<td>Alice Springs, NT</td>
<td>Alice Springs Airport (15590)</td>
<td>-23.7951</td>
<td>133.8890</td>
</tr>
<tr>
<td>Broome, WA</td>
<td>Broome Airport (3003)</td>
<td>-17.9475</td>
<td>122.2353</td>
</tr>
<tr>
<td>Carnarvon, WA</td>
<td>Carnarvon Airport (6011)</td>
<td>-24.8878</td>
<td>113.6700</td>
</tr>
<tr>
<td>Charleville, QLD</td>
<td>Charleville Aero (44021)</td>
<td>-26.4139</td>
<td>146.2558</td>
</tr>
<tr>
<td>Cobar, NSW</td>
<td>Cobar MO (48027)</td>
<td>-31.4840</td>
<td>145.8294</td>
</tr>
<tr>
<td>Darwin, NT</td>
<td>Darwin Airport (14015)</td>
<td>-12.4239</td>
<td>130.8925</td>
</tr>
<tr>
<td>Forrest, WA</td>
<td>Forrest Aero (11004)</td>
<td>-30.8389</td>
<td>128.1139</td>
</tr>
<tr>
<td>Giles, WA</td>
<td>Giles Meteorological Office (13017)</td>
<td>-25.0341</td>
<td>128.3010</td>
</tr>
<tr>
<td>Hobart, TAS</td>
<td>Hobart Airport (94008)</td>
<td>-42.8339</td>
<td>147.5033</td>
</tr>
<tr>
<td>Laverton, VIC</td>
<td>Laverton RAAF (87031)</td>
<td>-37.8565</td>
<td>144.7566</td>
</tr>
<tr>
<td>Moree, NSW</td>
<td>Moree Comparison (53048)</td>
<td>-29.4819</td>
<td>149.8383</td>
</tr>
<tr>
<td>Townsville, QLD</td>
<td>Townsville Aero (32040)</td>
<td>-19.2483</td>
<td>146.7661</td>
</tr>
<tr>
<td>Wagga, NSW</td>
<td>Wagga Wagga AMO (72150)</td>
<td>-35.1583</td>
<td>147.4575</td>
</tr>
<tr>
<td>Woomera, SA</td>
<td>Woomera Aerodrome (16001)</td>
<td>-31.1558</td>
<td>136.8054</td>
</tr>
</tbody>
</table>

I used the method of bilinear interpolation to interpolate the variables $T, U, V$ and $\Phi$ at each location from the regular $2.5^\circ \times 2.5^\circ$ grid of the ERA-40 dataset. Bilinear interpolation uses the values of the variable at the four adjacent grid points which surround a point of interest to calculate a value for the variable at that point.
Figure 3.4: A map showing the Australian locations chosen for the analysis.

Calculating results for a location using bilinear interpolation from the ERA-40 grid means that the interpolated values are restricted to the range defined by the values at the surrounding grid points. This means that local maxima or minima that might actually exist at a given location will be “averaged out” by the interpolation and therefore the interpolated value will underestimate or overestimate the existing maximum/minimum. This means that results for a location calculated via bilinear interpolation will tend to flatten extremes that direct observations of that location might reveal.
3.1.3 Comparing ERA-40 Results to In Situ Measurements

We can test the accuracy of statistics calculated from the ERA-40 data by comparing them with the same statistics calculated from actual observations taken at high altitude. Maher and Lee (1977), published by the Bureau of Meteorology (BOM), provides such statistics. It reports monthly and annual statistics for different climate variables calculated from data collected at a number of BOM weather stations across Australia. The list of BOM weather stations that were reported on includes all fifteen locations listed in Table 3.3. Statistics at each location were calculated for data collected over the period January 1957–December 1975, except for Albany (April 1965–December 1975), Cobar (May 1962–December 1975), and Moree (April 1964–December 1975), since these weather stations started operating after 1957. Observations were made once daily, at 2300GMT. Because of the focus on the upper air, there are statistics for a large range of pressure levels, from the surface up to 5 hPa. Nine of the pressure levels used in Maher and Lee (1977) also appear in the ERA-40 data: 850 hPa, 700 hPa, 600 hPa, 500 hPa, 400 hPa, 300 hPa, 200 hPa, 150 hPa, and 100 hPa. Maher and Lee (1977) reported statistics for geopotential height (in units of $10^1$ m), temperature (in °C), eastward wind component ($U$ velocity) (in ms$^{-1}$), and northward wind component ($V$ velocity) (in ms$^{-1}$). Geopotential height, $U$ velocity, and $V$ velocity were specified to the nearest whole unit; temperature was reported to the nearest 0.1 of a degree.

The means of these four variables in (Maher and Lee, 1977) will be compared with the means calculated from the ERA-40 data for each location (using bilinear interpolation as discussed earlier). The ERA-40 value at a given location will be the interpolated spatial mean within a $2.5 \times 2.5^\circ$ grid square; this is going to be compared with a point measurement made at the same location. The scale of the spatial resolution of the ERA-40 dataset means that the ERA-40 values will interpolated from synoptic-scale features; the BOM values, based on point measurements, will incorporate smaller-scale features as well as reflect what was happening at the synoptic scale. Although synoptic-scale features may be highly relevant at high altitudes, substantial mesoscale (or even microscale) features at particular locations (that are not captured by the ERA-40 dataset) might result in differences between the two sets of results.

The ERA-40 data has a time resolution of 6 hours, but I will only use one observation per day (the observation at 0000 GMT is most suitable, being nearest to the timing of the BOM observations). For each variable, I will calculate the annual
and monthly means at each location and pressure level, using the same observation periods as the BOM data. Since there are fifteen locations and nine pressure levels, there will be 135 comparisons for each statistic (e.g. annual mean, January mean) for each climate variable. The actual comparison is as straightforward as calculating the difference between each pair of means, defined as $x_{\text{ERA-40}} - x_{\text{BOM}}$. The results of this validation study, using the methods described here, are reported in Section 4.1.
3. Method

3.2 FEG Performance

3.2.1 Minimum Autorotation Wind Speed

Review

The minimum autorotation wind speed \( v_{\text{min}} \) is calculated using the method outlined by Jabbarzadeh Khoei (1993, p.73) and later outlined again by Roberts and Shepard (Roberts and Shepard, 2003).

This method assumes that the elevation angle \( \beta \) (that is, the angle of the tether to the horizontal at ground level) is constant, which implies that (i) the forces (horizontal and vertical) acting on the FEG are in equilibrium, and (ii) the ratio of net aerodynamic lift to net aerodynamic drag is constant. Another assumption is that the lift from each rotor contributes equally to supporting the weight of the FEG. Jabbarzadeh Khoei (1993, p.39) used these assumptions to derive the following equation, introduced in Section 2.2.16:

\[
C_{\text{LW}} (1 - \tan (\alpha_c + a_1) \tan \beta) = \frac{mg_0}{N \pi R^2} \frac{1}{(1/2) \rho v^2} \quad (3.15)
\]

where \( C_{\text{LW}} \) is the windmill lift coefficient, \( \alpha_c \) is the control axis angle, \( a_1 \) is the rotor backward tilt angle, \( m \) is the total mass of the FEG (including the platform and the tether), \( g_0 \) is standard gravity, \( N \) is the number of rotors on the FEG, \( R \) is the radius of the rotor blades, \( \rho \) is air density, and \( v \) is the free stream wind speed. Jabbarzadeh Khoei (who used a specific case \( N = 2 \) of this equation) made the substitution \( C_{\text{LWOP}} = C_{\text{LW}} (1 - \tan (\alpha_c + a_1) \tan \beta) \) to obtain:

\[
C_{\text{LWOP}} = \frac{mg_0}{N \pi R^2} \frac{1}{(1/2) \rho v^2} \quad (3.16)
\]

This particular equation is arranged to emphasise the role that two physical quantities play in defining the windmill lift coefficient (multiplied by a function of angles): the term \( mg_0/N \pi R^2 \) is the disk loading of the FEG, and \( (1/2) \rho v^2 \) is the free stream dynamic pressure. Thus, \( C_{\text{LWOP}} \) can be regarded as the ratio of these two quantities. Jabbarzadeh Khoei (1993, p.73) rearranged this equation to obtain an expression for the wind speed:
3.2. FEG Performance

\[ v = \sqrt{\frac{mg_0}{N\pi R^2}} \frac{1}{\frac{1}{2}\rho C_{\text{LWOP}}} \] (3.17)

The minimum wind speed for an FEG can be found by determining the conditions that maximise \( C_{\text{LWOP}} \). The minimum wind speed is the lowest wind speed in which the FEG rotors will autorotate and keep the FEG aloft, without any power input from the ground. It also follows that at this wind speed, no net power will be generated.

**Tether Model**

I shall model the tether during FEG flight as a straight line extending from the ground at an elevation angle \( \beta \) to the position of the FEG fuselage at height \( Z \). This is illustrated in Figure 3.5. I have chosen this model for two reasons: (i) it is simple to calculate and (ii) it will always underestimate the length (and therefore weight) of any real tether actually employed.

A straight-line tether is a crude approximation of how a tether would behave in reality, as it ignores both the weight of the tether and the aerodynamic loading on the tether. If tether weight were taken into account, the tether would assume a catenary curve shape between the FEG platform and the anchoring point on the ground. Taking into account the aerodynamic loading on the tether would change the shape of the tether curve further. Additionally, the elevation angle \( \beta \) would change over the length of the tether, and the angle of the tether at the ground would most likely not be the same as the angle of the tether at the FEG platform (unlike in Figure 3.5, where \( \beta \) is constant for the entire tether).

Since realistic tether models would deflect the tether shape away from the straight line between anchoring point and FEG, the straight line model represents the shortest tether length geometrically possible. By using this tether model, calculations of FEG performance will be made using a shorter tether length (and therefore a smaller tether mass) than is achievable in practice. As a result, the calculations are likely to overestimate FEG performance by a non-trivial amount.

Although not realistic, this choice of tether model is conservative, in that this tether model contributes to calculating a “ceiling” for expected FEG performance. The results calculated in this thesis would very likely be overly optimistic compared to real-world performance. An actual FEG would have have a longer (and therefore
heavier) tether, and the extra mass would adversely affect FEG performance (when compared to the over-idealised situation calculated using the methods in this thesis for an FEG with identical parameters such as rotor diameter and operating altitude).

![Diagram showing the simplified tether model to be used for calculating the total tether mass.](image)

The length of the tether, \( L \), is calculated by:

\[
L = \frac{Z}{\sin \beta}.
\]  
(3.18)

The total mass of the tether, \( m_{\text{tether}} \), is calculated by:

\[
m_{\text{tether}} = \lambda_{\text{tether}} L = \frac{Z}{\sin \beta},
\]  
(3.19)

where \( \lambda_{\text{tether}} \) is the tether mass per unit length.

**Calculating the minimum wind speed**

When it comes to actually using Equation 3.17, we need to break the total mass term \( m \) down into platform mass (fuselage, rotor blades, generators, etc., which does not change) and tether mass (varies with altitude). Using the tether model from Section 3.2.1, we can update Equation 3.17 like so:

\[
v = \sqrt{\frac{\left( m_{\text{platform}} + \lambda_{\text{tether}} \frac{Z}{\sin \beta} \right) g_0}{N \pi R^2} \frac{1}{\frac{1}{2} \rho C_{LWOP}}},
\]  
(3.20)

where \( m_{\text{platform}} \) is the FEG platform mass.

In order to use Equation 3.20, we need to know the values of all the terms on the right hand side of the equation. Now, \( m_{\text{platform}}, N, R, \) and \( \lambda_{\text{tether}} \) will be known as part of the FEG design. The values for \( Z \) and \( \rho \) will come from the annual mean
geopotential height and air density of the FEG operating location/pressure level. This leaves $\beta$ and $C_{L\text{WOP}}$.

Jabbarzadeh Khoei (1993) used a $\beta$ value of 40°. Roberts (2000) also used 40° (and called it a “reasonable” value), as did Roberts and Shepard (2003) (although according to this paper, the value of 40° was “arbitrarily chosen”). Much earlier, Roberts (1984) performed calculations using a $\beta$ value of 30°, but did note that this was a minimum value. Roberts (2011) considers a range of $\beta$ values, and settles on a value of 35°. Given all this, I will use a $\beta$ value of 40° in my calculations.

As mentioned above, $C_{L\text{WOP}}$ is a function of $C_{L\text{W}}$, $\alpha_c$, $a_1$ and $\beta$. The methods for calculating $C_{L\text{W}}$, $\alpha_c$ and $a_1$ are complicated and I won’t go into the details here. Thankfully, Jabbarzadeh Khoei (1993) thoroughly investigated the conditions that maximised $C_{L\text{WOP}}$, and modified code to output this quantity. I made use of this code to find the maximum possible $C_{L\text{WOP}}$, 0.616, which occurs when $\mu = 0.105$ and $\alpha_c = 22.1^\circ$, for untwisted blades ($\theta_1 = 0$ and a collective pitch of $\theta_0 = 8.4^\circ$). This agrees closely with Roberts et al. (2007), which states that a control axis angle of around 24° and a tip-speed ratio of 0.10 are the operating parameters for autorotating in the lowest possible wind speed.

It is the case that $C_{L\text{W}}$ is dependent on the tip-speed ratio $\mu$, the collective blade pitch (the pitch angle at the hub of the rotor) $\theta_0$, and the blade twist $\theta_1$. This means that $C_{L\text{W}}$ results can be used for any FEG with these same rotor blade properties, operating at the same tip-speed ratio. As long as the blades remain the same (rotor diameter doesn’t matter), this maximum value of $C_{L\text{WOP}}$, 0.616, will remain valid.

Putting it together, the minimum wind speed for autorotation for a FEG can be calculated using the following equation:

$$v_{\text{min}} = \sqrt{\frac{\left( m_{\text{platform}} + \lambda_{\text{tether}} \frac{Z}{\sin 40^\circ} \right) g_0 \frac{1}{N\pi R^2}}{\frac{1}{2}(0.616)\rho}}.$$  \hspace{1cm} (3.21)

3.2.2 Rated Wind Speed

The rated wind speed $v_{\text{rated}}$, defined as the wind speed at which an FEG starts to produce its rated power output, is dependent on the specific design parameters of the FEG. To some extent, its value is a choice, in that a FEG designer decides upon a particular rated power output. I will determine the value of $v_{\text{rated}}$ using the following procedure. Using the code implementing the extended lifting rotor theory of Gessow and Crim (1952) that was used in Ho (1992) and Jabbarzadeh Khoei
(1993), both $C_P$ and $C_{LW}$ values can be found for a rotor with specific control axis angle, pitch angle, tip speed ratio and blade twist values. $C_{LW}$ in turn provides the value for $C_{LWOP}$. Using a look-up table of every combination of control axis angle, pitch angle, and tip speed ratio, for a specified value of blade twist, each row having an associated $C_P$ and $C_{LWOP}$, we do the following:

- For each row in the table, use the $C_{LWOP}$ value and all the required FEG parameter values to calculate $v_{min}$, using Equation 3.20.
- For each row in the table, which now includes a $v_{min}$ value, use that $v_{min}$, along with the $C_P$ value, $A$, and $\rho$ to calculate the power output of the rotor, via $P = \frac{1}{2}C_P\rho Av_{min}^3$.
- Of all the rows in the table, keep only those with $P \geq P_{rated}$.
- Of the remaining rows, choose the row with the lowest $v_{min}$. This $v_{min}$ is actually $v_{rated}$, it is the minimum wind speed at which at least $P_{rated}$ can be produced. To think about it another way, the true minimum wind speed calculated in Section 3.2.1 is the rated wind speed when the rated power output is zero.

Thinking of $v_{rated}$ as a “minimum” wind speed of sorts makes intuitive sense. At winds above $v_{rated}$, the operating parameters of the FEG can be tweaked to reduce its efficiency at converting wind power (i.e. reduce $C_P$), such that the FEG will still produce the rated power. $v_{rated}$ represents the wind speed at which such tweaking away from a single set of optimum operating conditions will result in less than the rated power being produced.

### 3.2.3 Maximum Wind Speed

For my analyses, I’m choosing the maximum wind speed $v_{max}$ to be the wind speed at the 95th percentile of the annual wind speed distribution at each pressure levels at 100–600 hPa over Moree, a site right under the jet stream. For pressure levels 700–925 hPa, where wind speeds are lower (and it is feasible that an FEG might be able to operate in a wind speed beyond the 95th percentile at these low levels) I will use the same value as for 600 hPa. These values should be high enough that I won’t accidently cut off winds that a real FEG undergoing tether tension, etc. could have withstood.
3.2.4 Calculating Capacity Factors

The capacity factor of a power plant is the total energy that was actually generated by the power plant over a year, divided by the total energy output that would have been had the power plant been operating at its rated capacity for the entire year:

$$CF = \frac{E_{\text{generated}}}{E_{\text{rated}}}$$

(3.22)

Calculating the capacity factor of a FEG is straightforward: we just need to (i) calculate the power $P_i$ being output by the FEG at each time step $i$ in the data (making the assumption that the wind speed remains constant over the duration of each 6-hour time step, and so the power density in the wind will also be constant), and then (ii) multiply the power at each time point $i$ by the length of each time point (6 hours for ERA-40), (iii) sum up the energy generated at each of the $N$ time points to obtain the total energy generated over the year\(^1\), and finally (iv) calculated the rated energy output for the year (given that we know the rated power of the FEG we are analysing):

$$E_{\text{generated}} = \sum_{i=1}^{N} (6)(3600)P_i$$

(3.23)

$$E_{\text{rated}} = (6)(3600)(N)P_{\text{rated}}$$

(3.24)

The rated power of a FEG should always be known, since it is a deliberate decision made during the design process. The part that requires the most calculation is the actual power $P_i$ being output by the FEG at each time step $i$:

$$P_i = \frac{1}{2}C_{P_i}\rho_iAv_i^3$$

(3.25)

where $C_{P_i}$ is the power coefficient at the time step $i$, $\rho_i$ is the air density at each time step $i$, $A$ is the area of the rotors, and $v_i$ is the wind speed at each time step $i$. $\rho_i$ and $v_i$ come from the ERA-40 data (air density will be held constant at its annual mean value, and so won’t vary with time). The area of the rotors will come from the design of the FEG. The only thing that isn’t known is the value of $C_{P_i}$, which is determined by the method in the following sections.

Determining Power Coefficient for Given Wind Speed

The method for determining $C_P$ given a particular wind speed $v$ is somewhat similar to the procedure for finding the rated wind speed, outlined in Section 3.2.2. In

\(^1\)For a 365 day year, there will be $N = 1460$ 6-hour time points.
particular, we’re looking for the maximum value of $C_P$ that a particular set of operating parameters can bring about, given the wind speed $v$. Once again, using a long look-up table of every combination of control axis angle, pitch angle, and tip speed ratio, for a specified value of blade twist, each row having an associated $C_P$ and $C_{LWOP}$, we do the following:

- Check: is $v < v_{\text{min}}$, or $v > v_{\text{max}}$? If so, stop now, there is no point looking for a $C_P$ value—the FEG cannot autorotate in the wind $v$.

- For each row in the table, use the $C_{LWOP}$ value and all the required FEG parameter values to calculate $v_{\text{min}}$, using Equation 3.20.

- Remove all rows where $v_{\text{min}} > v$. This removes operating parameters that would require a minimum wind speed greater than the current wind speed—they are not feasible in this wind.

- For each remaining row in the table, use the $C_P$ value to calculate the power that would be produced in the current wind, via $P = \frac{1}{2} C_P \rho A v^3$ ($\rho$ and $A$ will be known).

- Remove all rows where $P > P_{\text{rated}}$. This eliminates operating parameters that produce power in excess of the rated power output—these too are not feasible in the wind $v$.

- (If there are no operating parameters that can bring the generated power $P$ down to below $P_{\text{rated}}$, then that might be an indication that the wind $v$ is too strong for FEG operation, in which case the FEG should be landed, or lowered in altitude to a safer wind speed.)

- Of the remaining rows in the table, select the set of operating parameters which maximise $P$. If there is more than one set of operating parameters with the same maximum value of $P$, then select the one with the highest $v_{\text{min}}$. The value of $C_P$ associated with this set of parameters is the one to use.

This procedure can be done ahead of time for a given FEG design, calculating the maximum $C_P$ for a range of wind speeds $0 \leq v \leq v_{\text{min}}$. This results in a $v$-$C_P$ power curve, which can be used directly to look up the $C_P$ for a given value of $v$. Each power curve will be unique to the specific FEG design, just like $v_{\text{min}}$ and $v_{\text{rated}}$. 
**Procedure for Power Calculation for Given Wind Speed**

Now that we can determine $C_P$ in Equation 3.25, we can put everything together. Figure 3.6 shows a flowchart of the procedure of calculating the power at every time step at a particular location/pressure level. As can be seen, the rated power $P_{\text{rated}}$, minimum wind speed $v_{\text{min}}$, maximum wind speed $v_{\text{max}}$, and rated wind speed $v_{\text{rated}}$ need to be known. Once again, these are determined from the specific FEG parameters.

![Flowchart](image)

Figure 3.6: Flowchart showing the how the power output $P_i$ at each time step $t_i$ is determined from the wind speed $v_i$ at each time step.

When considering the performance at all pressure levels below the rated level, this procedure can be applied to all pressure levels separately, and then for each time step, the optimal power result is chosen from all the pressure levels, and the FEG
3. Method

is deemed to have increased or decreased its operating altitude for that time step (for ease of calculation, I’m assuming that the FEG can switch between pressure levels instantaneously, which is a generous concession). Once this procedure has been completed for every time step in the period being considered, the $P_i$ can be summed together in Equation 3.23, and the capacity factor calculated from there.
Chapter 4

Results

4.1 Validation of ERA-40-Derived Means Against BOM Means

Section 3.1.3 outlined how climate statistics calculated from the ERA-40 data could be validated against the same statistics calculated from measurements made by the Bureau of Meteorology (BOM). Annual means for temperature, geopotential height, eastward wind component ($U$ velocity), and northward wind component ($V$ velocity) were calculated from the ERA-40 data for each of nine pressure levels (850 hPa, 700 hPa, 600 hPa, 500 hPa, 400 hPa, 300 hPa, 200 hPa, 150 hPa, and 100 hPa) at each of fifteen locations across Australia (see Table 3.3). At each location, the ERA-40 data points used to calculate means were restricted to the same time period that the BOM means were calculated over (typically 1957–1975, except for Albany, Cobar, and Moree, as noted in Section 3.1.3). These results, calculated from the appropriate period of ERA-40 data, were compared to the annual means published in Maher and Lee (1977).

Figures 4.1, 4.3, 4.5, and 4.6 show a comparison of the ERA-40 and BOM data for temperature, geopotential height, eastward wind component ($U$ velocity), and northward wind component ($V$ velocity), respectively. Each scatterplot has 135 data points (means at nine pressure levels for fifteen locations).

The ERA-40 and BOM results are very highly correlated for all four variables. Temperature and geopotential height both have a correlation of +0.999, $U$ velocity has a correlation of +0.995, and $V$ velocity has a correlation of +0.901. Because the results for temperature and geopotential height are so tightly clustered around the unit slope, it is difficult to see in Figures 4.1 and 4.3 how the ERA-40 results differ.
from the BOM results. Figures 4.2 and 4.4 plot the difference between the ERA-40 and BOM results against the BOM results, which allows the differences between the two sets of results to be seen.

Figure 4.2 reveals that the differences in annual mean temperature were within ±0.5°C for the vast majority of locations and pressure levels, with only a few outliers outside that range. All differences were within ±1.0°C, inclusive. The ERA-40 results were evenly scattered between over-estimating and under-estimating the BOM values. There are a few outliers at around 15°C on the x-axis, where the ERA-40 results have overestimated the BOM values by 0.5-1.0°C. The relatively high temperature indicates that these are measurements taken low in the atmosphere (all these outliers are at the 850 hPa level)—the discrepancy might be explained by a local effect (e.g. specific geographical features) that wasn’t modelled by the ERA-40 dataset. Overall, the high correlation and small differences show that the ERA-40 temperature data is in perfectly adequate agreement with actual measurements.

Figure 4.4 shows that the ERA-40 results tend to slightly underestimate the BOM statistics for geopotential height, much more often than it overestimates. In both Figures 4.3 and 4.4, you can clearly see the stratification of the mean geopo-
Figure 4.2: A comparison of ERA-40-derived results with BOM results (Maher and Lee, 1977) for the annual mean temperatures calculated for fifteen locations and nine pressure levels. The y-axis shows the difference between the ERA-40 results and the BOM results.

Potential height values by pressure level. This is to be expected, given the relationship between pressure and height—the annual mean geopotential height varies relatively little between different locations, compared with the vast differences between adjacent pressure levels. The disagreement between the ERA-40 results and BOM measurements increases with increasing height; a possible explanation is that measurements at the highest altitudes are relatively sparse (since during the 1957–1975 period, high altitude measurements would have come from radiosondes launched at specific stations, and weather satellites only came online towards the very end of this period), and so the ERA-40 reanalysis has to “fill in” a lot of the gaps with values from climate models, which are more likely to diverge from actual measurements than at lower altitudes, where the density of measurements for the reanalysis model to draw upon to correct its modelling will tend to be higher. However, these differences are very small compared to the magnitude of the heights be considered, so any practical difference is negligible.

The results for $U$ velocity (Figure 4.5) are slightly more scattered (although still in very close agreement). There is a tendency for the ERA-40 results to overestimate the BOM results, especially for wind velocities between 15 and 25 m s$^{-1}$. In Figure
4.6 for $V$ velocity, the small range of velocities and the fact that the means are reported to the nearest whole number mean that there is a lot of overplotting. To overcome this, I have “jittered” the points in the scatter plot, so that all the points that should be on each exact integer $(x, y)$ coordinate are shown as clustered around it. This reveals that the ERA-40 results tended to underestimate the $V$ velocity measurements of the BOM data. It is possible that if the wind velocity values were specified to the first decimal point instead of rounded to the nearest whole number, we might see better agreement.

Overall, the results in this section have confirmed that climate statistics calculated from reanalysis data can adequately match those statistics calculated from actual measurements of the atmosphere. Since the accuracy of reanalysis data is well established, this was not about confirming that the reanalysis data itself is accurate, but rather that my data manipulation and calculation techniques are sound, and can produce reliable results.
4.1. Validation of ERA-40-Derived Means Against BOM Means

Figure 4.4: A comparison of ERA-40-derived results with BOM results (Maher and Lee, 1977) for the annual mean geopotential height calculated for fifteen locations and nine pressure levels. The y-axis shows the difference between the ERA-40 results and the BOM results.

Figure 4.5: A comparison of ERA-40-derived results with BOM results (Maher and Lee, 1977) for the annual mean eastward wind component (U velocity) calculated for fifteen locations and nine pressure levels. With the exception of results for Albany, Cobar, and Moree, the means are based on the period 1957–1975.
Figure 4.6: A comparison of ERA-40-derived results with BOM results (Maher and Lee, 1977) for the annual mean northward wind component \( (V \text{ velocity}) \) calculated for fifteen locations and nine pressure levels. With the exception of results for Albany, Cobar, and Moree, the means are based on the period 1957–1975.
4.2 Geopotential Height of Pressure Levels

In this section, I calculate the annual mean geopotential height of each pressure level over Australia, and examine the monthly variation of mean geopotential height at fifteen specific locations across Australia (see Table 3.3). Knowing the height in metres of a given pressure level, one can calculate the length of the tether required for an FEG to operate at that pressure level. If the geopotential height is stable enough over the year, then it’s simpler to use the annual mean geopotential height for tether length calculations, instead of having to re-calculate tether length at each time step in the ERA-40 data.

4.2.1 Annual Mean

Annual mean geopotential height was calculated for all ERA-40 grid points over Australia and at 12 pressure levels between 925 hPa and 100 hPa, inclusive. To calculate the annual mean, data from the entire period covered by the ERA-40 dataset, 1 September 1957 – 31 August 2002, was used. Therefore, the annual mean is actually the mean of 45 years of data. The results are shown in Figure 4.7.

The results reveal that on average, for each pressure level, geopotential height is approximately constant along lines of latitude and decreases from north to south. This pattern is especially pronounced at pressure levels 600 hPa and above. This has the consequence that results based on analysis of wind at a particular pressure level will correspond to a range of operating altitudes for a FEG, depending on the latitude of the FEG location. For example, a FEG operating at 4,200 m above Hobart (latitude 43° S) will on average be operating at the 600 hPa pressure level, while a FEG operating at the same 4,200 m height above Darwin (latitude 12° S) will on average be slightly below the 600 hPa level.

4.2.2 Seasonal Variation

I calculated the mean geopotential height by month for each of the fifteen locations. The calculations showed that the geopotential height of a pressure level varies over the year (this is expected, since the thickness, or difference in geopotential height between two pressure levels, is proportional to the temperature difference between the pressure levels. Since temperature has a clear seasonal cycle, it follows that the geopotential height difference between a given pressure level and the surface will likely exhibit a seasonal cycle as well). Figure 4.8 shows the monthly variation in
Figure 4.7: The annual mean geopotential height (in m) over Australia, at pressure levels 925 hPa, 850 hPa, 775 hPa, 700 hPa, 600 hPa, and 500 hPa. Calculated over the period 1 September 1957 – 31 August 2002.
Figure 4.7 (cont.): The annual mean geopotential height (in m) over Australia, at pressure levels 400 hPa, 300 hPa, 250 hPa, 200 hPa, 150 hPa, and 100 hPa. Calculated over the period 1 September 1957 – 31 August 2002.
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mean geopotential height for each pressure level above Moree. The deviation from the annual mean geopotential height at each pressure level is small—the largest monthly mean deviation from the annual mean at Moree is on the order of 4% of the value of the annual mean. Table 4.1 shows the month with the largest mean deviation from the annual mean geopotential height for each location and pressure level.

Table 4.1: Months with the largest absolute mean deviation from the annual mean geopotential height at pressure levels 100–925 hPa, by location. The table shows for each pressure level and location the month with the largest mean deviation from the annual mean, and the magnitude of the deviation. The deviation is expressed as a percentage of the annual mean geopotential height.

<table>
<thead>
<tr>
<th>Location</th>
<th>925 hPa</th>
<th>850 hPa</th>
<th>775 hPa</th>
<th>700 hPa</th>
<th>600 hPa</th>
<th>500 hPa</th>
<th>400 hPa</th>
<th>300 hPa</th>
<th>250 hPa</th>
<th>200 hPa</th>
<th>150 hPa</th>
<th>100 hPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albany</td>
<td>-2.4%</td>
<td>1.6%</td>
<td>1.6%</td>
<td>1.6%</td>
<td>1.7%</td>
<td>1.9%</td>
<td>2.0%</td>
<td>2.1%</td>
<td>2.1%</td>
<td>1.9%</td>
<td>1.6%</td>
<td>1.6%</td>
</tr>
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<tr>
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<td>Townsville</td>
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<tr>
<td>Wagga</td>
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<tr>
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</tr>
</tbody>
</table>

Table 4.1 makes it clear that the change in geopotential height over the course of a year is relatively small: the largest deviations from the annual mean geopotential height are about 5% of the annual mean value (most locations and pressure levels show far less deviation than that). Therefore, it is reasonable to make the approximation that each pressure level is at a fixed geopotential height (taken to be the annual mean value). Table 4.2 shows the annual mean geopotential heights of each pressure level above each location. The table includes the value of the geopotential
Figure 4.8: Monthly mean geopotential height at pressure levels 100–925 hPa over Moree. Vertical lines about each monthly mean indicate the middle 90% of the range of geopotential height observations for that month. The annotated horizontal lines denote the annual mean geopotential height for each pressure level.
height for each pressure level according to the US Standard Atmosphere (National Oceanic and Atmospheric Administration et al., 1976). The Standard Atmosphere values are closest to the annual means for Hobart, but in general are not suitable as stand-in values of geopotential height for a generic location on mainland Australia. On the mainland, the Standard Atmosphere will underestimate the geopotential height of the pressure level, and so tether lengths calculated using this value of height will be too short, underestimating the total weight of the FEG operating at that pressure level.

4.2.3 Summary

I don’t have the data required to calculate how far away from a pressure level a FEG can be before the results for that pressure level cease to be indicative of the wind conditions experienced by that FEG. Therefore all results based on pressure level should be interpreted as applying to a FEG operating at or very near the annual mean geopotential height of that pressure level.
Table 4.2: Annual mean geopotential height (in m) by pressure level and location.

<table>
<thead>
<tr>
<th>Location</th>
<th>925 hPa</th>
<th>850 hPa</th>
<th>775 hPa</th>
<th>700 hPa</th>
<th>600 hPa</th>
<th>500 hPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albany</td>
<td>796.7</td>
<td>1496.6</td>
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<td>5689.5</td>
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<tr>
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<td>795.7</td>
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<td>2300.5</td>
<td>3141.9</td>
<td>4386.0</td>
<td>5816.1</td>
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<tr>
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</table>

US Std Atmosphere | 7185 | 9164 | 10363 | 11784 | 13608 | 16180
4.3 Air Density

4.3.1 Annual Mean

Using the ERA-40 temperature data, I estimated the air density using equation 3.6 for each 6-hour time step, and then I calculated the annual mean of those estimates. I calculated the annual mean air density for all ERA-40 grid points over Australia and at 12 pressure levels between 925–100 hPa (inclusive). The annual means were calculated from the entire 45-year period covered by the ERA-40 data set. The annual means for each pressure level are shown in Figure 4.9.

Two things are immediately obvious in Figure 4.9. First, air density decreases as altitude increases. Second, there are bands of constant air density in the east-west direction, and this pattern becomes much more pronounced with altitude. At pressure levels between 925–200 hPa, air density increases with increasing latitude. In contrast, at 150-100 hPa, the gradient reverses and air density decreases with increasing latitude. The change in the direction of the north-south air density gradient that occurs between 200 hPa and 150 hPa is due to the temperature inversion at the tropopause.

4.3.2 Seasonal Variation

There is only one variable, temperature, in equation 3.6, the formula I used for calculating the air density (since the pressure level will always be treated as a constant). Given that temperature has a clear seasonal cycle, air density calculated from the temperature will be expected to have a seasonal cycle as well. I calculated the mean air density for each month at each pressure level above the fifteen locations across Australia. The monthly variation in air density for each pressure level above Moree is shown in Figure 4.10. Monthly variation is clearly observable at pressure levels 925–400 hPa, but at 300–100 hPa this variation reduces greatly, becoming approximately constant over the entire year.

Table 4.3 shows that monthly mean air density deviates from the annual mean by a maximum of ±3% across all locations and pressure levels. The maximum deviation seems to happen in February most often, although July and January are also common. This relatively small amount of deviation over the year may still have an impact on the viable operation of an FEG, but since power density is predominantly affected by changes in wind speed, I will simplify my calculations of power density by not taking the variation of air density into account. Instead, I will
Figure 4.9: The annual mean air density (in kg m$^{-3}$) over Australia, at pressure levels 925 hPa, 850 hPa, 775 hPa, 700 hPa, 600 hPa, and 500 hPa. Calculated over the period 1 September 1957 – 31 August 2002.
Figure 4.9 (cont.): The annual mean air density (in kg m$^{-3}$) over Australia, at pressure levels 400 hPa, 300 hPa, 250 hPa, 200 hPa, 150 hPa, and 100 hPa. Calculated over the period 1 September 1957 – 31 August 2002.
Figure 4.10: Monthly mean air density (in kg m$^{-3}$) at pressure levels 100–925 hPa over Moree. Vertical lines about each monthly mean indicate the middle 90% of the range of air density observations for that month. The annotated horizontal lines denote the annual mean air density for each pressure level.
4. Results

Table 4.3: Months with the largest absolute mean deviation from the annual mean air density at pressure levels 100–925 hPa, by location. The table shows for each pressure level and location the month with the largest mean deviation from the annual mean, and the magnitude of the deviation. The deviation is expressed as a percentage of the annual mean air density.

<table>
<thead>
<tr>
<th>Location</th>
<th>925 hPa</th>
<th>850 hPa</th>
<th>775 hPa</th>
<th>700 hPa</th>
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<th>400 hPa</th>
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<td>Apr</td>
<td>Feb</td>
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</tr>
<tr>
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<tr>
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<td>-0.5%</td>
<td>-0.7%</td>
<td>-0.8%</td>
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<tr>
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<td>-2.6%</td>
<td>-2.3%</td>
<td>-2.5%</td>
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<tr>
<td>Woomera</td>
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<td>-1.9%</td>
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<td>Feb</td>
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<td>Jan</td>
<td>Feb</td>
<td>Feb</td>
</tr>
</tbody>
</table>

use the annual mean air density at each pressure level to calculate power density. The annual mean densities for each location and pressure level are shown in Table 4.4, along with a comparison to the US Standard Atmosphere values for air density at those pressure levels. Unlike geopotential height, the standard atmosphere values of air density are not appreciably different from any of the annual mean air density values at locations across Australia, and so are an acceptable substitute for local mean values. However, I shall still use the annual mean values I calculated from the ERA-40 data for power density calculations.
Table 4.4: Annual mean air density (in kg m$^{-3}$) by pressure level and location.

<table>
<thead>
<tr>
<th>Location</th>
<th>925 hPa</th>
<th>850 hPa</th>
<th>775 hPa</th>
<th>700 hPa</th>
<th>600 hPa</th>
<th>500 hPa</th>
</tr>
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<tbody>
<tr>
<td>Albany</td>
<td>1.136</td>
<td>1.057</td>
<td>0.974</td>
<td>0.892</td>
<td>0.786</td>
<td>0.678</td>
</tr>
<tr>
<td>Alice Springs</td>
<td>1.092</td>
<td>1.023</td>
<td>0.950</td>
<td>0.874</td>
<td>0.770</td>
<td>0.661</td>
</tr>
<tr>
<td>Broome</td>
<td>1.084</td>
<td>1.013</td>
<td>0.942</td>
<td>0.867</td>
<td>0.762</td>
<td>0.653</td>
</tr>
<tr>
<td>Carnarvon</td>
<td>1.102</td>
<td>1.027</td>
<td>0.950</td>
<td>0.873</td>
<td>0.769</td>
<td>0.661</td>
</tr>
<tr>
<td>Charleville</td>
<td>1.103</td>
<td>1.033</td>
<td>0.958</td>
<td>0.881</td>
<td>0.774</td>
<td>0.666</td>
</tr>
<tr>
<td>Cobar</td>
<td>1.115</td>
<td>1.043</td>
<td>0.967</td>
<td>0.888</td>
<td>0.782</td>
<td>0.674</td>
</tr>
<tr>
<td>Darwin</td>
<td>1.090</td>
<td>1.018</td>
<td>0.942</td>
<td>0.864</td>
<td>0.758</td>
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<tr>
<td>Forrest</td>
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<td>0.963</td>
<td>0.884</td>
<td>0.779</td>
<td>0.672</td>
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<td>Giles</td>
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<td>1.020</td>
<td>0.948</td>
<td>0.874</td>
<td>0.771</td>
<td>0.663</td>
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<tr>
<td>Hobart</td>
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<td>1.072</td>
<td>0.989</td>
<td>0.906</td>
<td>0.798</td>
<td>0.689</td>
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<tr>
<td>Laverton</td>
<td>1.137</td>
<td>1.060</td>
<td>0.979</td>
<td>0.898</td>
<td>0.791</td>
<td>0.683</td>
</tr>
<tr>
<td>Moree</td>
<td>1.114</td>
<td>1.043</td>
<td>0.967</td>
<td>0.888</td>
<td>0.781</td>
<td>0.673</td>
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<tr>
<td>Townsville</td>
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<td>0.949</td>
<td>0.869</td>
<td>0.762</td>
<td>0.654</td>
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<tr>
<td>Wagga</td>
<td>1.125</td>
<td>1.053</td>
<td>0.975</td>
<td>0.894</td>
<td>0.787</td>
<td>0.680</td>
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<tr>
<td>Woomera</td>
<td>1.117</td>
<td>1.044</td>
<td>0.965</td>
<td>0.886</td>
<td>0.780</td>
<td>0.673</td>
</tr>
<tr>
<td>US Std Atmosphere</td>
<td>1.139</td>
<td>1.063</td>
<td>0.986</td>
<td>0.909</td>
<td>0.802</td>
<td>0.693</td>
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<th>Location</th>
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<th>300 hPa</th>
<th>250 hPa</th>
<th>200 hPa</th>
<th>150 hPa</th>
<th>100 hPa</th>
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<td>Albany</td>
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<td>0.453</td>
<td>0.388</td>
<td>0.318</td>
<td>0.243</td>
<td>0.166</td>
</tr>
<tr>
<td>Alice Springs</td>
<td>0.551</td>
<td>0.437</td>
<td>0.377</td>
<td>0.316</td>
<td>0.251</td>
<td>0.176</td>
</tr>
<tr>
<td>Broome</td>
<td>0.544</td>
<td>0.432</td>
<td>0.375</td>
<td>0.316</td>
<td>0.253</td>
<td>0.180</td>
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<tr>
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<td>0.377</td>
<td>0.316</td>
<td>0.250</td>
<td>0.175</td>
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<td>0.380</td>
<td>0.316</td>
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<td>0.317</td>
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<tr>
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<td>0.447</td>
<td>0.384</td>
<td>0.317</td>
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<td>0.169</td>
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<td>0.378</td>
<td>0.316</td>
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<td>0.392</td>
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<td>0.164</td>
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<td>0.384</td>
<td>0.317</td>
<td>0.245</td>
<td>0.169</td>
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<td>0.376</td>
<td>0.316</td>
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<td>0.390</td>
<td>0.318</td>
<td>0.243</td>
<td>0.165</td>
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<tr>
<td>Woomera</td>
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<td>0.448</td>
<td>0.385</td>
<td>0.317</td>
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<td>0.395</td>
<td>0.321</td>
<td>0.242</td>
<td>0.163</td>
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4.4 Power Density

In this section, I present my own calculation of the annual mean power density over Australia, as well as the annual power density at the 5th, 25th, 50th (median), 75th, and 95th percentiles, calculated using the ERA-40 data. I also investigate the seasonality of power density.

4.4.1 Annual Means

The annual mean power densities for pressure levels 925 to 100 hPa calculated from the ERA-40 data are shown in Figure 4.11. The power density at each time step in the ERA-40 dataset was calculated from the cube of the “instantaneous” wind speed at each time point, and the annual mean air density for that pressure level and location (the suitability of the annual mean air density for power density calculation is established in Section 4.3).

These means were calculated in order to check the claims made in a number of papers about the mean power density of the jet stream over Australia. Roberts et al. (2007) claims that (annual mean) power densities of 19 kW m\(^{-2}\) are available. Figure 4.11 shows that this is approximately correct, although a rather high estimate—the maximum annual mean power densities occur at 250–200 hPa, at 27–30° S in latitude. The contours show that annual means of at least 16 kW m\(^{-2}\) occur in two pockets, one on the coast of Western Australia, and the other on the coast of New South Wales. It is entirely possible that these pockets represent mean power densities of 19 kW m\(^{-2}\) or higher, although they are concentrated in only two small areas of the continent. The pockets are contained within an east-west band at the same latitude where the mean power density is at least 14 kW m\(^{-2}\).

Figure 4.11 also shows the annual mean power for pressure levels at lower altitudes: such means were never reported in the FEG literature, even though operating altitudes much lower than the jet stream were suggested. Consider the 600 hPa level, which has an altitude of 4.2–4.6 km across Australia, a candidate altitude for FEG operation according to the literature. The annual mean power density is much lower at this level than at the jet stream. North of 24° S, the mean power density is less than 1 kW m\(^{-2}\), and only the southern coast of the mainland has a mean greater than 2 kW m\(^{-2}\). Tasmania has the highest mean power density, between 2.5–3.5 kW m\(^{-2}\). Mean power densities at lower altitudes are lower still. The ridge of high mean power density along 30° S that is a feature at jet stream levels (the
Figure 4.11: The annual mean power density (in kW m$^{-2}$) over Australia, at pressure levels 925 hPa, 850 hPa, 775 hPa, 700 hPa, 600 hPa, and 500 hPa, calculated using the ERA-40 dataset. Calculated over the time period covered by the ERA-40 dataset, 1 September 1957 – 31 August 2002.
Figure 4.11 (cont.): The annual mean power density (in kW m$^{-2}$) over Australia, at pressure levels 400 hPa, 300 hPa, 250 hPa, 200 hPa, 150 hPa, and 100 hPa, calculated using the ERA-40 dataset. Calculated over the time period covered by the ERA-40 dataset, 1 September 1957 – 31 August 2002.
ridge is clearly visible at levels 400–150 hPa) does not exist at levels 925–500 hPa. The mean power densities at 4 km and below, if they had been reported in the FEG literature, would have been around 0.3–3.5 kW m\(^{-2}\), depending on precise altitude and location. While this range of values is still higher than the typical mean power density at surface level, it’s an order of magnitude smaller than the mean power density at jet stream level.

Next, I calculated the annual mean power density at 250 hPa for each of the fifteen Australian locations in Table 3.3. The contour map of power density at 250 hPa originally from Atkinson et al. (1979) and reproduced in a number of other papers shows the values of power density at 25 locations, including all of the locations in 3.3. The two sets of means are compared in Table 4.5 and plotted in Figure 4.12.

Table 4.5: Comparison of annual mean power density values at 250 hPa reported in Atkinson et al. (1979) (calculated over an unknown period) with values calculated from the ERA-40 data (over the entire dataset period 1957–2002), for each of fifteen locations across Australia. The ERA-40 values for the locations are interpolated from the ERA-40 grid. The difference is defined as the ERA-40 value minus the Atkinson et al. value.

<table>
<thead>
<tr>
<th>Location</th>
<th>Power Density (kW m(^{-2})) (Atkinson et al., 1979)</th>
<th>Power Density (kW m(^{-2})) (ERA-40)</th>
<th>Difference (kW m(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Albany</td>
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<td>-0.98</td>
</tr>
<tr>
<td>Alice Springs</td>
<td>11.12</td>
<td>10.13</td>
<td>-0.99</td>
</tr>
<tr>
<td>Broome</td>
<td>2.05</td>
<td>2.14</td>
<td>0.09</td>
</tr>
<tr>
<td>Carnarvon</td>
<td>11.53</td>
<td>11.89</td>
<td>0.36</td>
</tr>
<tr>
<td>Charleville</td>
<td>16.04</td>
<td>14.65</td>
<td>-1.39</td>
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<tr>
<td>Cobar</td>
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<td>13.29</td>
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<td>Darwin</td>
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<tr>
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<tr>
<td>Giles</td>
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<td>8.85</td>
<td>0.62</td>
</tr>
<tr>
<td>Woomera</td>
<td>17.28</td>
<td>14.47</td>
<td>-2.81</td>
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</table>

This comparison is not as exact as the comparisons performed in Section 4.1,
Figure 4.12: Scatterplot of the annual mean power density values at 250 hPa reported in Atkinson et al. (1979) vs annual mean values calculated from the ERA-40 data, for each of fifteen locations across Australia.

because I was unable to determine the date range of the data used to calculate the means in the Atkinson et al. (1979) map. The ERA-40 annual mean calculations used the entire 45 years of data. The means in the Atkinson et al. (1979) map would have had to be calculated over fewer than 45 years of data. Given this, I do not expect that the two sets of means will necessarily match closely, due to the effects of climate trends and interannual variability that will depend on the precise period of time used for calculation.

Figure 4.12 shows that agreement between the two sets of means is OK (the correlation is +0.98), although the four locations with the highest mean power densities on the Atkinson et al. (1979) map, Charleville, Forrest, Woomera, and Moree, have the largest differences. These four locations are around 25–32°S, right under the jet stream. In each case, the ERA-40 means are lower than the Atkinson et al. (1979) means. The ERA-40 means for these locations are roughly similar, at 14–15 kW m$^{-2}$. The Atkinson et al. (1979) means were 16–18 kW m$^{-2}$, meaning the differences are between 1–4 kW m$^{-2}$.

I’ve shown that my calculations of annual mean power density over Australia
broadly agree with the values published in the FEG literature, although my calculations could not confirm peak values of 19–20 kW m\(^{-2}\) claimed (for instance) by Roberts et al. (2007). Similarly, although my calculations for means at specific locations broadly agreed with those on the Atkinson et al. (1979) map, my calculated annual means for those specific locations at the jet stream latitude (Charleville, Forrest, Woomera, Moree) were lower by 1–4 kW m\(^{-2}\). These discrepancies are probably explained in part by the radiosonde soundings data used in Atkinson et al. (1979), which would have included contributions from mesoscale motions that the grid-interpolated ERA-40 data does not capture.

My calculations also presented the mean power densities at 600 hPa (4.2–4.4 km) and below, which is where the FEG literature says FEGs would operate. However, the literature never reported the mean power densities at these levels. I have done this and shown that had the literature reported them, they would have been around 0.3–3.5 kW m\(^{-2}\), depending on precise altitude and location. Also, the influence of the jet stream on mean power density (in the form of a high mean power density ridge at 30° S) appears to be absent at these lower altitudes.

### 4.4.2 Annual Percentiles

The previous section calculated means in order to compare them with values published in the FEG literature. However, I won’t be discussing mean power density any further, and will instead use quantiles (e.g. the median) to summarise power density. This is because the distribution of power density is highly skewed, and so in this case the mean is not an intuitive measure of central tendency.

Instead of the mean the median power density at each pressure level over Australia is presented in Figure 4.13. The median power density has a straightforward interpretation: half of the year, the power density will be higher than the median power density, and the other half of the year, it will be lower. In terms of the operation of a FEG, this is particularly useful: it means that for half of the year, FEG output will be at least the value of the output when the power density in the wind is at its median value. The other half of the year, the FEG output will be less than that. This doesn’t take in account downtime for maintenance, or downtime due to the winds being too strong (and so the FEG can’t actually take advantage of all power density values above the median), but it is an acceptable approximation.

Figure 4.13 shows that the median annual power density is lower than the mean power density at the same location and pressure level. This is expected, due to the
Figure 4.13: The annual median power density (in kW m⁻²) over Australia, at pressure levels 925 hPa, 850 hPa, 775 hPa, 700 hPa, 600 hPa, and 500 hPa, calculated using the ERA-40 dataset. Calculated over the time period covered by the ERA-40 dataset, 1 September 1957 – 31 August 2002.
Figure 4.13 (cont.): The annual median power density (in kW m\(^{-2}\)) over Australia, at pressure levels 400 hPa, 300 hPa, 250 hPa, 200 hPa, 150 hPa, and 100 hPa, calculated using the ERA-40 dataset. Calculated over the time period covered by the ERA-40 dataset, 1 September 1957 – 31 August 2002.
skewed distribution. The patterns of mean and median power density are similar: the lines of constant power density run east-west, and power density tends to increase towards the south. The exception is the jet stream at levels 300–150 hPa, where the highest values of power density are found in an east-west ridge at about 30° S.

Had the FEG literature reported the median power density instead of the mean, it would have reported that the median power density at jet stream levels (250–200 hPa), along a ridge at about 27–30° S was about 7–8 kW m$^{-2}$, with peaks of up to 9–10 kW m$^{-2}$ (in the same pockets on the western and eastern coasts of Australia that were seen for the mean). This is much lower than the annual means calculated in Figure 4.11 (which were 14–16 kW m$^{-2}$, so about half), and the peaks of 9–10 kW m$^{-2}$ are about half the value of the 19–20 kW m$^{-2}$ quoted in the FEG literature for the highest annual mean power density. At 600 hPa, the median power density is less than 1 kW m$^{-2}$ across the entire Australian mainland, and Tasmania has a median power density of between 1–1.5 kW m$^{-2}$. Again, this works out to be about half the value of mean power density at the same location.

I have presented the median (50th percentile) power density here, because of the widespread use of the median as a measure of central tendency, however for wind power applications, the entire distribution is important. The annual 5th, 25th, 50th, 75th, and 95th percentiles of power density at each pressure level over Australia are presented in Appendix B.
4.4.3 Annual Distribution By Location

I calculated the annual distribution of power density for all pressure levels above each of the fifteen locations of Australia. Presenting power density at a single location allows the variation with altitude to be seen. The results are in Figures 4.14–4.28. They reveal the following observations:

- Below 400 hPa, no location reaches 19–20 kW m$^{-2}$, even at the 95th percentile.

- The jet stream is the dominant feature on each plot—it is always associated with the highest power density. Every location shows a “bump” at 250 hPa, indicating that power density reaches higher values at that level.

- The locations that are closest in latitude to the jet stream ridge (Charleville, Cobar, Forrest, Moree, Woomera) have especially pronounced peaks at the jet stream level of 250 hPa.

- Three locations have much less power density than the others, and appear to be obviously unsuitable for generating wind power at altitude: Broome, Townsville, and especially Darwin. This is primarily an effect of latitude—all three locations are in the northern half of Australia, north of the jet stream ridge.

- The distribution of power density is skewed such that the mean is consistently between the 50th and 75th percentiles, often closer to the 75th than the 50th.
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Figure 4.14: The annual distribution of power density (in kW m\(^{-2}\)) over Albany, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density.

Figure 4.15: The annual distribution of power density (in kW m\(^{-2}\)) over Alice Springs, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density.
Figure 4.16: The annual distribution of power density (in kW m\(^{-2}\)) over Broome, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density.

Figure 4.17: The annual distribution of power density (in kW m\(^{-2}\)) over Carnarvon, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density.
Figure 4.18: The annual distribution of power density (in kW m$^{-2}$) over Charleville, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density.

Figure 4.19: The annual distribution of power density (in kW m$^{-2}$) over Cobar, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density.
Figure 4.20: The annual distribution of power density (in kW m\(^{-2}\)) over Darwin, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density.

Figure 4.21: The annual distribution of power density (in kW m\(^{-2}\)) over Forrest, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density.
Figure 4.22: The annual distribution of power density (in kW m\(^{-2}\)) over Giles, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density.

Figure 4.23: The annual distribution of power density (in kW m\(^{-2}\)) over Hobart, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density.
Figure 4.24: The annual distribution of power density (in kW m$^{-2}$) over Laverton, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density.

Figure 4.25: The annual distribution of power density (in kW m$^{-2}$) over Moree, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density.
Figure 4.26: The annual distribution of power density (in kW m$^{-2}$) over Townsville, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density.

Figure 4.27: The annual distribution of power density (in kW m$^{-2}$) over Wagga, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density.
The annual distribution of power density (in kW m$^{-2}$) over Woomera, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density.

Figure 4.28: The annual distribution of power density (in kW m$^{-2}$) over Woomera, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density.
4.4.4 Seasonal Variation

So far, I have presented annual statistics summarising power density, which doesn’t capture the fact that the distribution of power density changes over the course of the year, following a seasonal oscillation. Although the FEG literature acknowledges that the available power density is subject to seasonal change, this is never adequately quantified. In this section, I report the seasonal variation of power density over Australia.

I’ve defined the seasons as groups of three adjacent months: December–February (DJF), March–May (MAM), June–August (JJA), and September–November (SON). These approximate the timing of the four seasons in the southern hemisphere: Summer, Autumn, Winter, and Spring, respectively. I calculated the mean and percentiles (5th, 25th, 50th, 75th, 95th) of the power density for each of the seasons, for each pressure level. There are too many plots to show them all, so I have just reported the median. The median power density for all pressure levels 925–100 hPa by season are in Appendix B. Here, I will just show the seasonal medians for 600 hPa and 250 hPa.

Figure 4.29 shows the median power density over Australia at 600 hPa for each of the seasons. Median power density is lowest in DJF and MAM: most of mainland Australia has a median power density of less than $0.5 \text{ kW m}^{-2}$. Tasmania has a median power density of 1–2 kW m$^{-2}$. During JJA and SON, the median increases, so that the mainland south of $21^\circ$ S (during JJA) and $24–27^\circ$ S (during SON) has a median power density of at least $0.5 \text{ kW m}^{-2}$. The 1 kW m$^{-2}$ contour line has crept north to cover the southern coast of Australia (in particular over the south of Western Australia). The median power density over Tasmania during JJA and SON has remained broadly the same: 1–2 kW m$^{-2}$. The seasonal pattern, clearly evident over mainland Australia, is not as strong at latitudes south of about $40^\circ$ S.

Figure 4.30 shows the median power density over Australia at the level of the jet stream, 250 hPa. Here, contrast between seasons is extreme. In the summer months (DJF), the median power density is less than 4 kW m$^{-2}$ across the entirety of the Australian mainland, and there is no sign of the high power density ridge extending east-west at $27–30^\circ$ S that was evident on the map for the annual median power density (Figure 4.13). During these months, the median increases towards the south, similar to what was observed at lower altitudes. In MAM, the ridge reappears (with a peak median power density of above 6 kW m$^{-2}$), and by JJA, it has increased to at least triple the annual median value: the peak of the ridge
4.4. Power Density

Figure 4.29: The median (50th percentile, P50) annual power density (in kW m\(^{-2}\)) over Australia at 600 hPa by season. The seasons are defined as four groups of three adjacent months: Summer (December-February, DJF), Autumn (March-May, MAM), Winter (June-August, JJA), and Spring (September-November, SON).
Figure 4.30: The median (50th percentile, P50) annual power density (in kW m$^{-2}$) over Australia at 250 hPa by season. The seasons are defined as four groups of three adjacent months: Summer (December-February, DJF), Autumn (March-May, MAM), Winter (June-August, JJA), and Spring (September-November, SON).
between 27–30° S is at least 27 kW m\(^{-2}\). The power density dies down during SON, with the median values in the ridge dropping to about 11–13 kW m\(^{-2}\).

I calculated the seasonal distributions of power density at all pressure levels above the fifteen locations. The results are in Figures 4.31–4.45, and show the following:

- For all locations except Hobart, JJA had the highest power density (that is, the value of the 95th percentile was the highest across all seasons).
- For all locations except Hobart, DJF had the lowest power density (that is, the value of the 95th percentile was the lowest across all seasons).
- Hobart experiences the least amount of seasonal variation, which is reflected in the distributions of power density for each season. The change in distribution between seasons is relatively small. The power density peaks at 250 hPa and 300 hPa are almost equal in size, unlike for most other locations, where 250 hPa is the clear peak.
- The locations identified as unsuitable in Section 4.4.3 (Broome, Darwin, Townsville) do not exhibit as much variation as the other locations, but DJF is consistently identifiable as the season with the lowest power density.
- At the jet stream locations (Charleville, Cobar, Forrest, Moree, Woomera), the contrast between DJF and JJA is very high.
- At all locations, the contrast between the MAM and SON distributions is smaller than the DJF/JJA contrast. At the jet stream locations, there is higher power density during SON than during MAM.
Figure 4.31: The distribution of power density (in kW m\(^{-2}\)) by season over Albany, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density. The seasons are defined as four groups of three adjacent months: Summer (December-February, DJF), Autumn (March-May, MAM), Winter (June-August, JJA), and Spring (September-November, SON).
Figure 4.32: The distribution of power density (in kW m$^{-2}$) by season over Alice Springs, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density. The seasons are defined as four groups of three adjacent months: Summer (December-February, DJF), Autumn (March-May, MAM), Winter (June-August, JJA), and Spring (September-November, SON).
### Results

<table>
<thead>
<tr>
<th>Season</th>
<th>Power Density (kW m$^{-2}$)</th>
<th>Mean</th>
<th>Median</th>
<th>5th − 95th Pctile</th>
<th>25th − 75th Pctile</th>
</tr>
</thead>
<tbody>
<tr>
<td>BROOME (DJF)</td>
<td>100</td>
<td>775</td>
<td>850</td>
<td>925</td>
<td>700</td>
</tr>
<tr>
<td>BROOME (MAM)</td>
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<td>775</td>
<td>850</td>
<td>925</td>
<td>700</td>
</tr>
<tr>
<td>BROOME (JJA)</td>
<td>100</td>
<td>775</td>
<td>850</td>
<td>925</td>
<td>700</td>
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<tr>
<td>BROOME (SON)</td>
<td>100</td>
<td>775</td>
<td>850</td>
<td>925</td>
<td>700</td>
</tr>
</tbody>
</table>

**Figure 4.33:** The distribution of power density (in kW m$^{-2}$) by season over Broome, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density. The seasons are defined as four groups of three adjacent months: Summer (December-February, DJF), Autumn (March-May, MAM), Winter (June-August, JJA), and Spring (September-November, SON).
Figure 4.34: The distribution of power density (in kW m\(^{-2}\)) by season over Carnarvon, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density. The seasons are defined as four groups of three adjacent months: Summer (December-February, DJF), Autumn (March-May, MAM), Winter (June-August, JJA), and Spring (September-November, SON).
Figure 4.35: The distribution of power density (in kW m\(^{-2}\)) by season over Charleville, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density. The seasons are defined as four groups of three adjacent months: Summer (December-February, DJF), Autumn (March-May, MAM), Winter (June-August, JJA), and Spring (September-November, SON).
Figure 4.36: The distribution of power density (in kW m$^{-2}$) by season over Cobar, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density. The seasons are defined as four groups of three adjacent months: Summer (December-February, DJF), Autumn (March-May, MAM), Winter (June-August, JJA), and Spring (September-November, SON).
Figure 4.37: The distribution of power density (in kW m\textsuperscript{−2}) by season over Darwin, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density. The seasons are defined as four groups of three adjacent months: Summer (December-February, DJF), Autumn (March-May, MAM), Winter (June-August, JJA), and Spring (September-November, SON).
Figure 4.38: The distribution of power density (in kW m\(^{-2}\)) by season over Forrest, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density. The seasons are defined as four groups of three adjacent months: Summer (December-February, DJF), Autumn (March-May, MAM), Winter (June-August, JJA), and Spring (September-November, SON).
Figure 4.39: The distribution of power density (in kW m$^{-2}$) by season over Giles, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density. The seasons are defined as four groups of three adjacent months: Summer (December-February, DJF), Autumn (March-May, MAM), Winter (June-August, JJA), and Spring (September-November, SON).
Figure 4.40: The distribution of power density (in kW m\(^{-2}\)) by season over Hobart, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density. The seasons are defined as four groups of three adjacent months: Summer (December-February, DJF), Autumn (March-May, MAM), Winter (June-August, JJA), and Spring (September-November, SON).
Figure 4.41: The distribution of power density (in kW m\(^{-2}\)) by season over Laverton, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density. The seasons are defined as four groups of three adjacent months: Summer (December-February, DJF), Autumn (March-May, MAM), Winter (June-August, JJA), and Spring (September-November, SON).
### Figure 4.42: The distribution of power density (in kW m\(^{-2}\)) by season over Moree, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density. The seasons are defined as four groups of three adjacent months: Summer (December-February, DJF), Autumn (March-May, MAM), Winter (June-August, JJA), and Spring (September-November, SON).
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Figure 4.43: The distribution of power density (in kW m\(^{-2}\)) by season over Townsville, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density. The seasons are defined as four groups of three adjacent months: Summer (December-February, DJF), Autumn (March-May, MAM), Winter (June-August, JJA), and Spring (September-November, SON).
Figure 4.44: The distribution of power density (in kW m\(^{-2}\)) by season over Wagga, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density. The seasons are defined as four groups of three adjacent months: Summer (December-February, DJF), Autumn (March-May, MAM), Winter (June-August, JJA), and Spring (September-November, SON).
Figure 4.45: The distribution of power density (in kW m$^{-2}$) by season over Woomera, for pressure levels 925–100 hPa. For each pressure level, the 5th, 25th, 50th (median), 75th, and 95th percentiles of power density are shown, along with the mean power density. The seasons are defined as four groups of three adjacent months: Summer (December-February, DJF), Autumn (March-May, MAM), Winter (June-August, JJA), and Spring (September-November, SON).
4.5 Wind Lulls and FEG Downtime

So far, I have calculated results pertaining to the nature of high altitude winds, the energy source of the FEGs. The next step is to calculate how these winds affect FEG performance.

4.5.1 Downtime of Demonstration Craft

Section VII of Roberts et al. (2007, p.141) provides details of a Demonstration Craft, with a rated output of 240 kW. The rated wind speed (18.4 m s\(^{-1}\)) and autorotation wind speed (11.5 m s\(^{-1}\)) of the craft are both applicable at an altitude of 15,000 feet (4,600 metres). We can think of 4,600 metres as the “rated” operating altitude.

If we were to calculate the proportion of time (over a particular period) that the wind speed is below the autorotation wind speed of 11.5 m s\(^{-1}\) at 4,600 metres, we’d have a useful metric for evaluating the performance of the Demonstration Craft: this would be the proportion of time (over a particular period) that the Demonstration Craft was unable to operate at its rated altitude. During these times, the Demonstration Craft could either be operating at a lower altitude, or it could be landed on the ground due to insufficient winds at any altitude below the rated operating altitude.

Since the ERA-40 dataset stratifies variables by pressure level, I can’t look up the wind speed at an altitude of 4,600 metres exactly. By looking at the average geopotential height of each pressure level, the pressure level closest in height to 4,600 metres can be used as an indicator of what the wind might be doing at 4,600 metres. Figure 4.7 shows that the mean geopotential height at the 600 hPa pressure level is closest to (although consistently lower than, by a few hundreds of metres) the Demonstration Craft’s operating altitude of 4,600 metres. Assuming that wind speeds at the 600 hPa level are broadly indicative of wind speeds a few hundred metres above, the proportion of time (expressed as a percentage) during the period 1st September 1957–31st August 2002 that the wind speed was below 11.5 m s\(^{-1}\) is shown in Figure 4.46.

Figure 4.46 shows that the percentage of time during 1957–2002 that the wind was below 11.5 m s\(^{-1}\) changes with latitude, but tends to remain the same across longitudes, forming east-west bands with a constant percentage of downtime. The percentage is greatest in the north of Australia, and decreases towards the south. The figure indicates that long-term, mainland Australia would expect insufficient
Figure 4.46: The percentage of time during the period 1st September 1957–31st August 2002 (the entire time domain of the ERA-40 dataset) that wind speed was below 11.5 m s$^{-1}$ at 600 hPa over Australia.
winds to maintain the demonstration craft at its rated operating altitude of 4,600 m for at least 40% of the year, while Tasmania would expect insufficient winds between 30% and 40% of the year. Regions of Australia north of Victoria and the southern tip of Western Australia would expect insufficient winds for at least 50% of the year. Regions north of a latitude of 12° S (northern parts of Queensland and the Northern Territory) would expect insufficient winds at least 90% of the year.

Since the 600 hPa pressure level is in general below the Demonstration Craft’s operating altitude, and that wind speeds tend to increase with altitude, the results in Figure 4.46 probably over-estimate the percentage of downtime that would occur at 4,600 metres. I calculated the percentage of time during 1957–2002 that the wind speed was below 11.5 m s\(^{-1}\) at 500 hPa, which is at an altitude of 5,600–5,800 m. Since the winds are stronger at 500 hPa, this would provide an under-estimate. This is shown in Figure 4.47.

The proportion of downtime over Australia is indeed less at 500 hPa compared to 600 hPa. Most of area of the mainland north of 24° S has more than 50% downtime, compared with most of the mainland north of 33° S having at least 50% downtime at 600 hPa. The actual proportion of downtime at 4,600 m is likely to be closer to the values at 600 hPa than at 500 hPa, since 500 hPa is about 1,000 m higher and 600 hPa is only about a few hundred metres lower.

Even so, Figures 4.46 and 4.47 strongly indicate that over most of mainland Australia, the Demonstration Craft would have been able to maintain its rated operating altitude of 4,600 metres for less than half of the period 1st September 1957–31st August 2002.

However, even if the wind is insufficient to maintain the Demonstration Craft at its rated operating altitude of 4,600 metres, the wind at a lower altitude might be sufficient to keep it aloft (and even generating power). If this were the case, the Demonstration Craft would not have to land. In order to take the lower altitude winds into account, I would need to know the minimum wind speed for autorotation at lower altitudes.

I calculated the estimated minimum wind speed for autorotation \(v_{\text{min}}\) for the Demonstration Craft for all the grid points in the ERA-40 dataset at pressure levels 600 hPa, 700 hPa, 775 hPa, 850 hPa, and 925 hPa. Using the formula in Section 3.2.1, I was able to calculate the \(v_{\text{min}}\) value applicable to the specific air density and geopotential height of each grid point.

Figure 4.48 shows the proportion of time over the period 1957–2002 that the
Figure 4.47: The percentage of time during the period 1st September 1957–31st August 2002 (the entire time domain of the ERA-40 dataset) that wind speed was below $11.5 \text{ m s}^{-1}$ at 500 hPa over Australia.
Demonstration Craft would have been landed, taking into account the minimum wind speeds required for autorotation at each pressure level 925–600 hPa. In this figure, the Demonstration Craft is only counted as “landed” if the wind speed was insufficient for autorotation at every pressure level at a single location and time point. The Figure shows that the Demonstration Craft would have been landed for about 50% of the period 1957–2002 along the northern coast of Australia at 18° S and higher. Across all of Australia, the Demonstration Craft would have been landed for at least 20% of the time (at least 25% for all parts except for Tasmania and the south-west corner of Western Australia). A Demonstration Craft located on the east coast of New South Wales would have been landed at least 40% of the time, which is higher than for the rest of New South Wales and Southern Queensland.

These results show that the Demonstration Craft with the parameters as outlined in Roberts et al. (2007) would be expected to spend anywhere from 20–50% of the time grounded due to insufficient wind if trialed in Australia, depending on location. In addition, the results of Figure 4.46 suggest that the Demonstration Craft would spend at least 30% of the time below its rated operating altitude of 4,600 metres (for most locations in Australia north of 36° S the Demonstration Craft would spend at least 50% of the time below the rated operating altitude).

Seasonal Variation

As Section 4.4.4 showed, high altitude winds have a strong seasonal pattern, and this will affect FEG downtime. I calculated the seasonal percentage of time that the wind at 600 hPa would be less than the autorotation wind speed 11.5 m s$^{-1}$, to show how the Demonstration Craft would be affected by season. Figure 4.49 shows the results.

The figure makes clear that in the summer months (December–February) and autumn months (March–May) during the period 1st September 1957–31st August 2002, a Demonstration Craft located almost anywhere on mainland Australia would spend more than half the time unable to autorotate at the rated pressure level of 600 hPa. The craft may be able to remain aloft at a lower level, however. The winter months June–July have the least proportion of time below 11.5 m s$^{-1}$, with all locations south of 21° S having downtime of less than 50%. These results strongly indicate that a FEG might end up spending most of the summer months grounded, in most locations across Australia, in particular in northern locations.
Figure 4.48: The percentage of time during the period 1st September 1957–31st August 2002 (the entire time domain of the ERA-40 dataset) that the demonstration craft would have been landed (that is, the wind speed was below the autorotation wind speed $v_{\text{min}}$ at 600 hPa, and similarly for all the pressure levels below) over Australia.
Figure 4.49: Percentage of the time during each season within the period 1st September 1957–31st August 2002 that the wind speed was below 11.5 m s$^{-1}$ at pressure level 600 hPa. The seasons are defined as four groups of three adjacent months: Summer (December-February, DJF), Autumn (March-May, MAM), Winter (June-August, JJA), and Spring (September-November, SON).
4. Results

4.5.2 Mass-Area Ratio and FEG Downtime

As already seen in Section 3.2.1, the formula for the minimum wind speed required to remain aloft ($v_{min}$, derived by Jabbarzadeh Khoei (1993)) relies on the ratio of the total FEG mass $m$ to FEG rotor area $A$:

$$v_{min} = \sqrt{\frac{\frac{mg}{A} g}{\frac{1}{2} \rho C_{LWOP}}}.$$  (4.1)

Each FEG design will have a mass-area ratio particular to it. By investigating the effect of mass-area ratio on the minimum wind speed $v_{min}$ and the resulting downtime, analysis need not be restricted to individual FEG designs, but a wide range of possible FEG configurations.

The value of $C_{LWOP}$ is also subject to the specific FEG design. However, for this analysis, I have chosen to focus on FEG designs which yield the highest possible value of $C_{LWOP}$, as reported in Section 3.2.1. I will consider FEGs with untwisted rotor blades ($\theta_1 = 0^\circ$), operating at a control axis angle $\alpha_c = 22.1^\circ$ and tip speed ratio $\mu = 0.105$, for a $C_{LWOP}$ value of 0.616. This approach means that the results in this section will report the lowest possible $v_{min}$ and downtime that FEGs are capable of (without significant changes to their fundamental design).

The form of Equation 4.1 shows that, all other variables remaining constant, $v_{min}$ increases with the square root of the mass-area ratio. Figure 4.50 shows the relationship between $v_{min}$ and mass-area ratio for twelve pressure levels from 925 to 100 hPa. Since Equation 4.1 contains air density and not air pressure, the pressure levels are actually inferred from the values of air density used; the US Standard Atmosphere was used to nominate air density values for each pressure level (see Table 4.4 for the specific values). Since $v_{min}$ is inversely proportional to the square root of the air density, pressure levels higher in the atmosphere with lower air density will have higher values of $v_{min}$ for a constant mass-area ratio. The relatively small variations of air density with time and location means that values of $v_{min}$ shown in Figure 4.50 are indicative of minimum wind speeds at most locations over Australia, and for all times of year.

Although, note that at higher altitudes, the same fuselage will have a higher mass/area ratio, since the tether adds weight. More than just the effect of lowered air density needs to be taken into account when calculating $v_{min}$ at increasing altitude.
4.5. Wind Lulls and FEG Downtime

Figure 4.50: The effect of mass/area ratio on the minimum wind speed required to remain aloft, using the formula introduced by Jabbarzadeh Khoei (1993).

**FEG Downtime vs Mass-Area Ratio, by Location**

Figure 4.51 shows the effect of mass-area ratio on the proportion of time that a FEG with that mass-area ratio would be unable to even autorotate at that level (via the value of $v_{\text{min}}$, the minimum wind speed required for autorotation). I calculated the relationship between mass-area ratio and the proportion of downtime at each pressure level for each of the fifteen locations across Australia listed in Table 3.3.
Figure 4.51: The effect of mass/area ratio on the annual percentage of downtime at pressure levels 925–100 hPa, for Albany, Alice Springs, and Broome. The percentage of downtime was calculated over the total length of the ERA-40 dataset, 1957–2002. The minimum wind speed for each value of mass/area ratio and pressure level is calculated using the annual average air density for each location (see Table 4.4).
Figure 4.51 (cont.): The effect of mass/area ratio on the annual percentage of downtime at pressure levels 925–100 hPa, for Carnarvon, Charleville, and Cobar. The percentage of downtime was calculated over the total length of the ERA-40 dataset, 1957–2002. The minimum wind speed for each value of mass/area ratio and pressure level is calculated using the annual average air density for each location (see Table 4.4).
Figure 4.51 (cont.): The effect of mass/area ratio on the annual percentage of downtime at pressure levels 925–100 hPa, for Darwin, Forrest, and Giles. The percentage of downtime was calculated over the total length of the ERA-40 dataset, 1957–2002. The minimum wind speed for each value of mass/area ratio and pressure level is calculated using the annual average air density for each location (see Table 4.4).
Figure 4.51 (cont.): The effect of mass/area ratio on the annual percentage of
downtime at pressure levels 925–100 hPa, for Hobart, Laverton, and Moree. The
percentage of downtime was calculated over the total length of the ERA-40 dataset,
1957–2002. The minimum wind speed for each value of mass/area ratio and pressure
level is calculated using the annual average air density for each location (see Table
4.4).
Figure 4.51 (cont.): The effect of mass/area ratio on the annual percentage of downtime at pressure levels 925–100 hPa, for Townsville, Wagga, and Woomera. The long term is defined as the total length of the ERA-40 dataset, 1957–2002. The minimum wind speed for each value of mass/area ratio and pressure level is calculated using the annual average air density for each location (see Table 4.4).
4.6 Capacity Factors

4.6.1 Demonstration Craft

Using the methods outlined in Section 3.2.4, I calculated the average capacity factor of the Demonstration Craft described in Roberts et al. (2007) for each point over Australia, operating no higher than the 600 hPa pressure level. For these calculations, I did not use the specified values for \( v_{\text{min}} \) and \( v_{\text{rated}} \), but instead calculated them for the specific annual mean geopotential height and air density at each point. I also calculated the \( v_{\text{min}} \) and \( v_{\text{rated}} \) values for each pressure level below 600 hPa, in anticipation of analysing the performance of the Demonstration Craft at these lower altitudes as well as the rated altitude. The calculated values for \( v_{\text{min}} \) and \( v_{\text{rated}} \) are shown in Figures 4.52 and 4.53 respectively.

These figures show that at each pressure level, there is relatively little variation in \( v_{\text{min}} \) and \( v_{\text{rated}} \) over Australia. Partly this is due to the artifact that the values were rounded to the nearest 0.1 m s\(^{-1}\), but contour maps of the unrounded values would have still shown very little variation. At the 600 hPa level, over all locations in Australia, my calculated values of \( v_{\text{min}} \) and of \( v_{\text{rated}} \) are higher than the values offered in Roberts et al. (2007), 11.5 m s\(^{-1}\) and 18.4 m s\(^{-1}\), respectively, which were for 4,600 m, higher in altitude than the 600 hPa level (and therefore less dense air and a longer tether). This may be due to differences in the air density value used, or a different value for \( C_{\text{LWOP}} \), or the calculation of tether weight—it is unclear.

Figure 4.54 shows the average capacity factor over Australia not just at the rated pressure level 600 hPa, but at each pressure level below that. I calculated the capacity factors at each pressure level on the assumption that the Demonstration Craft was confined to operating at that level. That means that if the wind speed at that pressure level was insufficient to maintain autorotation, the Demonstration Craft would have to land, and could not autorotate/generate power at a lower level (if possible). A capacity factor was calculated for each of the 45 years in the ERA-40 dataset, 1 September–31 August, and then I took the average of those capacity factors.

The figure shows that a Demonstration Craft confined to operating at 600 hPa at almost any point over mainland Australia would have a capacity factor of less than 0.35. A Demonstration Craft operating over Tasmania would have a capacity factor of between 0.4 and 0.5. Locations north of 27° S would have a capacity factor of less than 0.2. These capacity factor values are about the same as those reported
Figure 4.52: The calculated value of $v_{\text{min}}$, the minimum wind speed required to remain aloft via autorotation, for the Demonstration Craft over Australia, when operating at pressure levels 925–600 hPa. The annual mean air density and geopotential height have been used in the calculation of $v_{\text{min}}$ at each grid point.
Figure 4.53: The calculated value of $v_{\text{rated}}$, the wind speed at which the craft generates rated power (240 kW), for the Demonstration Craft over Australia, when operating at pressure levels 925–600 hPa. The annual mean air density and geopotential height have been used in the calculation of $v_{\text{rated}}$ at each grid point.
for conventional, ground-based wind turbines. In the far south west of the map, in the Southern Ocean, capacity factors do increase to above 0.7, but these are not possible locations for a FEG.

However, confining the operation of a FEG to a single pressure level is not necessary, as it can change altitude as required. Roberts and Shepard (2003) pointed out the improvement in their capacity factor calculations when they took into account the generating potential of winds below the rated altitude. Figure 4.55 calculates the average capacity factor of the Demonstration Craft over Australia at 600 hPa, taking all pressure levels below into account. At each time point, the potential power output at each pressure level was calculated, and the maximum chosen. The FEG was then deemed to have spent the 6 hour time step operating at that optimal level. As expected, this results in higher average capacity factor values, but most of the mainland still has a capacity factor of less than 0.4. Only the southern tip of Tasmania has a capacity factor greater than 0.5. Locations north of 21°S have an average capacity factor of less than 0.2.

Figures 4.54 and 4.55 demonstrate that if the 240 kW Demonstration Craft were to be tested at any location in Australia, it would be expected to perform no better than a conventional ground-based turbine, and in the northern half of the country, it might perform worse.
4.6. Capacity Factors

Figure 4.54: The average value of capacity factor $CF$ for the Demonstration Craft over Australia, when operating at pressure levels 925–600 hPa. Here, the Demonstration Craft is confined to operation at each rated pressure level. The average $CF$ is based on 45 $CF$ results calculated for each year 01 September–31 August, for 1957–2002.
Figure 4.55: The average value of capacity factor $CF$ for the Demonstration Craft over Australia, when operating at a maximum pressure level of 600 hPa. Here, the Demonstration Craft was allowed to change its operating pressure level at each time step in order to maximum power output. The average $CF$ is based on 45 $CF$ results calculated for each year 01 September–31 August, for 1957–2002.
4.6. Capacity Factors

Seasonal Variation

The seasonal variation of capacity factors is important from an electricity generation point of view, since in months with lower average capacity factors, alternate sources of power generation would be required to supplement output (assuming that electricity demand does not track the supply of high altitude winds). To get the seasonal average capacity factor, I calculated the capacity factor for each three-month season of each of the 45 years in ERA-40, and then took the average. Figure 4.56 shows the seasonal variation of the capacity factor of the Demonstration Craft at 600 hPa, when operation is confined to 600 hPa only. Figure 4.57 shows the seasonal variation of capacity factor when lower pressure levels are allowed to be used when optimal.

Both figures show that capacity factors are highest in September–November and June–August, when much of the mainland has a capacity factor of between 0.3 and 0.5. In contrast, capacity factors in December–February and March–May are lower: most of the mainland has an average value of less than 0.3. These low capacity factors in the summer and autumn months reflect the result shown in Section 4.5.1, that the Demonstration Craft would spend much of its time grounded due to insufficient winds (and hence, little opportunity to generate power).
Figure 4.56: The average seasonal value of capacity factor $CF$ for the Demonstration Craft over Australia, when operating at pressure level 600 hPa. Here, the Demonstration Craft is confined to operation at 600 hPa. The average $CF$ for each season (SON, DJF, MAM, JJA) is based on 45 $CF$ results calculated for each season each year in the ERA-40 dataset.
4.6. Capacity Factors

Figure 4.57: The average seasonal value of capacity factor $CF$ for the Demonstration Craft over Australia, when operating at a maximum pressure level of 600 hPa. Here, the Demonstration Craft was allowed to change its operating pressure level at each time step in order to maximum power output. The average $CF$ for each season (SON, DJF, MAM, JJA) is based on 45 $CF$ results calculated for each season each year in the ERA-40 dataset.
Chapter 5

Discussion

5.1 Implications of Results

5.1.1 Wind Power Density at Sub-Jet Stream Levels

Figure 4.4 showed that mean power density was a maximum at jet stream levels (200–300 hPa), and a location-by-location comparison of means showed that the ERA-40 values were close to the values reported in the FEG literature, except for the locations with the highest means reported in the FEG literature (Charleville, Forrest, Moree, Woomera), where the ERA-40 values were lower. Following the advice of Archer and Caldeira (2009), I calculated percentiles of power density over Australia, and showed that at 600 hPa, the lowest level at which Roberts et al. (2007) envisions FEGs would operate (and in particular, the proposed 240 kW Demonstration Craft), the annual median power density would be less than 1.0 kW m$^{-2}$ over mainland Australia, and between 1–1.5 kW m$^{-2}$ over Tasmania. These calculations were performed to fill in the gap left in the FEG literature, where power density (other than the annual mean value in the jet stream core) was not reported. Half the year with a power density above 1 kW m$^{-2}$ is still very high compared to ground-based wind turbines, but is low compared with what is available the jet stream.

This has implications for the size and power output of FEGs, implications which are not discussed sufficiently in the literature—a rotor in a wind with power density 1 kW m$^{-2}$ would need to have ten times the cross sectional area of a rotor in a wind with power density 10 kW m$^{-2}$ (the highest median power density at jet stream levels over Australia) in order to generate the same amount of power overall. Given there is a limit to how large rotors can be (due to the strength of materials, etc.), a FEG designed to operate in 1 kW m$^{-2}$ winds (i.e. at sub-jet stream altitudes)
cannot simply have its rotor area increased by an arbitrary factor in order to achieve the same power output as a FEG operating in 10 kW m\(^{-2}\) winds (i.e. in the jet stream). Thus, feasibly-designed FEGs operating at sub-jet stream altitudes would be expected to have much lower power outputs than FEGs operating at jet stream levels.

The seasonality of the power density showed that the summer and autumn months have far less power available in the wind compared to the winter and spring. This was true at all pressure levels, including at jet stream levels, where the jet stream had retreated very far to the south. This too has implications for FEG output, with abundance in the winter months, but paucity in the summer. This issue is mentioned but not quantified in the literature.

5.1.2 Downtime

The results in Section 4.5.1, calculating the expected downtime of the 240 kW Demonstration Craft described in Roberts et al. (2007), show that at most locations in mainland Australia, the Demonstration Craft would spend at least 30–40% of the year unable to operate at its rated altitude of 4,600 m, due to insufficient winds. The analysis took into account that perhaps the FEG could operate at a lower altitude instead of having to land altogether, and this showed that the FEG would be landed for at least 25% of the year. Tasmania was slightly better, with between 20–25% downtime. A look at the seasonality showed that downtime was not evenly distributed over the year—it would occur much more often in summer and autumn, and less often in winter and spring.

The FEG literature has mentioned that 30 hours per week would be the average downtime of a FEG at the best locations. This figure implies annual downtime for 18% of the year. It’s unclear if this figure is exclusively applied to jet stream level FEGs, but at the 600 hPa level over Australia, I did not find a single location with an annual downtime this low. Further, the distribution of the downtime indicates that during the summer and autumn months, a FEG in most locations in Australia would be severely under-utilised. The exception is Tasmania, where the wind speed (and thus power density) is much more stable all year round. Roberts et al. (2007) suggests migrating the FEGs north and south over the course of the year to track the best conditions, but the scale of change in downtime over Australia means that FEGs would have have to move over most of the length of the Australian mainland to maintain consistent wind conditions, and even then, in the summer months most
locations would still subject to greater periods of wind lulls than in the winter months.

Given these general seasonal patterns, and the likely expense of keeping FEGs “at the ready”, and the fact that periods of sufficient wind can’t necessarily be predicted easily (and so it’s likely that the FEG would be inefficient at “catching” periods of sufficient winds), it seems that FEGs would not be economical in nearly all of Australia for around 3–6 months of the year (with the possible exception of Tasmania, and parts of the southern coast of the mainland).

5.1.3 Capacity Factors

My calculations of the expected capacity factor for the 240 kW Demonstration Craft show that capacity factor over Australia would not be appreciably higher than the capacity factor of a conventional ground-based wind turbine, and would in fact be lower than the average conventional wind turbine in the entire northern part of Australia (north of around 24° S). The seasonal analysis shows that there is a strong seasonal variation, with the winter and spring months being better, and the summer and autumn months worse.

This brings up two major problems for the FEG. The first is that the supposed advantage of the FEG, stated in the literature a number of times, is that it has a superior capacity factor in the range 0.6–0.9, which may make it a candidate for supplying baseload power. I could not reproduce such figures for Australia in my analysis. If, as my results show, the FEG does not have an overwhelming advantage in terms of capacity factor, then the case for it is no longer convincing. A FEG with a capacity factor of 0.3–0.5 (or even a group of them) is not attractive if a conventional ground-based wind farm is likely to have a similar capacity factor (as detailed in Section 2.1), and for what would most probably be a considerably lower cost on a per-rotor area basis.\footnote{And despite recent difficulties in the location and planning of wind farms faced by wind farm developers in Australia, that would appear to be far easier than negotiating the dedicated air space (and land space) required for FEGs.}

The second problem is seasonality. The seasonal pattern of the winds mean that capacity factors for part of the year aren’t going to be the same as as the capacity factor for the whole year. This means that at a particular fixed location on the Australian mainland, it may not be economical to operate during summer and autumn. Although Roberts et al. (2007) suggests moving FEGs north or south
with the seasons may address the problem of seasonality, I am hesitant. The results of Figure 4.57 in the previous chapter show that the latitude of lines of constant capacity factor ($CF$) vary markedly over the course of a year. For instance, the 0.3 $CF$ contour line is at 21°S over Australia in the winter months, but during the summer months the contour line has moved south to about 33°S (and as far south as 36°S over the east coast of the continent). To maintain a near-constant capacity factor all year round, FEGs would either need to relocate very far south of their winter operating location in the summer (which raises logistic and economic problems), or the FEGs could remain located in the south of the continent all year round (defeating the point of north-south migration).

5.2 A Lack of Success

In the Introduction to the Symposium on Failed Innovations, Braun (1992) outlines a number of different reasons why innovations fail: technical problems; problems of production and manufacturing; economic power and market considerations; development of rival technologies; moral arguments; and institutional resistance. Braun also lists the findings of Project SAPPHO, which compared successful innovations in industry with unsuccessful innovations, focusing on points of difference between the two. Project SAPPHO found that successful commercial innovations tended to have the following qualities, in contrast to unsuccessful innovations: they had a better understanding of user needs; they paid more attention to marketing/publicity; they perform their development work more efficiently; they make use of outside scientific/technical expertise; the individuals involved have more authority and seniority (Rothwell et al., 1974, pp.259–260).

It is not straightforward to define what counts as success or failure in the case of the FEG. The FEG sits somewhere in between the extremes of explicitly commercial industrial innovation (the kind studied in Project SAPPHO) and pure academic research. From the academic end, success might be gauged by the experimental confirmation of the theory and models presented in the literature (i.e. test flights). The wider adoption and development of the idea by the research community might be another, along with grants and funding. Given the FEG’s origin in a University setting, these seem relevant, and in this context, market-oriented measures of success aren’t appropriate. Also relevant, however, is the commercialisation agenda explicitly pursued by the FEG proponents themselves over the years. This means
that things like investment, customers, market share, and development of products need to be considered. Given that commercialisation has been the explicit goal for the FEG, it makes sense to focus on that as the primary measure for the success or failure of the FEG. It’s also difficult to decide on what counts as outright failure, given that the FEG is still actively promoted (the most recent presentation about the concept was in 2015, see Roberts (2015)), and thus still has the potential to succeed on whatever criteria might be specified in the future. Given this, it’s better to think in terms of success, or a lack of success so far.

With all this in mind, I can say that the FEG has not been successful. However, this statement needs to be qualified. It is clearly the case that the FEG concept is technically feasible: over the years, several small-scale crafts have flown and even generated (trivially small) amounts of power. In this sense, the FEG is a success, since it has been proven experimentally to be able to do what it needs to (take off, land, manoeuvre, generate power, etc., albeit perhaps under controlled, limited conditions), and I don’t dispute that. However, as noted above, the FEG project has always been broader than demonstrating basic technical feasibility (this is necessary, but not sufficient). In this section, I lay out the reasons why I say the FEG has not been a success.

5.2.1 No Commercialisation

The most recent Executive Summary from Sky Windpower discusses their product called the WATTS, the Wind Airborne Tethered Turbine System (Sky WindPower, 2013). It would have a rated output of 6–15 kW, would operate at altitudes of 500–2000 feet, and have a predicted capacity factor of 2–3 times that of a typical ground-based turbine. WATTS is described as “near ready for customer testing” (p.1). This was in May 2013.² Since then, there have been no more updates about WATTS, or its commercial availability. I contacted Sky Windpower in January 2015 asking about the status of WATTS and its availability, but have not heard anything back from them.

Despite having successfully generated power using a prototype FEG at low altitude in December 2011 (Gelbaum, 2013), Sky Windpower has not yet brought the WATTS, or any other craft, to market. While Sky Windpower has partnered with a group called Velocity Cubed Technologies to help develop the FEG (Shepard and

²The Sky WindPower Executive Summary from July 2012 also states that WATTS is “near ready for customer testing” (Sky WindPower, 2012, p.1).
Bringing new technology to market is a very long and difficult process, and so a lack of commercialisation so far is by no means a damning indictment. However, a commercially available FEG would be one of the strongest arguments for the success of the FEG.

5.2.2 No Flights at Altitude

As mentioned above and in earlier chapters, there have been small-scale, low altitude test flights of the FEG going back over 30 years. However, there is no evidence in the literature, or from other sources like the Sky WindPower website, that a FEG has been tested at the proposed operating heights kilometres up in the atmosphere. Regardless of its theoretical potential, extensive high altitude testing is a crucial step towards the FEG becoming a viable option for electricity generation, and as far as I can tell, it has not happened yet.

As noted in the literature a number of times, at low altitudes (below a few hundred metres) the tether can be modelled as straight and massless (Roberts, 2000; Roberts and Shepard, 2003; Roberts et al., 2007), but it is above this altitude that tether effects become important (performance issues like weight, strength, and dynamic effects like oscillations). Although extensive modelling has been done (Murthy, 2000), this would have to be confirmed with experimental evidence.

Of course, there are barriers to high altitude test flights, a significant one being air space approval. Roberts and Shepard (2003) mentioned that Sky Windpower had both FAA and CASA approval for the testing of a 50kW FEG at an unspecified altitude, but there has been no mention of airspace permission since then.

Without actual test flights at high altitude, the FEG cannot be considered a success, because it leaves its central tenet (the ability to generate megawatts of power at altitudes of 4–12km) unproven.

5.2.3 The Relative Success of Other Projects

One response to my contention that the FEG has not been a success might be that I am holding the FEG to too high a standard, and that despite the shortcomings I have pointed to, the FEG has been as successful as a new alternative energy technology could expect to be.

If the FEG was the only technology of its kind, trying to harness high altitude
winds, then this objection might have been valid. However, the FEG is now one of many technologies attempting to generate electricity from high altitude winds (although none are attempting to harness the jet stream, or anywhere near that high), and some of these other projects have achieved commercial success. Two projects stand out in particular: Makani Power and Altaeros Energies, both based in the US.

Makani Power has developed an energy kite system, based on the cross-wind kite power concept described by Loyd (1980) (in the same Journal of Energy that Fletcher and Roberts (1979) had published in). The craft resembles a fixed wing aircraft with small turbines set into the wings. The craft flies in a loop in sufficient winds (as low as 4 m s\(^{-1}\)), at an altitude of 140–310 m. Makani was acquired by Google X in 2013 (Ahrens et al., 2013b), and has been working towards a 600 kW craft since. Makani is not generating electricity commercially yet, but with the funding from Google has performed extensive testing of a 28-foot wingspan craft at altitudes of a few hundred metres. In April 2015, Makani began testing of the 600 kW craft, which has a wingspan of 84 feet and reaches an altitude of 450 m (Duhaime-Ross, 2015).

Altaeros Energies, founded in 2010 at the Massachusetts Institute of Technology, has developed a Buoyant Airborne Turbine (BAT), an inflatable ring which houses a rotor/turbine. The ring provides the lift and stability, while the horizontal-axis turbine generates electricity. This venture has been the most commercially successful of any airborne wind energy project. Most notably, Altaeros have secured a $1.3 million grant from the Alaskan Energy Authority to operate their BAT for 18 months at an altitude of 1,000 feet (Altaeros Energies, 2014). Before this, they did a test at 500 feet in 2013. They also have funding from the US Department of Agriculture, and in 2015 secured $7 million dollars in funding from the National Science Foundation (National Science Foundation, 2015) for further development.

The Altaeros press release announcing the contract with the Alaskan Energy Authority also mentions the burgeoning commercialisation of other high altitude wind projects:

Investment into the high altitude wind sector has recently gained momentum with the acquisition of U.S.-based Makani Power by Google in 2013. Recent investment in EU airborne wind energy companies has included 3M’s funding of Nature Technology Systems (Germany), DSM Venturing’s funding of SkySails (Germany), KLM Royal Dutch Airlines’
funding of Ampyx Power (The Netherlands), and Sabic Ventures’ funding of KiteGen (Italy). (Altaeros Energies, 2014, p.2)

Aside from the commercial and testing successes other projects have enjoyed, there’s also the fact that a AWE concept other than the FEG has won the “popularity contest” of the AWE research community. The cross-wind kite concept is the basis for the majority of AWE projects today. In the 2013 volume *Airborne Wind Energy*, of the 35 chapters contributed by AWE researchers, over 20 were based on the cross-wind kite concept (Ahrens et al., 2013a). There was no chapter on the rotary-wing concept/FEG, whether contributed by Dr Bryan Roberts or Sky Wind-Power, or anyone else. I checked with the editors, and they confirmed this. (There were also only two chapters concerning lighter-than-air approaches, one of which was contributed by researchers at Altaeros Energies.)

So, the FEG has not succeeded in two ways: in an absolute sense, by not meeting the criteria that are inescapably necessary for the project to succeed (indeed, necessitated by the FEG proponents’ own goals), and in a relative sense, given competing technological concepts in the same space have enjoyed success on both criteria.

### 5.3 Inadequacies in the FEG Literature

For most of the history of the FEG project, the only substantial source of information about the FEG has been in the academic engineering literature, starting with the publication of Fletcher and Roberts (1979). Therefore, the content of those papers, and the presentation of that content (claims, arguments, results) has been the only way to evaluate the FEG. However, the literature is inadequate for a careful, independent evaluation in the following ways:

- There are missing analyses which are thoroughly straightforward and tractable (and were decades ago, when the papers were written) but seemingly not done or unpublished. When performed independently (as I have done in this thesis, and which could have easily been done by others), they reveal serious deficiencies with the FEG, such as the analysis of downtime (Section 4.5) and capacity factor (Section 4.6).

- There are issues with the presentation of the jetstream as a energy source that are not answered, for example its substantial seasonal variation (this is before the recent discussion about limits to energy extraction from the jetstream,
summarised in Section 2.3.4, is considered). Similarly with regards to the rotor performance analysis.

- The details of optimistic claims about performance are inconsistent within and between papers. There is a lack of information about key parameters, making not only replication difficult, but also getting a full picture of the FEG’s expected operation.

- Not one specific criticism about the FEG from the academic literature is ever addressed or even acknowledged.

- Some details are hidden in unobtainable references, making checking claims impossible.

5.3.1 Missing Analyses

Power Density

Every paper written about the FEG begins with a mention of the average power density at jet stream levels—up to 20 kW m$^{-2}$ at the best locations. This claim comes from the two studies of the power available at high altitude—Atkinson et al. (1979) and O’Doherty and Roberts (1982). The FEG literature relies heavily on these studies; they were both cited often in subsequent papers$^3$. Five papers even reproduced a contour map of power density at 250 hPa that was originally from Atkinson et al. (1979)$^4$.

Initially, this made complete sense: the early papers were fixated on harnessing the jet stream core at altitudes of 10–12 km. The original pre-FEG paper “Electricity Generation from Jet-Stream Winds” (Fletcher and Roberts, 1979) was explicitly and exclusively focused on jet stream altitudes. Roberts and Blackler (1980) acknowledged the jet stream as the “ultimate objective”, although the authors were very careful to mention (three times) that they did not intend to imply that the

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$^4$Fletcher and Roberts (1979), Roberts and Blackler (1980), Roberts and Shepard (2003), Roberts (2011), and Roberts (2012a).
rotary wing concept would necessarily have to operate at such a high altitude\(^5\) (although every example and calculation in the paper was for an altitude of 35,000 feet). Blackler et al. (1981) also referred to the “ultimate objective or prize” of energy conversion at the tropopause level, but hastened to point out that their paper would be focused on the performance of a prototype craft at a much lower, more practical altitude, and not on high altitude performance.

However, there is a shift in the papers from 1997 onwards in the envisioned operating altitude. In Roberts and Strudwicke (1997), the authors mention that the craft “is intended to be flown in the vast and powerful jet streams” (p.425), followed up by noting that the jet streams are in the tropopause region (although this is not expressed quantitatively, in terms of metres or hectopascals).\(^6\) In the next section, we’re told “[for] high altitudes, typically around 5 kilometres, the steady state performance has been studied mathematically.” (p.425–426) This is curious; 5 kilometres was not discussed as a potential operating altitude in any of the literature published before 1997 that I was able to obtain. We’re also told that the steady state performance of the craft has been studied for this altitude. This just means the performance of the craft in a constant wind speed, using established rotor theories. But the mention of a study at a specific altitude indicates something more than just modelling rotors with an arbitrary incoming wind speed, it implies that the properties of the wind at that level were taken into account (including, importantly, the power density). Now, because this paper is focused on describing a control system for stabilising the FEG when perturbed, nothing more is said about the study at 5 km since it is largely irrelevant. However, I wish to point out the seeming contradiction between intending the FEG to operating in the jet stream, but then performing an analysis at half the altitude of the jetstream (and referring to that altitude as both “high” and “typical”).

This contrast becomes cemented in Roberts (2000). The average power density of 20 kW m\(^{-2}\) in jet stream winds is used to introduce the concept of the FEG, with

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\(^5\)“This note is not intended to specifically relate to operations at the tropopause level.” (p.68)

“This altitude [35,000 feet] has been chosen for demonstration purposes. Such an altitude is not necessarily optimal, nor is it claimed to be practically achievable. It is only chosen in order to demonstrate the interfacing problems and how these might be solved in a pragmatic fashion.” (p.79) “The assumptions and altitudes used are introduced only for demonstration purposes and do not necessarily represent a final design.” (p.85)

\(^6\)This paper is unusual in that it does not reference Atkinson et al. (1979) or O’Doherty and Roberts (1982). The reason it didn’t is probably because the paper was about the results of a stability simulation, and wind power statistics are not relevant.
references to Atkinson et al. (1979) and O’Doherty and Roberts (1982) to back up the claims of 17 kW m$^{-2}$ over the US and 19 kW m$^{-2}$ over Australia. In this paper, the slightly non-specific reference to an operating altitude of 5 km in Roberts and Strudwicke (1997) has become an unequivocal endorsement of an operating altitude of 4 km as providing the best return on investment. The operating altitude is of crucial importance and is a balancing act, because “[at] lower altitudes the wind resource begins to wane excessively while at higher altitudes, adjacent to the jet stream core, the cost associated with higher transmission voltages become less beneficial.” (p.5, my emphasis) In this same section, optimal parameters of a theoretical 3.1 MW craft are determined for a rated operating altitude of 4.57 km (15,000 feet).\footnote{Table 2 in Roberts (2000), which summarises the performance of the theoretical FEG (output, capacity factor, monetary value of energy produced, etc.), contains two columns: the first for operation at 15,000 feet (which corresponds to the details of the FEG given in neighbouring Table 1), and the second for operation at 30,000 feet. The fact that results for operation at 30,000 feet were calculated is not mentioned anywhere else in the paper.}

The clear implication a reader would draw from Roberts (2000) is that the specific values of wind speeds and power densities at the jet stream core near the tropopause are not relevant, because an optimally-performing FEG would not be operating anywhere near that high up. The relevant results would be power density calculations at around 4 km, but they are not provided in this paper, while the irrelevant jet stream power densities are reported.

The appeal of the FEG (indeed, its reason to be) ultimately rests on the availability of a high power density energy source: high altitude winds, and in particular, the jet stream. The FEG literature, originating from a concept designed with the jet stream in mind (and so initially quite rightly calculating estimates of power density at jet stream levels) has revised the operating altitude down to far below the jet stream. A corresponding re-calculation of the expected power density at these lower levels has not been included in the literature. If the calculations had been reported, then they would have shown what I reported in Figure 4.11: at the 600 hPa level, an annual mean power density of around 1–1.5 kW m$^{-2}$ at latitude 27–30° S, which was the optimal latitude range for the jet stream level. The mean value is an order of magnitude lower than the prominently-reported jet stream values. If, as I suggest, the median power density was reported in addition to or instead of the mean, then locations around 27–30° S would have a median power density of less than 0.5 kW m$^{-2}$.

However, the FEG literature need not have waited for my analysis based on a
reanalysis dataset to reveal these numbers. Power density estimates at levels below the jet stream could have easily been calculated all the way back in 1979, if the authors of Atkinson et al. (1979) had been inclined (I have not seen the report, so cannot be sure of what pressure levels they studied, apart from 250 hPa). Atkinson et al. (1979) had access to sounding data from the Bureau of Meteorology, and if they could have supplied data for 250 hPa, then they certainly could have provided data for the lower levels. Moreover, O’Doherty and Roberts (1982) actually did calculate the annual mean power density at pressure levels ranging from 900–200 hPa for 54 locations across the US. The annual mean power density at 600 hPa above New York, NY (the location usually mentioned in the literature as having the highest power density in the US at jet stream level, 16.3 kW m\(^{-2}\)) is 4.85 kW m\(^{-2}\).\(^8\) The fact that calculations of capacity factors for FEGs operating at 15,000 feet appear in Roberts (2000) and Roberts and Shepard (2003) means that data on the power densities and wind speeds at that level must have been obtained and actively used.

There is an absence of any quantitative details about power density at levels below the jet stream in the FEG literature, when (i) they could have been calculated or already were calculated, and (ii) they were relevant to the operating altitudes being discussed (this is especially acute in Roberts (2000), Roberts and Shepard (2003), and Roberts et al. (2007), when altitudes much lower than the jet stream are explicitly mentioned). It wasn’t due to a general disinclination towards reporting power density values, because the FEG papers always made sure to mention the high power densities at jet stream level. This gives the impression of neglect (that is, a critical element of the project, the operating altitude, has changed, but a supporting element of the paper, the magnitude of the energy resource, has not been updated to reflect this), and/or confusion (that is, by referring to the potential of “jet stream winds” and then advocating an operating altitude of around 4 km, the authors are mistaken about the altitude of the jet stream).

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\(^8\)The actual value in the table is 1.85 kW m\(^{-2}\) for 600 hPa, but I suspect it is a typo, since it seems very low compared to the 600 hPa results for other nearby locations. The power density over New York at 700 hPa is 3.03 kW m\(^{-2}\). It is highly unlikely that the average power density at 600 hPa would be so much lower than the value for 700 hPa.
5.3.2 Lack of Details about Specialist Knowledge

The Jet Stream

While the problems identified in the previous section would have struck a generic reader, readers with even relatively basic knowledge of the jet stream might have been especially struck by the brevity of consideration given to seasonality. The seasonal latitudinal shift of the jet stream and the relative strength of the jet stream winds in winter (and the relative weakness of the jet stream winds in summer) has been well known to climatologists and meteorologists since the late 1940s (Rossby and Willett, 1948). Gibbs (1952) looked specifically at the mean jet stream over Australia, and noted the difference in latitude and strength of the summer and winter jets.

To a certain extent, the FEG literature does acknowledge the seasonality of the jet stream, but the change in magnitude between the seasons is never quantified (except in Fletcher and Roberts (1979), before the rotary wing concept, where the monthly mean power density over Charleville is plotted for jet stream altitudes, and the difference is stark).

Rotor and Helicopter Theory

Rong et al. (2012) perform an analysis of tethered rotorcraft performance, using momentum theory and blade element theory. The authors briefly review the previous work done (all from the FEG literature), and make several important points. Below is the entirety of the relevant paragraph.

The aerodynamic performance of the tethered rotorcraft has been briefly examined by Roberts and Shepard. Based on work done by Ho, and Jabbarzadeh Khoei, Roberts and Shepard found that, when the tip speed ratio is fixed, the power coefficient $C_P$ adopts an inverted U-shape curve with respect to the angle between the wind direction and the plane of rotation, where $C_p = P/(\rho \pi R^2 W^3/2)$. However, the tip speed of blades is simply defined as the component of the wind normal to the rotor axis by them, which is not a realistic situation. Moreover, it is still unclear how the produced power is affected by the tip speed, the induced flow and the attachment angle. It is also unknown what the maximum power and optimum operational conditions should be under various loading conditions. Such gap has created obstacles in the consid-
The authors mention that the blade tip speed definition used in the FEG literature is not realistic, but to me that is less important than the sentences that follow. Rong et al. (2012) are pointing out that technical details about the performance of the FEG have been left unclear in the FEG literature up to that point (they are aware of the Ho and Jabbarzadeh Khoei theses from the early 1990s, so it is unlikely that this stems from an inadequate review of the available FEG literature). They go on to comment that these “gaps” have created obstacles in the consideration of FEGs.

### 5.3.3 Inconsistency of Results and Claims

The way Roberts et al. (2007) report results makes it difficult to get a complete picture of all the parameters that affect the performance of the FEG. Seemingly arbitrary changes in the operating altitude occur in different situations. The abstract refers to FEGs operating at 4,600 m and above. The familiar statistics about the average power density at jet stream level over Australia and the US are cited in the Introduction, and a study of reanalysis data confirmed an average power density of 10 kW m$^{-2}$ at “the jet stream’s typical latitudes and altitudes” (p.137). So far, the focus has been on jet stream-level winds, and that is further supported when the average capacity factor at locations across the US is reported as 80% at an altitude of 10,000 m.

However, this trend is broken when discussing the minimum wind speed for autorotation. The authors tell us that “autorotation at a minimal wind speed is fundamental to the systems performance” (p.139), immediately followed by “A typical minimum wind speed for autorotation is around 10 m/s at an operating altitude of 15 000 ft (4600 m)” (p.139). Now, 4,600 m turns out to be the proposed operating altitude of the Demonstration Craft, but the authors go to the trouble of specifying a minimum wind speed of 11.5 ms$^{-1}$ for that particular design anyway. For the purposes of reporting typical values of that particular parameter, the altitude was abruptly reduced to half.

When calculating the capacity factors for a theoretical 3.4 MW FEG, the operating altitude was taken as up to 9,000 m, and a formula was given for calculating the rated wind speed at each altitude (a similar formula for the minimum wind speed was not provided for the range of altitudes up to 9,000 m). The three sites that were analysed were all US sites, but for an unstated reason the maximum altitude
considered was 9,000 m, instead of the 10,000 m used previously when reporting the average capacity factor across the US.

In another section, the authors acknowledge that the winter months have strongest winds, and the summer months the weakest. To illustrate this, they report the difference between capacity factors calculated for summer and winter above Patiala, India at 10,700 m (35,000 feet). Up until this point, all location-specific statistics had been based on US locations. The context is that India’s hydrogen gas production industry might benefit from FEG electricity generation in the winter, to enough produce hydrogen gas for use in the summer, when the FEG would not generate much. However, it’s not just winds over India that have large seasonal differences, but it was only mentioned because there was an application for energy storage.

A reader interested in further investigating the claims made in Roberts et al. (2007) is stymied; the minimum wind speed, a fundamental parameter, is not reported for the altitudes which seem to matter most to the authors: 9–10 km. Similarly, the seasonality, although shown to make a dramatic difference over India, was not reported for the otherwise detailed capacity factor and cost of energy calculations for the three US sites. Additionally, unlike theoretical FEGs described in Roberts (2000) and Roberts and Shepard (2003), the rotor diameter is not specified for the 3.4 MW FEG. Here is the problem in a nutshell: the details provided in the paper are insufficient for a reader to properly evaluate the claims made. Moreover, the results reported do not include details of potential issues or important parameters (minimum wind speed, seasonality) that are mentioned as important to consider elsewhere in the very same paper. This draws attention to the inadequacy of details provided, and leaves the reader with the distinct impression that important questions have been left unanswered.

5.3.4 FEG Criticism Ignored

As I wrote in Section 2.2.18, two papers (Fletcher et al. (1983) and Fletcher (1983)) make specific criticisms about the FEG, about the short life of rotor and gearbox components adding to the cost of electricity generation, and about the problem of the allowable tether angles limiting the range of control axis angles the FEG can adopt, affecting its performance. Now, it is possible that Fletcher’s arguments are wrong, and that the FEG is not affected by the problems he outlines. Even so, there is no evidence in the FEG literature of acknowledgement of these criticisms (not even to rebut them).
Roberts had to have known about these criticisms, given that he was a colleague of Fletcher at the University of Sydney at the time and had co-authored the 1979 paper with him. Additionally, Fletcher (1983) was referenced by Jabbarzadeh Khoei (1993) in his thesis, supervised by Roberts, which chose a tether angle value of $\beta = 40^\circ$ (although the thesis contains no discussion of the problems raised by Fletcher).

The closest the FEG literature gets to answering the first objection is by eschewing cyclic pitch control (i.e. the ability to change the pitch angle of the rotor blades over each rotation in order to tilt the craft in a certain direction) and relying on collective pitch control (i.e. changing the pitch of all rotor blades at once) to stabilise the FEG. Roberts (2000) states that “[this] absence of cyclic pitch control leads to a great reduction in the fatigue loads on the rotor heads and their control linkage. This enormously enhances the life and simplicity of the system and ensures a rugged generator arrangement” (p.6). The claim is repeated in Roberts et al. (2007, p.138) and Roberts (2011). It’s not clear if Fletcher had cyclic pitch control in mind when writing about the high replacement costs of rotary wing craft, but even so, the generator gearbox was also mentioned as a short-life component, which is not addressed in the FEG literature.

The second criticism isn’t addressed in the literature, either. The tether angle value of $\beta = 40^\circ$ is simply provided without explanation when discussing the minimum wind speed for autorotation and the equation investigated by Jabbarzadeh Khoei (1993). The range or limits of $\beta$ are not discussed in the literature until Roberts (2011), where tether angles of 35–56 are used in calculations (whether or not these tether angles are feasible is not discussed). This might mean that Fletcher’s criticism had tacitly been taken on board, except for the fact that the optimal control axis angle $\alpha_c$ for maximising $C_{PW}$ is reported in the literature to be around $50–55^\circ$, which is too high according to Fletcher’s argument.

### 5.3.5 Unobtainable References

As I noted in the Literature Review chapter, I could not obtain some FEG-related papers. This problem is sometimes unavoidable in research, and is not the fault of the authors. This problem is not what I’m raising, though; the FEG literature contains a couple of examples of making claims based on references that by their nature are impossible to obtain other than through the authors.

Roberts and Strudwicke (1997) cites “private notes” written by Roberts, written in 1985 when presenting the equations of motion for the lateral translation of a
5.3. Inadequacies in the FEG Literature

Inadequacies in the FEG Literature

FEG. The reference is for details of analytical derivation of the equations, which is not provided in the paper. The theses of Ho (1992) and Strudwicke (1995) are also cited for this analytical derivation. The equations of motion are presented again in Roberts (2000), but in this paper the references for the analytical derivation are Ho (1992), Strudwicke (1995) and Roberts and Strudwicke (1997).

Roberts (2000) references “a confidential proposal to NorthPower” for the claim that a careful study of best return on investment for the FEG had been performed, and shown that 4 km is the optimal operating altitude. (As mentioned in the Literature Review chapter, NorthPower is a New Zealand based power company.) No other details of that study (assumptions, models, etc.) are provided.

Roberts and Shepard (2003) also cites “private notes” written by Roberts (undated), when stating that a number of detailed equilibrium studies had been performed. Ho (1992) and Jabbarzadeh Khoei (1993) are also cited as such studies. This paper cites the confidential proposal to NorthPower as well, this time as a reference for the claim that an aluminium-Kevlar composite could be used for the tether (it’s unclear if the reference is supposed to contain details of the tether construction, or details demonstrating its feasibility for the FEG, or something else). In the same sentence, an aluminium-Spectra composite tether is stated as a possibility, and the reference for that is undated “private communications” between the paper’s authors.

Roberts et al. (2007) makes the same claim about the detailed equilibrium studies having been performed, citing Ho (1992) and Jabbarzadeh Khoei (1993), but this time “private communications” by Roberts over 1991–1993 are cited instead of the private notes cited previously.

Now, in any journal or conference paper, there will be details that are too tedious to include due to a scarcity of pages, time, etc. Additionally, it is conventional to cite private communications. However, a reference is usually expected to be a discrete and specific piece of work external to the paper citing it, and typically (but not always) published or otherwise accessible.

In the particular case of the FEG literature, details of calculations or analyses that make up part of the argument of the paper, but have not been published, are being presented as a separate, complete pieces of work, comparable with published articles. The rhetorical implication of providing a reference to a work is that the cited work is reliable, and that further details are unnecessary in the citing paper. When a reference is made to a published work to support some claim, the reader
can consult the work to decide whether that is justified. In the case of references to
unpublished (and non-specific) private notes and communications, a reader has no
way making that judgment.

In the case of the confidential proposal to NorthPower, citing it as a reference
sends two messages: first, that the reference contains precisely those technical de-
tails that would demonstrate its economic viability (i.e. the core purpose of the
FEG project). Second, by choosing to describe it as “confidential”, the authors
give the impression of having predetermined that those crucial details will not be
published or made available for scrutiny. In the context of an academic paper, this
apparent approach to argument is confusing (although if considered as a description
or promotion of a commercial product, it is less so).

This minor issue of how unpublished works are cited speaks to a broader tension
in the FEG literature, between commercial aspiration and academic rigour. By
mixing aspects of both into the one paper, the effectiveness of the paper is blunted
by a confusion of competing priorities.
Chapter 6

Conclusion

6.1 Summary

My review of the FEG literature showed that there were gaps in reported results (the power density of the wind at lower altitudes, the seasonality of the winds, and the effect of insufficient winds on FEG operation and capacity factor) that I tried to fill. I made tried as much as possible to make generous assumptions that would not artificially disadvantage the FEG in calculations. My results showed that, contrary to the claims made in the FEG literature, downtime was a much more serious problem and capacity factors were much lower, comparable in magnitude to ground-based wind turbines. I say that the FEG, as described in the literature, is not an economical prospect for baseload electricity generation (the downtime and capacity factor results are so clear that sophisticated cost-benefit analysis is not necessary).

The calculations I performed were straightforward, and could have been performed by any interested reader of the FEG literature. They, like me, would have found that the results of the calculations have severe consequences for the economic operation of the FEG. These same calculations could have easily been calculated by the FEG authors too, but they either didn’t, or they did but did not report them in their papers. This is despite those same papers impressing upon the reader, for example, that the minimum wind speed for autorotation was a crucial parameter for FEG operation.
6.2 Evaluation of Claims

In the Introduction chapter, I listed three broad claims that were present in the FEG literature. Here, I return to those claims and respond to them given the results of my analysis.

**FEGs can generate more electricity (per unit rotor area) than conventional, ground-based wind turbines, due to the higher power density of high altitude winds.**

This is essentially correct. It is very clear from Section 4.4 that a FEG operating at high altitude will in general be able to capture wind with higher power density than ground-based turbines can (assuming a typical power density at the surface is about 0.5 kW m\(^{-2}\)). This means that a turbine with a given swept area would generate more power at altitude than at the ground.

However, as Section 4.4 also showed, power density (at a particular location) is subject to variation with altitude and the time of year. The distribution of power density over time is also highly skewed, making the annual mean power density (the metric repeatedly cited in the FEG literature) a misleading summary statistic for quantifying the available power density at altitude.

These features of the wind resource (combined with the requirement of a minimum wind speed to remain aloft, as well as downtime for maintenance) mean that the higher power densities are not always available. The optimistic values of an annual average power density of 18–20 kW m\(^{-2}\) cited in the FEG literature do not capture the full complexity of the high altitude wind resource, especially since more recent papers explicitly lower the envisioned operating altitude from jet stream levels to around 4–5 km, where power densities are also much lower (whether summarised by mean or median).

**FEGs can be deployed across a large area (in particular, throughout a 1,000 km wide band extending from Perth to Brisbane in Australia). This means that FEGs can be strategically located to integrate with existing power networks.**

Superficially, this is true: FEGs may be located anywhere across Australia, assuming land and airspace permission can be obtained. At any location, given sufficient wind, a FEG would be able to generate electricity some of the time. However, to be a
success, a FEG would have to be able to generate electricity economically at a given location. Although I did not attempt to investigate the economic performance of a FEG, I did look at downtime, which would be a primary factor in the economic performance.

Section 4.5.1 showed that the Demonstration Craft would be landed due to insufficient wind for at least 45% of the year in parts of Australia north of about $21^\circ$ S. There was also a pocket of downtime at least 40% of the year along the east coast of New South Wales. The entirety of mainland Australia and Tasmania would experience at least 20% downtime over the course of a year.

My results indicate that the entire northern region of Australia is unsuitable for FEGs. I'm assuming that any location with a downtime of over 40% of the year is highly unlikely to be economical (a thorough economic analysis may show this to be wrong, but I regard my assumption as reasonable). In contrast, Tasmania and the southern coast of mainland Australia are the best places for FEGs. The east-west band across Australia, at about $27^\circ-33^\circ$ S, which is where the jet stream sits, is somewhere in between.

The area over which a FEG may be viable is still large (i.e. most of the continent), and the scale of the upper atmosphere does mean that the precise location of a FEG is a relatively minor issue. However, I expect that more sophisticated technical and economic analyses would tend to reduce the viable locations for the FEG, rather than expand them. This would be further restricted by land use and airspace issues, regardless of the technical merits.

**FEGs have much higher capacity factors than conventional ground-based wind turbines, making them a potential candidate for base load power generation.**

Base load power generation sets a very high standard for FEG performance, requiring capacity factors in the order of 80–90%. Although the FEG literature claims these capacity factors were possible (over the United States, at least), I could not produce comparable results for Australia. Section 4.6 shows that capacity factors for the Demonstration Craft were about the same as for ground-based wind turbines, or lower. These results provide no reason to prefer FEGs ahead of conventional ground-based wind turbines (which would almost certainly be cheaper in every case).

Overall, I found that the claims of FEG performance were overly optimistic, and my results either did not match, or revealed a more complicated picture than
described in the literature.

6.3 The Future of the FEG

There seems to be something of a rekindling of interest in tethered rotorcraft in the last couple of years. Three research groups of engineers in the US have published papers with the intention of providing a more rigorous theoretical treatment of the tethered rotor (Rong et al., 2012; Rimkis and Das, 2013; Rancourt et al., 2014). Removing the assumptions and limitations of the rotor theory used in the early days of the FEG project is one of the goals. Although all are very theoretical and rarified at the moment, these research groups will eventually have to incorporate the actual conditions of the upper atmosphere into their modelling, and take the more practical issues like seasonality, downtime, and its effect on the cost of electricity generation into account. It is as if the concept is starting afresh with a new generation of researchers, only this time it is coming into a field with an established research community, and with a now-established leader in the form of the cross-wind kite concept.

Even if the issues I have outlined in this thesis can be overcome (with improved design and materials for instance), there are still many, many technical, economic, and regulatory challenges for the FEG, in whatever form it finally takes. It may end up smaller in scale, lower in operating altitude, and specific in application rather than a general, baseload electricity provider. There may be a role for the FEG eventually, even though it may not be on as grand a scale as was first envisioned in the FEG literature decades ago.
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University of Western Sydney, Sydney, Australia.

Springer.

Conference and Exhibit.

Appendix A

Correspondence

First email to Bryan Roberts, sent 4th May, 2007

Dear Prof. Roberts,

I am a MSc student at the University of Melbourne, working with Prof. Ian Simmonds in Climatology, and Dr. Neil Thomason in History and Philosophy of Science. My recently begun Masters thesis, which may be converted to a Doctorate, examines your FEG proposal. I'm focusing on its feasibility as well as its relative neglect by the wider scientific community. I have read as many of your papers as I have been able to obtain, read your website and followed your project in the media. I have a BA and BSc, both with high first class Honours. Both my Honours theses were in physics; one in the foundations of quantum mechanics (at Melbourne University) and the other in first-principles calculations of crystal structure (at Monash University).

I think your proposal has a real chance of solving our energy problems and thus helping to reduce greenhouse gas emissions and counter global warming. I do not understand why it has seemingly been so neglected. Perhaps there are serious engineering or climatological flaws that I'm not yet aware of. As a first step, I plan to analyse the seasonal distribution of power densities and wind velocities at altitudes between 3km and 7km over the eastern states of Australia, in order to replicate the figures quoted in your papers. I’d like to be able to make a fair and proper comparison between your data and my calculations, so any advice or details on how you arrived at your figures would be greatly appreciated. In addition, I’m interested in performing a much deeper analysis of wind speed distribution over shorter time periods, to get (for instance) a more detailed break-down of the expected "down-time" of a FEG due to slow winds, especially over the summer, when electricity
demand peaks. Would these calculations be beneficial to you? As my research progresses, I may run into technical questions; I hope you’d be able to help me if necessary.

I’ve been able to collect a number of your papers, but some technical documents and conference papers have been hard to obtain. I’d be grateful if you could send me a copy of the following papers:


Yours sincerely,

Steven Kambouris
Second email to Bryan Roberts, sent 14th July, 2008

Dear Professor Roberts,

I’m Steven Kambouris, a Master of Science student at the University of Melbourne. I’m writing my thesis on your invention, the Flying Electric Generator. I wrote to you last year with questions about the wind data you used; thank you very much for replying. When you wrote you said you had been ill; I hope you are in better health now.

My research has made progress since I last contacted you, however I’m currently concerned with a particular set of problems. I’ve been trying to understand the details of an aerodynamic analysis of a FEG, with one particular aim of being able to replicate figure 4 (power coefficient as a function of control axis angle) of your 2007 paper for myself. I have read the 1952 report by Gessow and Crim (as referenced by your 2007 paper), but am not confident of being able to reliably adapt that analysis to the case of a FEG without more information. Another hope is to find more details of how to determine the minimum wind speed required for a FEG to remain aloft. Again, I am not confident of being able to successfully apply the analysis shown in, say, equation 4 (of your 2003 paper with Mr Shepard) without more information.

I have had some success using an analysis largely based on Glauert’s theory of the autogyro (found in a University of Calgary thesis by D. C. Brophy, 1995 and subsequent paper by J. A. C. Kentfield and D. C. Brophy, 1997) to perform some calculations for FEGs, but I’d prefer to be able to use the same analysis as yourself to understand and evaluate the performance of FEGs.

I am in the process of obtaining copies of the theses by Ho and Jabbarzadeh in order to further understand the analysis of aerodynamics of a FEG at a large control axis angle. Can you recommend any other theses, papers, books or other resources that would assist me in this particular task?

I also have a couple of inquiries about the four-rotor, 3.4MW platform that you use for the economic analysis in your 2007 paper. I wasn’t able to find the diameter or specification of the rotors that the 3.4MW platform would use; could you provide me with those details? I’d also be very interested to know the minimum no-power autorotation wind speed of the 3.4MW platform: you reported a very useful equation (equation 4) relating the rated wind speed and height - is the same possible with the autorotation wind speed?

I would be extremely grateful for any advice you can provide. I’ve carbon-copied this email to the co-authors of your 2007 paper, and would welcome a reply from
anyone who could help.

Yours sincerely,

Steven Kambouris
Letter to Clive Fletcher, sent 25th September, 2008

Dear Dr Fletcher,

I’m Steven Kambouris, a Master of Science student at the University of Melbourne. I am writing my Masters thesis on Professor Bryan Roberts’ Flying Electric Generator. My aim is to evaluate the feasibility of the concept, given that there seems to have been relatively little critical attention paid to it.

During my research, I have had difficulty obtaining particular unpublished reports. My university library was unable to locate copies of the reports on my behalf, and suggested I contact the authors directly. I wrote to Professor Roberts, but unfortunately he was unable to help me with this request. As a co-author, is it possible that you still possess copies of the following reports?


If you are able to provide me with any of these reports, I would be very happy to compensate you for your trouble and ensure there is no cost to you.

In addition, I have read your 1983 paper, “On the Rotary Wing Concept for Jet Stream Electricity Generation.” It is the only paper I have found which outlines a limitation of the rotary wing concept in technical, quantitative terms. Are you aware of any other papers which discuss problems with the rotary wing concept? In my searches, I have not found any papers outlining a technical criticism of the rotary wing concept other than your own.

I appreciate that you are busy, and would be extremely grateful for any help with these questions. Thank you very much for your time.

Yours sincerely,

Steven Kambouris
Dear Dr Roberts,

I’m Steven Kambouris, I wrote to you years ago in 2007 and 2008 requesting some papers written by you and colleagues that I couldn’t locate. I’m writing again because I am finishing my thesis at the University of Melbourne, and I’d like to ask if it is possible to obtain from you copies of the following papers, please:


If you’re unable to provide these papers, would any of your colleagues possibly have copies?

I’d also greatly appreciate it if you could answer my additional questions about the calculations in your papers, which I’ve read over but am still not sure about:

• Could you please provide the details of how you calculate capacity factors for particular platform designs? For instance, do you construct a power curve of power coefficient vs. wind speed and apply it to a year’s worth of wind data? Does the capacity factor apply to the FEG/EGR operating at the rated altitude only (and presumably landing altogether when the wind at that altitude is inadequate), or does the capacity factor take flying/generating at altitudes below the rated altitude into account (i.e. there are multiple power curves, for different altitudes due to the change in air density)?

• Is the formula for calculating the minimum wind speed required for autorotation (found in Jabbarzadeh’s thesis, but mentioned in your 2003 and 2007 papers) still the best way for calculating the minimum wind speed (and the accompanying control axis angle and tip speed ratio), or has another method superseded it?

• The preferred operating altitude of a FEG/EGR is not entirely clear to me. Originally, I believe you were intending to operating in the jet stream (10–12 km), but over subsequent papers over the years, the operating altitude could be as low as 4km. What do you currently think is the optimal operating altitude for a FEG/EGR?
• Have you or your colleagues performed any recent studies of the power density at 4 km, or sub-jet stream levels, since Atkinson, et al (1979) and O’Doherty and Roberts (1982)? For instance, have you made use of the various reanalysis datasets available (ERA, NCAR)? You used ERA-15 data in your 2007 paper, has there been any further work on analysing the power density at altitude?

Thank you very much,

Steven Kambouris
Dear Bryan,

Thank you very much for your email, I really appreciate you taking the time to reply. I also very much appreciated the Aero Soc. paper, I’d been trying to obtain a copy of it through my library for some time. It was very interesting reading, and it included explanations that I hadn’t seen in any of your previous papers.

The variation of the tether angle with the mode of operation was one; previously, I’d only seen a beta value of 40 degrees considered (based on Jabbarzadeh’s thesis work). The only problem with tether angles lower than 40 degrees is that the tether length becomes longer - at 30 degrees the tether would be twice the altitude. Tether strength (to prevent it breaking under its own weight) becomes an issue then, particularly if the rotorcraft was ever to actually operating in the jet stream proper, at 10-12 km. To me, it seems the tether is the main problem to be solved to get up to those extreme altitudes.

Maximum disk loading was the other issue I was glad to see discussed. It seems to me that in order to keep the disk loading small (and hence the minimum wind speed required for autorotation low, at 10 m/s as you suggested), rotorcraft (and tethers) would need to be made from strong, light-weight materials - I assume the availability of such materials at an economic price would be a primary limiting factor.

Thank you for outlining the capacity factor calculation method, that was very useful. The one drawback of the annual capacity factor value is that it shows the aggregate performance over the year, and doesn’t indicate the seasonal variation that occurs. As you’ve noted in previous papers, the summer months have far less generating potential than the winter months. I’ve used a climate reanalysis data set (ERA-40, published by the ECMWF) to investigate winds at altitude over Australia, rather than Bureau of Meteorology radiosonde data directly.

Finally, some other airborne wind energy projects (Altaeros Energies, and Makani Power) have enjoyed some success with (non-rotorcraft) designs that operate at much lower altitudes than the rotorcraft - a few hundred metres, rather than kilometres. Could a smaller, lower-rated (much less than 1 MW per unit) rotorcraft operating at a similar low altitude be a viable commercial option? Or have you always envisioned the larger, higher altitude, rotorcraft, to provide baseload energy generation?

Thank you very much once again, and kindest regards,

Steven Kambouris
Appendix B

Power Density Over Australia
Figure B.1: The long-term 5th (P05), 25th (P25), 50th (P50), 75th (P75), and 95th (P95) percentiles of power density (in kW m$^{-2}$) over Australia, at pressure level 925 hPa, calculated using the ERA-40 dataset. The long-term is the time period covered by the ERA-40 dataset, 1 September 1957 – 31 August 2002.
Figure B.2: The long-term 5th (P05), 25th (P25), 50th (P50), 75th (P75), and 95th (P95) percentiles of power density (in kW m$^{-2}$) over Australia, at pressure level 850 hPa, calculated using the ERA-40 dataset. The long-term is the time period covered by the ERA-40 dataset, 1 September 1957 – 31 August 2002.
Figure B.3: The long-term 5th (P05), 25th (P25), 50th (P50), 75th (P75), and 95th (P95) percentiles of power density (in kW m$^{-2}$) over Australia, at pressure level 775 hPa, calculated using the ERA-40 dataset. The long-term is the time period covered by the ERA-40 dataset, 1 September 1957 – 31 August 2002.
Figure B.4: The long-term 5th (P05), 25th (P25), 50th (P50), 75th (P75), and 95th (P95) percentiles of power density (in kW m\(^{-2}\)) over Australia, at pressure level 700 hPa, calculated using the ERA-40 dataset. The long-term is the time period covered by the ERA-40 dataset, 1 September 1957 – 31 August 2002.
Figure B.5: The long-term 5th (P05), 25th (P25), 50th (P50), 75th (P75), and 95th (P95) percentiles of power density (in kW m$^{-2}$) over Australia, at pressure level 600 hPa, calculated using the ERA-40 dataset. The long-term is the time period covered by the ERA-40 dataset, 1 September 1957 – 31 August 2002.
Figure B.6: The long-term 5th (P05), 25th (P25), 50th (P50), 75th (P75), and 95th (P95) percentiles of power density (in kW m$^{-2}$) over Australia, at pressure level 500 hPa, calculated using the ERA-40 dataset. The long-term is the time period covered by the ERA-40 dataset, 1 September 1957 – 31 August 2002.
Figure B.7: The long-term 5th (P05), 25th (P25), 50th (P50), 75th (P75), and 95th (P95) percentiles of power density (in kW m$^{-2}$) over Australia, at pressure level 400 hPa, calculated using the ERA-40 dataset. The long-term is the time period covered by the ERA-40 dataset, 1 September 1957 – 31 August 2002.
Figure B.8: The long-term 5th (P05), 25th (P25), 50th (P50), 75th (P75), and 95th (P95) percentiles of power density (in kW m\(^{-2}\)) over Australia, at pressure level 300 hPa, calculated using the ERA-40 dataset. The long-term is the time period covered by the ERA-40 dataset, 1 September 1957 – 31 August 2002.
Figure B.9: The long-term 5th (P05), 25th (P25), 50th (P50), 75th (P75), and 95th (P95) percentiles of power density (in kW m$^{-2}$) over Australia, at pressure level 250 hPa, calculated using the ERA-40 dataset. The long-term is the time period covered by the ERA-40 dataset, 1 September 1957 – 31 August 2002.
Figure B.10: The long-term 5th (P05), 25th (P25), 50th (P50), 75th (P75), and 95th (P95) percentiles of power density (in kW m\(^{-2}\)) over Australia, at pressure level 200 hPa, calculated using the ERA-40 dataset. The long-term is the time period covered by the ERA-40 dataset, 1 September 1957 – 31 August 2002.
Figure B.11: The long-term 5th (P05), 25th (P25), 50th (P50), 75th (P75), and 95th (P95) percentiles of power density (in kW m\(^{-2}\)) over Australia, at pressure level 150 hPa, calculated using the ERA-40 dataset. The long-term is the time period covered by the ERA-40 dataset, 1 September 1957 – 31 August 2002.
Figure B.12: The long-term 5th (P05), 25th (P25), 50th (P50), 75th (P75), and 95th (P95) percentiles of power density (in kW m$^{-2}$) over Australia, at pressure level 100 hPa, calculated using the ERA-40 dataset. The long-term is the time period covered by the ERA-40 dataset, 1 September 1957 – 31 August 2002.
Figure B.13: The median (50th percentile, P50) annual power density (in kW m$^{-2}$) over Australia at 925 hPa by season. The seasons are defined as four groups of three adjacent months: Summer (December-February, DJF), Autumn (March-May, MAM), Winter (June-August, JJA), and Spring (September-November, SON).
Figure B.14: The median (50th percentile, P50) annual power density (in kW m\(^{-2}\)) over Australia at 850 hPa by season. The seasons are defined as four groups of three adjacent months: Summer (December-February, DJF), Autumn (March-May, MAM), Winter (June-August, JJA), and Spring (September-November, SON).
Figure B.15: The median (50th percentile, P50) annual power density (in kW m$^{-2}$) over Australia at 775 hPa by season. The seasons are defined as four groups of three adjacent months: Summer (December-February, DJF), Autumn (March-May, MAM), Winter (June-August, JJA), and Spring (September-November, SON).
Figure B.16: The median (50th percentile, P50) annual power density (in kW m$^{-2}$) over Australia at 700 hPa by season. The seasons are defined as four groups of three adjacent months: Summer (December-February, DJF), Autumn (March-May, MAM), Winter (June-August, JJA), and Spring (September-November, SON).
Figure B.17: The median (50th percentile, P50) annual power density (in kW m$^{-2}$) over Australia at 600 hPa by season. The seasons are defined as four groups of three adjacent months: Summer (December-February, DJF), Autumn (March-May, MAM), Winter (June-August, JJA), and Spring (September-November, SON).
Figure B.18: The median (50th percentile, P50) annual power density (in kW m$^{-2}$) over Australia at 500 hPa by season. The seasons are defined as four groups of three adjacent months: Summer (December-February, DJF), Autumn (March-May, MAM), Winter (June-August, JJA), and Spring (September-November, SON).
Figure B.19: The median (50th percentile, P50) annual power density (in kW m\(^{-2}\)) over Australia at 400 hPa by season. The seasons are defined as four groups of three adjacent months: Summer (December-February, DJF), Autumn (March-May, MAM), Winter (June-August, JJA), and Spring (September-November, SON).
Figure B.20: The median (50th percentile, P50) annual power density (in kW m\(^{-2}\)) over Australia at 300 hPa by season. The seasons are defined as four groups of three adjacent months: Summer (December-February, DJF), Autumn (March-May, MAM), Winter (June-August, JJA), and Spring (September-November, SON).
Figure B.21: The median (50th percentile, P50) annual power density (in kW m$^{-2}$) over Australia at 250 hPa by season. The seasons are defined as four groups of three adjacent months: Summer (December-February, DJF), Autumn (March-May, MAM), Winter (June-August, JJA), and Spring (September-November, SON).
Figure B.22: The median (50th percentile, P50) annual power density (in kW m$^{-2}$) over Australia at 200 hPa by season. The seasons are defined as four groups of three adjacent months: Summer (December-February, DJF), Autumn (March-May, MAM), Winter (June-August, JJA), and Spring (September-November, SON).
Figure B.23: The median (50th percentile, P50) annual power density (in kW m$^{-2}$) over Australia at 150 hPa by season. The seasons are defined as four groups of three adjacent months: Summer (December-February, DJF), Autumn (March-May, MAM), Winter (June-August, JJA), and Spring (September-November, SON).
Figure B.24: The median (50th percentile, P50) annual power density (in kW m\(^{-2}\)) over Australia at 100 hPa by season. The seasons are defined as four groups of three adjacent months: Summer (December-February, DJF), Autumn (March-May, MAM), Winter (June-August, JJA), and Spring (September-November, SON).
B. Power Density Over Australia
Appendix C

Code for the Calculation of FEG Operating Parameters

The following FORTRAN code comes from Appendix B of Jabbarzadeh Khoei (1993) and was used by me to calculate FEG parameters for different values of tip speed ratio. It has been modified by me very slightly to format the output.

```fortran
PROGRAM GC
IMPLICIT NONE
C THIS PROGRAM CALCULATES THE ROTOR CHARACTERISTICS
C USING GEESOW AND CRIM'S HIGH INFLOW THEORY.
C
REAL M,L1,L2,K1,K2,K3,K4,K5,K6,K7,K8,K9,K10,K11,
& K12,K13,K14,K15,K16,K17,K18,L,LH,ACD(1000),COPT1(1000)
&,CPW(1000),CLW(1000),DMAX1(100),DMAX2(100),DMAX3(100)
&,DMAX4(100),DT1(25),CLWOP(1000),ALCA1D(1000),COPT2(1000)
&,CQW(1000),COPT3(1000),NM(60),P(1000),D1MAX(100),D2MAX(100)
&

C THIS PROGRAM CALCULATES MAXIMUM WINDMILL PARAMETERS SUCH AS
C CPW, CLW FOR TIP SPEED RATIOS BETWEEN 0.05 TO 1.75 AND WRITE THEM
C IN A FILE. FOR ANY PARAMETERS WHICH YOU WOULD LIKE TO HAVE THE
C RESULT JUST INPUT THE PARAMETER NAME (E.G. CLW) IN CALL STATEMENT
C FOR SUBROUTINES IN LINES 243, 244. THE RESULTS FILE NAME IS
C MAXM.DAT

INTEGER KLID,K,N,NT0,NT1,NCQS,NM
INTEGER I,NMM
REAL A0H,A,B,GA,S,BETAD,A0,ERR,D2,AC,A1D,A1,A2H,A2,A1H
REAL AA,CL,CD,BB,B1,AL,AR4,AR1,B1H,B2H,B3,C2,BETA
REAL CC,F1,CQ,CV,CT,CQS,CTW,DO,D1,F2,F3,G1,TSR,T0,TOD
REAL T1,TCTS,T1D
CHARACTER F*20

C NSTALL IS THE STALL LIMIT PARAMETER
AL=13
C WRITE(*,*) "AL IS ",AL

CLOSE(UNIT=7)
OPEN(UNIT=7,FILE='/Users/steven/gc_t1_0-15.dat')
WRITE(7,*)'T1, AC, CPW, CLWOP, MU, TO, CQ, CLW, CT, CTW'

C DEFINE THE VALUE OF TWIST
```
DO 3000 NT1=0.15
     T1D=NT1*1.0

C DEFINE THE RANGE OF TIP SPEED RATIO
C NM= 0,MU=0.050; NM=10,MU=0.075; NM=20,MU=0.100;
C NM=30,MU=0.125; NM=40,MU=0.150; NM=50,MU=0.175;
C NM=60,MU=0.200.
DO 3000 NM=0,60
     I=0
     M=NM*.0025+0.05

C DEFINE THE RANGE OF CQ/S
DO 1000 NCQS=0,35
     CQS=NCQS*.000625
     DO 1000 NT0=-400,100
     TOD=NT0*.1
     KLID=0
     CV=57.29578
     T0=T0D/CV
     T1=T1D/CV

C INPUT THE ROTOR AND THE TETHERED SYSTEM CHARACTERISTICS
DATA A,B,GAM,S,BETA/5.73,0.97,10.0,0.05,40./
     BETA=BETAD/CV
     A0=0.0
     A1=0.0
     A2=0.0
     A0H=0.0
     LH=0.0
     K=0
     N=0
     CL=1.2
     CD=1.1
     D0=0.0087
     D1=-0.0216
     D2=0.40

C EVALUATION OF LAMBDA FOR VARIOUS CQ/S VALUES
C AA = COEFFICIENT OF L**2
C BB = COEFFICIENT OF L**1
C CC = COEFFICIENT OF L**0
F1=T1**3*B**6/30.-T1*B**3/3.
F2=B**2/2.-T1**2*B**4/8.
K1=D0+D1*SIN(T0)+D2*(SIN(T0)**2)
K7=D1*COS(T0)+D2*SIN(2.*T0)
K8=T1*(2.*D2*COS(2.*T0)-D1*SIN(T0))
K9=T1**2*(D1/2.*COS(T0)+D2*2.*SIN(2.*T0))
K10=T1**3*(D1/6.*SIN(T0)-4.*D2/3.*COS(2.*T0))
K11=T1**4*(D1/24.*COS(T0)+2.*D2/3.*SIN(2.*T0))
K12=T1**5.*(4.*D2/15.*COS(2.*T0)-D1*SIN(T0)/120.)
K13=D2*COS(T0)**2
K14=D2*SIN(2.*T0)*T1
K15=D2*COS(2.*T0)*T1**2
K16=2./3.*D2*SIN(2.*T0)*T1**3
K17=D2/3.*COS(2.*T0)*T1**4
K18=2.*D2/15.*SIN(2.*T0)*T1**5

K=K+1
C3=A1**2/2.+B1**2/2.+2.*A2**2.+B2**2


AA=-G1+K13/8.*M**2+A*(F1*SIN(T0)+COS(T0)*(F2-M**2/8.)
&-CL/8./A*(M*(1.-M/2.))**2)
&+K10/6.)*K12/5.)*M**3 *((K7-A*SIN(T0))/28.27
&-(A1+0.1875*(A*COS(T0)))-CD/28.27*(1.-M/2.))
&+SIN(T0)*A*(F1*M*A1+B**3/3.-B**5*T1**2/10.)
&+COS(T0)*A*(B**4*T1/4.-B**6*T1**3/36.+F2*M*A1)
&-K8*M**4/64.

CC=A*SIN(T0)*(F1+F3+B2*(M*B)**2/8.-C2/4.*T1*B**4
&-C3/5.*T1*B**5)+A*COS(T0)*(F2+F3+M**2*B2**3*T1/12.
&-(F3-G1-M**4*(K13/32.*A0**2+K1/64.+CD/128.)

C SOLVING FOR LAMBDA VALUES
C THIS PART WAS MODIFIED TO GET ONLY POSITIVE VALUES OF LAMBDA AND
C IN THE CASE THAT BOTH LAMBDA VALUES ARE POSITIVE GET THE RESULTS
C FOR BOTH VALUES OF LAMBDA. (A. JABBARZADEH 18.3.93)

IF((BB**2-4.*AA*CC).LT.0.0) GOTO 66
L1=SQRT(BB**2-4.*AA*CC)
L2=(L1+BB)/((-2.)*AA)
L=(L1-BB)/(2.*AA)
IF((L1.LT.0.0).AND.(L2.LT.0.0)) GOTO 67
L=L1
ERR=ABS(ERR)-LH
IF((ERR).LT.0.000001) GOTO 70
LH=L
IF(K-20)24,24,65
C COMPARE THE RESULTS TO BE IN THE RANGE OF NONSTALL LIMIT.
70 AR4=(2.5*L+T0+(0.4+M)*T1+(1.+2.5*M)*A1)*CV
AR1=(L+T0+(1.+M)*T1+(1.+M)*A1)*CV
IF((ABS(DRA=4..LT.AL).AND.(AR1.LT.AL)).OR.
&((ABS(AR1-AL).LT.0.25))) THEN
IF(KLID.EQ.1) GOTO 24
IF(KLID.EQ.0) GOTO 64
ENDIF
GO TO 1000
C ITERATING FOR VALUES OF A0,A1,B1,A2,B2
24 N=N+1
A0=GA/2.*((COS(T0)*(B**2+4.)*T1+(1.+2.5*M)*A1)*CV
AR1=(L+T0+(1.+M)*T1+(1.+M)*A1)*CV
IF((ABS(DRA=4..LT.AL).AND.(AR1.LT.AL)).OR.
&((ABS(AR1-AL).LT.0.25))) THEN
IF(KLID.EQ.1) GOTO 24
IF(KLID.EQ.0) GOTO 64
ENDIF
GO TO 1000
C
C. Code for the Calculation of FEG Operating Parameters

\[ \begin{align*}
&+L*L*M/A/8.*CD*(1.-M/2.)**2 \\
&+0.0398/A*M**3*L*CL*(1.-M/2.)+0.0199/A*L* \\
&(1.-M/2.)*M**3*CD \\
&\text{B1}=(\text{COS}(T0)*\text{(M*B**5/10.*A0*T1*T1-M*B**3*3*A2/6.)} \\
&-0.05*A2*M**4-M*B**3*A0/3.) \\
&-\text{SIN}(T0)*\text{T1}*(M*B**4*A2/8.-M*B**4/4.*A0)) \\
&/\text{SIN}(T0)*\text{T1}**5/5.+T1*M*M*B**3/12. \\
&-\text{T1}**3*B**7/42.).-\text{COS}(T0)*\text{(B**4/4.)} \\
&+M*M*B/B/8.-T1**2/12.*B**6)) \\
&A1=(\text{SIN}(T0)*\text{(M*B**3*2./3.+.0.0265*M**4} \\
&-T1*(M*L*B**3/3.-M*B2*B**4/8.-0.0265*L*M**4)) \\
&-T1*T1/5.*M*B**5)+\text{COS}(T0)*\text{(M*L*B*B/2.} \\
&-T1*T1/8.*M*L*B**4-T1**3/18.*M*B**6) \\
&-0.01325*M*M**4*CL/A-0.2123*L*L*(M*(1.-M/2.)) \\
&**2*CD/A-L*M**3/16.*(1.-M/2.)*CL/A-L*(1.-M/2.) \\
&/32.*M**3*CD/A/\text{COS}(T0)*\text{(M*M*T1*B**3/12.-T1*B**5/5.} \\
&+T1*T1+3*(B**7/42.-M*M*B**5/120.) \\
&+\text{COS}(T0)\text{*(B**4/4.-(M*B)**2/8.}+M**4/32.+T1*T1/2. \\
&+(M*M*B**4/16.-B**6/6.)/(T1**4*B**8/192.) \\
&+B2=GA/6.\text{*(COS}(T0)\text{*(M*B**3*B1/3.-M*M*A0*B**B/4.} \\
&-A2*B**4/2.*A2/16.*M*M**4+T1*T1/2.\text{*(M*B**5/5.} \\
&-B1-A2*B**6/3.)).-\text{SIN}(T0)*\text{(T1}\text{*(M*B1*B**4/4.} \\
&-M*M*A0*B**3/6.-0.4*A2*B**5)) \\
&A2=6A/6.*\text{(SIN}(T0)\text{*(M**4/64.-M*B**2/2.)}**2 \\
&+T1*T1/16.+M*M*B**4)+\text{COS}(T0)*\text{(M*B**3/3.}.*A1 \\
&+B**4+B2/2.+0.0265*L*M**3+0.015*A1*M**4 \\
&-T1*M*M/6.**B**3-T1/T1/2.\text{*(M*B**5/5.}+A1 \\
&+B**6/3.)*B2))\text{*-M**4*CL/128.}/A \\
&-CD/B/A*(L*M*(1.-M/2.))**2+0.0265/A*M**3*L*CL \\
&+(1.-M/2.)*0.01327/A*L*(1.-M/2.)*M**3*CD \\
&\text{IF}(KLI.D.EQ.1) \text{GOTO 64} \\
&\text{IF}(\text{ABS}(A0-A0H).LT.0.000001) \text{GOTO 54} \\
&A0H=A0 \\
&A1H=A1 \\
&B1H=B1 \\
&A2H=A2 \\
&B2H=B2 \\
&\text{GOTO 24} \\
\end{align*} \]

C. CALCULATION OF THRUST COEFFICIENT, CONTROL AXIS

C. ANGLE AND WINDMILL PARAMETERS.

64 \text{TCTSA}=\text{SIN}(T0)*\text{*(B**3/3.+M*M*B/2.-.07073*M**3} \\
&-T1*(L*B**3/3.+0.03537*L*M**3) \\
&+T1**(B**5/10.+M*M**3/12.) \\
&+T1**3*L*B**5/30.+T1**4*B**7/168.) \\
&+\text{COS}(T0)*\text{(L*B**B/2.}+M*M*B2*B/4. \\
&+M*M*B4.-M**4/64.)*T1*T1*(M**4*L/128. \\
&-L*B**4/8.)*T1**3*(B**6/36.+M*M*B**4/48.)) \\
&+CL/A*(M*M/8.*L*(1.-M/2.)*M**3/28.27) \\
&+CD/A*(M*L*L/3.142*(1.-M/2.} \\
&+M*M*L/16.)*(1.-M/2.) \\
&I=I+1 \\
&CT=TCTSA/2.**S*A \\
&AC=ATAN(L/3M+CT/2.*/M/(SQRT(M*M+L*L))) \\
&ACD(I)=AC*CV \\
&CQ=CS**S \\

C. CALCULATION OF WINDMILL PARAMETERS

\text{TSR}=\text{COS}(AC)/M \\
\text{CPW}(I)=2.*CQ*TSR**3
CTW=2.*CT*TSR**2
CLW(I)=CTW*COS(A1+AC)
COPT1(I)=CLW(I)*CPW(I)
CLWOP(I)=CLW(I)*(1-(TAN(AC+A1))*TAN(BETA))
ALCA1D(I)=ACD(I)+A1D
COPT2(I)=CLWOP(I)*CPW(I)
CQW(I)=CPW(I)*TSR
COPT3(I)=CQW(I)*CLWOP(I)
P(I)=T0D

C WRITE WANTED PARAMETERS TO FILE (ENSURE HEADER NAMES MATCH)
WRITE(7,699) T1D,ACD(I),CPW(I),CLWOP(I),M,T0D,CQ,CLW(I),CT,CTW
699 FORMAT(F10.4,', ',F10.3,', ',F10.6,', ',F10.6,', ',F10.4,', ',&F10.2,', ',F10.8,', ',F10.6,', ',F10.6,', ',F10.6)
IF(KLID.EQ.1) GOTO 1000
IF((L1.GT.0.0).AND.(L2.GT.0.0)) THEN
KLID=1
L=L2
GOTO 70
ENDIF
GO TO 1000
65 WRITE(6,701)T1D,T0D,ERR,K,L
701 FORMAT(F6.2,' ',F6.2,' NO CONVERGENCE ERR=',F13.9,' K=',I5,&,' L=',F7.4)
GO TO 1000
66 WRITE(6,702)T1D,T0D
702 FORMAT(F6.2,' ',F6.2,' NO REAL SOLUTION FOR LAMBDA AA**2-4AA* &C<0 K=',I4)
GO TO 1000
67 WRITE(6,703)T1D,T0D
703 FORMAT(F6.2,' ',F6.2,' BOTH VALUES OF LAMBDA ARE NEGATIVE')
1000 CONTINUE

C SORTING BASED ON FIRST PARAMETER IN THE CALL STATEMENT
C CALL SORT(CLWOP,ACD,COPT2,CPW,CLW,COPT1,CQW,COPT3,P,I)
C CALL MAX(CLWOP,ACD,P,NM,D1MAX,D2MAX,D3MAX)
MM(NM)=M
3000 CONTINUE

CLOSE(UNIT=7)
STOP
END

SUBROUTINE SORT(D1,D2,D3,D4,D5,D6,D7,D8,D9,I)
C THIS SUBROUTINE SORTS VALUES IN ARRAYS D1 TO D9 BASED ON THE VALUES
C IN D1 FROM LARGE TO SMALL.
DIMENSION D1(1000),D2(1000),D3(1000),D4(1000),D5(1000),D6(1000),D7(1000),D8(1000),D9(1000)
REAL TEMP,TEMP2,TEMP3,TEMP4,TEMP5,TEMP1,TEMP6,TEMP7,TEMP8
DO 20 II=1,I
DO 20 IJ=II+1,I
IF(D1(II).LT.D1(IJ)) THEN
TEMP=D1(II)
TEMP1=D2(II)
TEMP2=D3(II)
TEMP3=D4(II)
TEMP4=D5(II)
TEMP5=D6(II)
TEMP6=D7(II)
TEMP7=D8(II)
TEMP8=D9(II)
20 CONTINUE
TEMP8 = D9(II)
D2(II) = D2(IJ)
D1(II) = D1(IJ)
D3(II) = D3(IJ)
D4(II) = D4(IJ)
D5(II) = D5(IJ)
D6(II) = D6(IJ)
D7(II) = D7(IJ)
D8(II) = D8(IJ)
D9(II) = D9(IJ)
D1(IJ) = TEMP
D2(IJ) = TEMP1
D3(IJ) = TEMP2
D4(IJ) = TEMP3
D5(IJ) = TEMP4
D6(IJ) = TEMP5
D7(IJ) = TEMP6
D8(IJ) = TEMP7
D9(IJ) = TEMP8
ENDIF
20 CONTINUE
RETURN
END

SUBROUTINE MAX(DM1, DM2, DM3, NM, D1MAX, D2MAX, D3MAX)

C THIS SUBROUTINE STORE THE FIRST VALUE IN DM1, DM2, DM3 IN 3 OTHER
C ARRAYS.

DIMENSION DM1(1000), DM2(1000), DM3(1000), D1MAX(100), D2MAX(100)
&, D3MAX(100)
D1MAX(NM) = DM1(1)
D2MAX(NM) = DM2(1)
D3MAX(NM) = DM3(1)
RETURN
END
Appendix D

R Code Used for Analysis

R Code for Calculating Power Density Statistics

# Thesis Results
# 08.02
# 02 Create a NetCDF file containing long-term summary statistics for P
# (for contour map plotting using GrADS).

# Load libraries/functions.

# Specify pressure levels, paths, other constants.
pressure.levels <- c(925, 850, 775, 700, 600, 500, 400, 300, 250, 200, 150, 100)
data.path <- "~/Thesis/Data/ERA-40/
molecular.weight <- 0.028966
gas.constant <- 8.3143

# Set up time and date index for the ERA40 datafiles.
ERA40.datetimes <- seq(from=ISOdatetime(1957, 9, 1, 0, 0,0, "GMT"),
  to=ISOdatetime(2002, 8, 31, 18, 0, 0, "GMT"),
  by="6 hours")
ERA40.chrtimes <- format(ERA40.datetimes, format="%Y-%m-%d %H:%M:%S",
  usetz=TRUE)

for (pressure.level in pressure.levels) {
  # 1. Import air density data.
  variable.type <- "d"
  netcdf.var.type <- "T"

  # Open NetCDF file.
  my.filename <- paste("ERA-40_au_", netcdf.var.type, ",", pressure.level,
    "hPa_19570901-20020831.nc", sep="")
  cat("[", format(Sys.time(), format="%H:%M:%S", usetz=FALSE),
    "] Now opening ", my.filename, " ... ", sep="")

  ERA40.data <- OpenNetcdfFile(netcdf.var.type, my.filename, data.path)

  # Convert raw imported NetCDF data into useful data.
  air.density <- (molecular.weight*pressure.level*100)/(gas.constant*ERA40.data)

  # Clean up.
rm(list=c("ERA40.data", "variable.type", "netcdf.var.type", "my.filename"))
cat("done!
", sep="")

# 2. Import wind speed data. 
variable.type <- "v"
netcdf.var.type <- "v"

# Open NetCDF file. 
my.filename <- paste("ERA-40_au_", netcdf.var.type, ",", pressure.level, "hPa_19570901-20020831.nc", sep="")
cat("[", format(Sys.time(), format="%H:%M:%S", usetz=FALSE), "] Now opening ", my.filename, " ... ", sep="")
wind.speed <- OpenNetcdfFile(netcdf.var.type, my.filename, data.path)

# Clean up. 
rm(list=c("variable.type", "netcdf.var.type", "my.filename"))
cat("done!
", sep="")

# 3. Calculate the power density, in units of kW m^{-3}. 
power.density <- (1E-3)*0.5*air.density*(wind.speed^3)

# Clean up. 
rm(list=c("air.density", "wind.speed"))
cat("done!
", sep="")

# 4. Calculate power density summary statistics. 
temp.var.name <- paste("P.P05", pressure.level, sep=".")
assign(temp.var.name, apply(power.density, c(1, 2), quantile, probs=c(0.05), names=FALSE, type=2))

temp.var.name <- paste("P.P25", pressure.level, sep=".")
assign(temp.var.name, apply(power.density, c(1, 2), quantile, probs=c(0.25), names=FALSE, type=2))

temp.var.name <- paste("P.mean", pressure.level, sep=".")
assign(temp.var.name, apply(power.density, c(1, 2), mean))

temp.var.name <- paste("P.median", pressure.level, sep=".")
assign(temp.var.name, apply(power.density, c(1, 2), median))

temp.var.name <- paste("P.P75", pressure.level, sep=".")
assign(temp.var.name, apply(power.density, c(1, 2), quantile, probs=c(0.75), names=FALSE, type=2))

temp.var.name <- paste("P.P95", pressure.level, sep=".")
assign(temp.var.name, apply(power.density, c(1, 2), quantile, probs=c(0.95), names=FALSE, type=2))
# Clean up.
rm(list=c("power.density", "temp.var.name"))
cat("done!\n", sep="")
}

# Create a NetCDF file containing the calculated statistics.
# Create data for NetCDF file dimensions.
longitudes <- seq(from=110, to=155, by=2.5)
lattitudes <- seq(from=-10, to=-45, by=-2.5)
time.entries <- (grep("2002-08-31 18:00:00 GMT", ERA40.chrtimes) - 1)/4

# Set up arrays for NetCDF output.
ncdf.array <- array(NA, dim=c(length(longitudes), length(lattitudes),
  length(pressure.levels), length(time.entries)))
ncdf.array.P05 <- ncdf.array
ncdf.array.P25 <- ncdf.array
ncdf.array.mean <- ncdf.array
ncdf.array.median <- ncdf.array
ncdf.array.P75 <- ncdf.array
ncdf.array.P95 <- ncdf.array

# Insert calculated data into arrays.
# Loop through each pressure level.
for (i in 1:length(pressure.levels)) {
  temp.var.name <- paste("P.P05", pressure.levels[i], sep=".")
  ncdf.array.P05[, , i, 1] <- get(temp.var.name)

  temp.var.name <- paste("P.P25", pressure.levels[i], sep=".")
  ncdf.array.P25[, , i, 1] <- get(temp.var.name)

  temp.var.name <- paste("P.mean", pressure.levels[i], sep=".")
  ncdf.array.mean[, , i, 1] <- get(temp.var.name)

  temp.var.name <- paste("P.median", pressure.levels[i], sep=".")
  ncdf.array.median[, , i, 1] <- get(temp.var.name)

  temp.var.name <- paste("P.P75", pressure.levels[i], sep=".")
  ncdf.array.P75[, , i, 1] <- get(temp.var.name)

  temp.var.name <- paste("P.P95", pressure.levels[i], sep=".")
  ncdf.array.P95[, , i, 1] <- get(temp.var.name)
}

# Clean up.
rm(list=c("i", "temp.var.name"))

# Set up NetCDF data file dimensions.
# Define lat, lon, pressure dimensions.
source("~/Thesis/Scripts/NetCDF/create.netcdf.file.dimensions.R")

# Define time dimension.
etcdf.time <- dim.def.ncdf(name="time",
  units="days since 1957-09-01 00:00:0.0",
  vals=time.entries, unlim=TRUE, create_dimvar=TRUE)

# 5th Percentile
netcdf.P05 <- var.def.ncdf(name="PP05", units="kW m^-3",
  dim=list(netcdf.lon, netcdf.lat, netcdf.lev,
    netcdf.time), missval=-1,
  longname="Power Density P05"
# 25th Percentile
```
netcdf.P25 <- var.def.ncdf(name="PP25", units="kW m^-3",
dim=list(netcdf.lon, netcdf.lat, netcdf.lev, netcdf.time), missval=-1,
longname="Power Density P25",
prec="double")
```

# Mean
```
netcdf.mean <- var.def.ncdf(name="Pmean", units="kW m^-3",
dim=list(netcdf.lon, netcdf.lat, netcdf.lev, netcdf.time), missval=-1,
longname="Power Density Mean",
prec="double")
```

# Median
```
netcdf.median <- var.def.ncdf(name="Pmed", units="kW m^-3",
dim=list(netcdf.lon, netcdf.lat, netcdf.lev, netcdf.time), missval=-1,
longname="Power Density Median",
prec="double")
```

# 75th Percentile
```
netcdf.P75 <- var.def.ncdf(name="PP75", units="kW m^-3",
dim=list(netcdf.lon, netcdf.lat, netcdf.lev, netcdf.time), missval=-1,
longname="Power Density P75",
prec="double")
```

# 95th Percentile
```
netcdf.P95 <- var.def.ncdf(name="PP95", units="kW m^-3",
dim=list(netcdf.lon, netcdf.lat, netcdf.lev, netcdf.time), missval=-1,
longname="Power Density P95",
prec="double")
```

# Set the output folder for the NetCDF file by changing working directory. setwd("~/Thesis/Data/Results/")

# Create the NetCDF file.
```
new.netcdf.file <- create.ncdf(filename="au_P_stats_overall_925-100hPa.nc",
vars=list(netcdf.P05, netcdf.P25, netcdf.mean, netcdf.median, netcdf.P75,
netcdf.P95),
verbose=FALSE)
```

```
put.var.ncdf(new.netcdf.file, varid="PP05", vals=ncdf.array.P05,
start=c(1,1,1,1), count=c(-1,-1,-1,-1), verbose=FALSE)
put.var.ncdf(new.netcdf.file, varid="PP25", vals=ncdf.array.P25,
start=c(1,1,1,1), count=c(-1,-1,-1,-1), verbose=FALSE)
put.var.ncdf(new.netcdf.file, varid="Pmean", vals=ncdf.array.mean,
start=c(1,1,1,1), count=c(-1,-1,-1,-1), verbose=FALSE)
put.var.ncdf(new.netcdf.file, varid="Pmed", vals=ncdf.array.median,
start=c(1,1,1,1), count=c(-1,-1,-1,-1), verbose=FALSE)
put.var.ncdf(new.netcdf.file, varid="PP75", vals=ncdf.array.P75,
start=c(1,1,1,1), count=c(-1,-1,-1,-1), verbose=FALSE)
put.var.ncdf(new.netcdf.file, varid="PP95", vals=ncdf.array.P95,
start=c(1,1,1,1), count=c(-1,-1,-1,-1), verbose=FALSE)
```

```
close(new.netcdf.file)
```
R Code for Calculating Capacity Factor

# Thesis Results
# 07.03
# 07 Simulation
# 03 Create power curve for 240kW demonstration craft.

# Round air density to 3 decimal places.
# Round geopotential height to nearest whole number.
# Round tether mass to 1 decimal place.
# Round wind speeds to 1 decimal place.

# Load libraries/functions.
#require(reshape)
#require(plyr)

pressure.levels <- c(925, 850, 775, 700, 600)
ERA40.path <- "~/Thesis/Data/ERA-40/

molecular.weight <- 0.028966
gas.constant <- 8.3143
rated.power <- 240000 # in Watts.
FEG.mass <- 520 # in kg.
rotor.radius <- 5.35 # in m.
rotor.area <- 4*pi*(5.35)^2 # in m^-2.
tether.unit.mass <- 115/1000 # in kg/m.
g.0 <- 9.80665 # in m/s^2.
C.LWOP.v.min <- 0.615934 # Obtained from , when mu = and ac = .
tether.angle <- 40 # in degrees.

# Calculate the mean air density and geopotential height for all the pressure
# levels below 600 hPa.
for (pressure.level in pressure.levels) {
  ##############################################################################
  # Air Density.
  ERA40.filename <- paste("ERA-40_au_T_", pressure.level, 
                         "hPa_19570901-20020831.nc", sep=")
  cat("[", format(Sys.time(), format="%H:%M:%S", usez=FALSE), 
       "] Now opening ", ERA40.filename, " ... ", sep="")

  ERA40.data <- OpenNetcdfFile("T", ERA40.filename, ERA40.path)
  cat("done!

  air.density <- (molecular.weight*pressure.level*100)/(gas.constant*ERA40.data)
  rm(list=c("ERA40.data"))

  mean.air.density <- apply(air.density, c(1, 2), mean)

  if (which(pressure.levels == pressure.level) == 1) {
    air.density.means <- array(NA, dim=c(dim(mean.air.density)[1],
                                    dim(mean.air.density)[2], length(pressure.levels)))
    air.density.means[ , , 1] <- round(mean.air.density, 3)
  } else {
    air.density.means[ , , which(pressure.levels == pressure.level)] <-
      round(mean.air.density, 3)
  }
  rm(list=c("air.density", "mean.air.density"))

  ##############################################################################
  # Geopotential Height.
  ERA40.filename <- paste("ERA-40_au_Z_", pressure.level, 
                          "hPa_19570901-20020831.nc", sep="")

  ...
```r
# Calculate the tether length at for each pressure level.
tether.mass <- round(tether.unit.mass*geopotential.height.means/
sin(pi*tether.angle/180), 1) # in kg.

# Calculate the autorotation threshold velocity for each pressure level.
v.min <- round(sqrt(((FEG.mass + tether.mass)*g.0/rotor.area)/
(0.5*air.density.means*C.LWOP.v.min)), 1)

# Calculate maximum wind speed for each location.
v.max <- 60 # in m/s

# Calculate rated wind speed for each location.

# Import data for CPW, CLWOP for twists 0-15 degrees.
twist.df <- read.table("~/gc_t1_0-15.dat", header=TRUE, sep="",)
operating.df <- twist.df[twist.df$T1==0,]
rm(list=c("twist.df"))

# Create an array for v.rated.
v.rated <- array(NA, dim=c(dim(air.density.means)[1],
dim(air.density.means)[2],
dim(air.density.means)[3]))

# Loop through each point of the v.rated array, calculate the v.rated wind
# speed.
for (i in 1:dim(v.rated)[1]) {
  cat("[", format(Sys.time(), format="%H:%M:%S", usetz=FALSE),
  "] i = ", i, ", 
  \n", sep="")
  for (j in 1:dim(v.rated)[2]) {
    for (k in 1:dim(v.rated)[3]) {
      # Calculate the m/A ratio at the current point.
m.A.ratio <- (FEG.mass + tether.mass[i, j, k])/rotor.area
      # Grab a temporary copy of the operating parameters data frame.
temp.df <- operating.df[which(operating.df$CLWOP > 0), names(operating.df)
      %in% c("AC", "CPW", "CLWOP", "MU")]
      
      # Calculate the AUTO threshold wind speed.
v.rated[i, j, k] <- v.min
    }
  }
}
```

The provided R code calculates various parameters such as geometric height, mean geopotential height, geopotential height means, and then uses these to calculate tether length at each pressure level, autorotation threshold velocity, and maximum wind speed. It also imports data for CPW, CLWOP for twists 0-15 degrees, and calculates the wind speed at rated conditions.
# Calculate the vmin for every value of CLWOP, for the current point.
temp.df$vmin <- sqrt((mA.ratio*g.0)/(0.5*air.density.means[i, j, k]*
temp.df$CLWOP))

# Calculate the power output associated with that vmin, for the current
# point.
temp.df$P <- round(0.5*(temp.df$CPW)*air.density.means[i, j, k]*rotor.area* 
(temp.df$vmin)^3, 0)

# Keep only those rows where P is greater than or equal to the rated power.
temp.df <- temp.df[which(temp.df$P >= rated.power), ]

# Keep only those rows where vmin is minimum.
temp.df <- temp.df[which(temp.df$vmin == min(temp.df$vmin)), ]

# If there is more than one minimum, choose the one with the highest CLWOP.
if (length(temp.df$vmin) > 1) {
  temp.df <- temp.df[which(temp.df$CLWOP == max(temp.df$CLWOP)), ]
  if (length(temp.df$vmin) > 1) {
    temp.df <- temp.df[1, ]
  }
}

# The single remaining vmin is the rated speed at this point.
v.rated[i, j, k] <- round(temp.df$vmin[1], 1)
rm(list=c("temp.df", "mA.ratio"))

# Create a CPW-v power curve for each point.

# Create range of wind speeds, up to maximum.
wind.speeds <- seq(0, v.max, 0.1)

# Create an array for CLWOP.
P.curve.CLWOP <- array(NA, dim=c(dim(v.rated)[1], 
  dim(v.rated)[2],
  dim(v.rated)[3],
  length(wind.speeds)))

# Create an array for CPW.
P.curve.CPW <- P.curve.CLWOP

# Create an array for AC.
P.curve.AC <- P.curve.CLWOP

# Create an array for MU.
P.curve.MU <- P.curve.CLWOP

# Create an array for the power output.
P.curve.output <- P.curve.CLWOP

for (i in 1:dim(P.curve.CPW)[1]) {
  for (j in 1:dim(P.curve.CPW)[2]) {
    cat("[", format(Sys.time(), format="%H:%M:%S", usetz=FALSE), 
        "] i = ", i, ", j = ", j, ", n", sep="")

  for (k in 1:dim(P.curve.CPW)[3]) {
    # Calculate the m/A ratio at the current point.
    mA.ratio <- (FEG.mass + tether.mass[i, j, k]/rotor.area
# Grab a temporary copy of the operating parameters data frame.
temp.df <- operating.df[which(operating.df$CLWOP > 0), names(operating.df) %in% c("AC", "CPW", "CLWOP", "MU")]

# Calculate the vmin for every value of CLWOP, for the current point.
temp.df$vmin <- round(sqrt((mA.ratio*g.0)/(0.5*air.density.means[i, j, k]*temp.df$CLWOP)), 2)

# For every wind speed in the hypothetical wind speed vector, 
# calculate the optimal CPW.
for (m in 1:dim(P.curve.CPW)[4]) {
  # Get the current wind speed.
  wind.speed <- wind.speeds[m]

  # If the wind is below v.min or above v.max for this point, set CPW to 0 
  # and move on.
  if (wind.speed < v.min[i, j, k] || wind.speed > v.max) {
    P.curve.CPW[i, j, k, m] <- 0
    P.curve.output[i, j, k, m] <- 0
    next
  }

  # Make a temp copy of the operating coefficients data frame, add some 
  # columns. 
  # Only include those conditions that have a lower vmin than the current 
  # speed.
  temp2.df <- temp.df[which(temp.df$vmin <= wind.speed), ]

  # If there are no valid operating conditions, record zero power output 
  # and move on.
  if (dim(temp2.df)[1] < 1) {
    P.curve.CPW[i, j, k, m] <- 0
    P.curve.output[i, j, k, m] <- 0
    rm(list=c("temp2.df"))
    next
  }

  # Calculate the power output for each operating condition.
  temp2.df$air.density <- air.density.means[i, j, k] # Add air density
  temp2.df$v <- wind.speed # Add current wind speed
  temp2.df$A <- rotor.area # Add rotor area
  temp2.df$P <- round(0.5*(temp2.df$CPW)*(temp2.df$air.density)*(temp2.df$A)*
                      (temp2.df$v)^3, 0)

  # Remove those with negative power.
  temp2.df <- temp2.df[which(temp2.df$P >= 0), ]
  if (dim(temp2.df)[1] < 1) {
    cat("No parameters produced positive power. (v = ", wind.speed, ")\n", sep="")
    P.curve.CPW[i, j, k, m] <- 0
    P.curve.output[i, j, k, m] <- 0
    rm(list=c("temp2.df"))
    next
  }

  # Remove those greater than the rated power.
  temp2.df <- temp2.df[which(temp2.df$P <= rated.power), ]
  if (dim(temp2.df)[1] < 1) {
    cat("All parameters produced power in excess of rated power. (v = ", wind.speed, ")\n", sep="")
    P.curve.CPW[i, j, k, m] <- 0
    P.curve.output[i, j, k, m] <- 0
# Find the condition which produces the most power at the current wind speed.
optimal.df <- temp2.df[which(temp2.df$P == max(temp2.df$P)),]

# If there is more than one optimal condition, choose the one with highest vmin.
if (dim(optimal.df)[1] > 1) {
  #cat("Max(P) returned ", dim(optimal.df)[1], " operating conditions for v = ",
  wind.speed," \n")
optimal.df <- optimal.df[which(optimal.df$vmin == max(optimal.df$vmin)),]
}

# If there is still more than one, just return the first in the data frame.
if (dim(optimal.df)[1] > 1) {
  optimal.df <- optimal.df[1,]
}

# Output the optimal operating conditions to their arrays.
P.curve.CPW[i, j, k, m] <- optimal.df$CPW[1]
P.curve.output[i, j, k, m] <- optimal.df$P[1]
P.curve.AC[i, j, k, m] <- optimal.df$AC[1]
P.curve.MU[i, j, k, m] <- optimal.df$MU[1]
P.curve.CLWOP[i, j, k, m] <- optimal.df$CLWOP[1]

rm(list=c("temp2.df", "optimal.df"))

rm(list=c("mA.ratio", "temp.df"))

# Set up time and date index for the ERA40 datafiles.
ERA40.datetimes <- seq(from=ISOdatetime(1957, 9, 1, 0, 0,0, "GMT"),
to=ISOdatetime(2002, 8, 31, 18, 0, 0, "GMT"), by="6 hours")
ERA40.chrtimes <- format(ERA40.datetimes, format="%Y-%m-%d %H:%M:%S",
usetz=TRUE)

actual.power.output <- array(NA, dim=c(dim(air.density.means)[1],
dim(air.density.means)[2], length(pressure.levels),
length(ERA40.chrtimes)))

for (k in 1:length(pressure.levels)) {
  # Open the wind speed NetCDF file for each pressure level.
  ERA40.filename <- paste("ERA-40_au_v_.", pressure.levels[k],
  "hPa_19570901-20020831.nc", sep="")
cat("[", format(Sys.time(), format="%H:%M:%S", usetz=FALSE),
  "] Now opening ", ERA40.filename, " ... ", sep="")

  v.netcdf <- OpenNetcdfFile("v", ERA40.filename, ERA40.path)
cat("done!\n", sep="")
}

# Round the values to the nearest 0.1.
v.netcdf <- round(v.netcdf, 1)

# Loop through and calculate the actual power output.
for (i in 1:dim(v.netcdf)[1]) {
  for (j in 1:dim(v.netcdf)[2]) {
    # For each wind speed value in the time series, find the power output
    # associated with it.
    for (n in 1:dim(v.netcdf)[3]) {
      # If the wind speed is at or below autorotation.
      if (v.netcdf[i, j, n] <= v.min[i, j, k]) {
        actual.power.output[i, j, k, n] <- 0
        next
      }
      # If the wind speed is above the maximum.
      if (v.netcdf[i, j, n] > v.max) {
        actual.power.output[i, j, k, n] <- 0
        next
      }
      # If the wind speed is at the rated wind speed.
      if (abs(v.netcdf[i, j, n] - v.rated[i, j, k]) < 1e-5) {
        actual.power.output[i, j, k, n] <- rated.power
        next
      }
      # If the wind speed is above the rated speed.
      if (v.netcdf[i, j, n] - v.rated[i, j, k] >= 0.1 - 1e-5) {
        actual.power.output[i, j, k, n] <- rated.power
        next
      }
      # If it’s in the range applicable to the power curve.
      actual.power.output[i, j, k, n] <- P.curve.output[i, j, k,
      which(abs(wind.speeds - v.netcdf[i, j, n]) < 1e-5)]
    }
  }
}
rm(list=c("v.netcdf"))

# For the 600-and-lower calculation, find the maximum power output at each lat,
# lon, and
# time point, over all of the pressure levels, and choose that (assume that the
# FEG had
# repositioned to that level for the 6 hours).
max.power.alllevels <- apply(actual.power.output[1:19, 1:15, , ],
c(1, 2, 4),
  max)

# Calculate the capacity factor for each year (and pressure level).
year.starts <- grep("-09-01 00:00:00", ERA40.chrtimes)
year.ends <- grep("-08-31 18:00:00", ERA40.chrtimes)

CF.atlevelonly <- array(NA, dim=c(dim(air.density.means)[1],
dim(air.density.means)[2],
dim(air.density.means)[3],
length(year.starts)))

CF.600andlower <- array(NA, dim=c(dim(air.density.means)[1],
dim(air.density.means)[2],

for (year in 1:length(year.starts)) {

  # Specify the time step entries for the current year.
  year.entries <- seq(year.starts[year], year.ends[year], 1)

  # Calculate the 600-and-lower CF.
  CF.600andlower[ , , year] <- apply(max.power.alllevels[ , , year.entries],
                                      c(1, 2),
                                      mean)/rated.power

  # For each pressure level, calculate the CF had the FEG remained precisely
  # at that
  # pressure level.
  for (k in 1:length(pressure.levels)){
    CF.atlevelonly[ , , k, year] <- apply(actual.power.output[1:19, 1:15, k, year.entries],
                                          c(1, 2),
                                          mean)/rated.power
  }
}

# Export the individual level CFs to a netcdf file.
setwd("~/Thesis/Data/Results/")
longitudes <- seq(from=110, to=155, by=2.5)
latitudes <- seq(from=-10, to=-45, by=-2.5)
time.entries <- grep("-09-01 00:00:00 GMT", ERA40.chrtimes)/4 - 1
source("~/Thesis/Scripts/NetCDF/create.netcdf.file.dimensions.R")
netcdf.time <- dim.def.ncdf(name="time",
                            units="days since 1957-09-01 00:00:0.0",
                            vals=time.entries, unlim=TRUE, create_dimvar=TRUE)
netcdf.CF <- var.def.ncdf(name="CF", units="none",
                          dim=list(netcdf.lon, netcdf.lat, netcdf.lev,
                                   netcdf.time), missval=-1,
                          longname="Capacity Factor",
                          prec="double")
new.netcdf.file <- create.ncdf(filename="au_CF_democraft_annual_925-600hPa.nc",
                               vars=list(netcdf.CF), verbose=FALSE)
put.var.ncdf(new.netcdf.file, varid="CF", vals=CF.atlevelonly,
            start=c(1,1,1,1), count=c(-1,-1,-1,-1), verbose=FALSE)
close(new.netcdf.file)
rm(list=c("new.netcdf.file", "netcdf.CF", "netcdf.lat", "netcdf.lon",
          "netcdf.time", "netcdf.lev"))

# Export the 600-level-and-lower CFs to a netcdf file.
CF.600below.netcdf <- array(NA, dim=c(dim(CF.600andlower)[1],
                                      dim(CF.600andlower)[2],
                                      1,
                                      dim(CF.600andlower)[3]))
CF.600below.netcdf[ , , 1, ] <- CF.600andlower
old.pressure.levels <- pressure.levels
pressure.levels <- min(pressure.levels)
source("~/Thesis/Scripts/NetCDF/create.netcdf.file.dimensions.R")
pressure.levels <- old.pressure.levels
rmlist(c("old.pressure.levels"))

netcdf.CF <- var.def.ncdf(name="CF", units="none",
dim=list(netcdf.lon, netcdf.lat, netcdf.lev,
netcdf.time), missval=-1,
longname="Capacity Factor",
prec="double")

new.netcdf.file <- create.ncdf(filename=
"au_CF_democraft_annual_600hPa_and_lower.nc",
vars=list(netcdf.CF), verbose=FALSE)
put.var.ncdf(new.netcdf.file, varid="CF", vals=CF.600below.netcdf,
start=c(1,1,1,1), count=c(-1,-1,-1,-1), verbose=FALSE)
close(new.netcdf.file)
rmlist(c("new.netcdf.file", "netcdf.CF", "netcdf.lat", "netcdf.lon",
"netcdf.time", "netcdf.lev"))

# Export the minimum wind speeds to NetCDF format.
# Export the rated wind speeds to NetCDF format.

v.min.netcdf <- array(NA, dim=c(dim(v.min)[1],
dim(v.min)[2],
dim(v.min)[3],
1))
v.rated.netcdf <- array(NA, dim=c(dim(v.rated)[1],
dim(v.rated)[2],
dim(v.rated)[3],
1))
v.min.netcdf[, , , 1] <- v.min
v.rated.netcdf[, , , 1] <- v.rated
time.entries <- grep("1957-09-01 00:00:00 GMT", ERA40.chrtimes) - 1
source("~/Thesis/Scripts/NetCDF/create.netcdf.file.dimensions.R")

netcdf.time <- dim.def.ncdf(name="time",
units="days since 1957-09-01 00:00:0.0",
vals=time.entries, unlim=TRUE, create_dimvar=TRUE)

netcdf.vmin <- var.def.ncdf(name="vmin", units="m/s",
dim=list(netcdf.lon, netcdf.lat, netcdf.lev,
netcdf.time), missval=-1,
longname="Minimum Wind Speed",
prec="double")

netcdf.vrated <- var.def.ncdf(name="vrated", units="m/s",
dim=list(netcdf.lon, netcdf.lat, netcdf.lev,
netcdf.time), missval=-1,
longname="Rated Wind Speed",
prec="double")

new.netcdf.file <- create.ncdf(filename=
"au_vmin_vrated_democraft_annual_925-600hPa.nc",
vars=list(netcdf.vmin, netcdf.vrated),
verbose=FALSE)

put.var.ncdf(new.netcdf.file, varid="vmin", vals=v.min.netcdf,
start=c(1,1,1,1), count=c(-1,-1,-1,-1), verbose=FALSE)
**Seasonal CFs.**

Calculate the capacity factor for each SON (and pressure level).

```r
grep("-09-01 00:00:00", ERA40.chrtimes)  # SON starts
```

```r
grep("-11-30 18:00:00", ERA40.chrtimes)  # SON ends
```

```r
CF.atlevelonly.SON <- array(NA, dim=c(dim(air.density.means)[1],
                           dim(air.density.means)[2],
                           dim(air.density.means)[3],
                           length(SON.starts)))
```

```r
CF.600andlower.SON <- array(NA, dim=c(dim(air.density.means)[1],
                           dim(air.density.means)[2],
                           length(SON.starts)))
```

```r
for (season in 1:length(SON.starts)) {
  # Specify the time step entries for the current SON.
  SON.entries <- seq(SON.starts[season], SON.ends[season], 1)

  # Calculate the 600-and-lower CF.
  CF.600andlower.SON[, , season] <- apply(max.power.alllevels[, ,
                                           SON.entries],
                                          c(1, 2),
                                          mean)/rated.power

  # For each pressure level, calculate the CF had the FEG remained precisely at
  # that
  # pressure level.
  for (k in 1:length(pressure.levels)){
    CF.atlevelonly.SON[, , k, season] <- apply(actual.power.output[1:19, 1:15, 
                                                              k, SON.entries],
                                           c(1, 2),
                                           mean)/rated.power
  }
}
```

**DJF CFs.**

Calculate the capacity factor for each DJF (and pressure level).

```r
grep("-12-01 00:00:00", ERA40.chrtimes)  # DJF starts
```

```r
grep("-02-28 18:00:00", ERA40.chrtimes)  # DJF ends
```

```r
CF.atlevelonly.DJF <- array(NA, dim=c(dim(air.density.means)[1],
                             dim(air.density.means)[2],
                             dim(air.density.means)[3],
                             length(DJF.starts)))
```

```r
CF.600andlower.DJF <- array(NA, dim=c(dim(air.density.means)[1],
                             dim(air.density.means)[2],
                             length(DJF.starts)))
```

```r
for (season in 1:length(DJF.starts)) {
  # Specify the time step entries for the current DJF.
  DJF.entries <- seq(DJF.starts[season], DJF.ends[season], 1)

  # Calculate the 600-and-lower CF.
```
CF.600andlower.DJF[, , season] <- apply(max.power.alllevels[, , DJF.entries],
  c(1, 2),
  mean)/rated.power

# For each pressure level, calculate the CF had the FEG remained precisely
# at that
# pressure level.
for (k in 1:length(pressure.levels)){
  CF.atlevelonly.DJF[, , k, season] <- apply(actual.power.output[1:19, 1:15, k, DJF.entries],
    c(1, 2),
    mean)/rated.power
}

# Calculate the capacity factor for each MAM (and pressure level).
MAM.starts <- grep("-03-01 00:00:00", ERA40.chrtimes)
MAM.ends <- grep("-05-31 18:00:00", ERA40.chrtimes)

CF.atlevelonly.MAM <- array(NA, dim=c(dim(air.density.means)[1],
  dim(air.density.means)[2],
  dim(air.density.means)[3],
  length(MAM.starts)))

CF.600andlower.MAM <- array(NA, dim=c(dim(air.density.means)[1],
  dim(air.density.means)[2],
  length(MAM.starts)))

for (season in 1:length(MAM.starts)) {
  # Specify the time step entries for the current MAM.
  MAM.entries <- seq(MAM.starts[season], MAM.ends[season], 1)
  # Calculate the 600-and-lower CF.
  CF.600andlower.MAM[ , , season] <- apply(max.power.alllevels[ , , MAM.entries],
    c(1, 2),
    mean)/rated.power

  # For each pressure level, calculate the CF had the FEG remained precisely
  # at that
  # pressure level.
  for (k in 1:length(pressure.levels)){
    CF.atlevelonly.MAM[ , , k, season] <- apply(actual.power.output[1:19, 1:15, k, MAM.entries],
      c(1, 2),
      mean)/rated.power
  }
}

# Calculate the capacity factor for each JJA (and pressure level).
JJA.starts <- grep("-06-01 00:00:00", ERA40.chrtimes)
JJA.ends <- grep("-08-31 18:00:00", ERA40.chrtimes)

CF.atlevelonly.JJA <- array(NA, dim=c(dim(air.density.means)[1],
  dim(air.density.means)[2],
  dim(air.density.means)[3],
  length(JJA.starts)))

CF.600andlower.JJA <- array(NA, dim=c(dim(air.density.means)[1],
  dim(air.density.means)[2],
  length(JJA.starts)))
for (season in 1:length(JJA.starts)) {
  # Specify the time step entries for the current JJA.
  JJA.entries <- seq(JJA.starts[season], JJA.ends[season], 1)

  # Calculate the 600-and-lower CF.
  CF.600andlower.JJA[, , season] <- apply(max.power.alllevels[, ,
    JJA.entries],
    c(1, 2),
    mean)/rated.power

  # For each pressure level, calculate the CF had the FEG remained precisely
  # at that
  # pressure level.
  for (k in 1:length(pressure.levels)){
    CF.atlevelonly.JJA[, , k, season] <- apply(actual.power.output[1:19, 1:15,
      k, JJA.entries],
      c(1, 2),
      mean)/rated.power
  }
}

###############################################################################
# Export seasonal CF to NetCDF.
#SON
time.entries <- (grep("-09-01 00:00:00 GMT", ERA40.chrtimes) - 1)/4
source("~/Thesis/Scripts/NetCDF/create.netcdf.file.dimensions.R")
netcdf.time <- dim.def.ncdf(name="time",
    units="days since 1957-09-01 00:00:0.0",
    vals=time.entries, unlim=TRUE, create_dimvar=TRUE)

netcdf.CF <- var.def.ncdf(name="CF", units="none",
    dim=list(netcdf.lon, netcdf.lat, netcdf.lev,
      netcdf.time), missval=-1,
    longname="Capacity Factor",
    prec="double")

new.netcdf.file <- create.ncdf(filename="au_CF_democraft_SON_925-600hPa.nc",
    vars=list(netcdf.CF), verbose=FALSE)
put.var.ncdf(new.netcdf.file, varid="CF", vals=CF.atlevelonly.SON,
    start=c(1,1,1,1), count=c(-1,-1,-1,-1), verbose=FALSE)
close(new.netcdf.file)
rm(list=c("new.netcdf.file", "netcdf.CF", "netcdf.lat", "netcdf.lon",
      "netcdf.time", "netcdf.lev"))

#DJF
time.entries <- (grep("-12-01 00:00:00 GMT", ERA40.chrtimes) - 1)/4
source("~/Thesis/Scripts/NetCDF/create.netcdf.file.dimensions.R")
netcdf.time <- dim.def.ncdf(name="time",
    units="days since 1957-09-01 00:00:0.0",
    vals=time.entries, unlim=TRUE, create_dimvar=TRUE)

netcdf.CF <- var.def.ncdf(name="CF", units="none",
    dim=list(netcdf.lon, netcdf.lat, netcdf.lev,
      netcdf.time), missval=-1,
    longname="Capacity Factor",
    prec="double")
new.netcdf.file <- create.ncdf(filename="au_CF_democraft_DJF_925-600hPa.nc",
vars=list(netcdf.CF), verbose=FALSE)

put.var.ncdf(new.netcdf.file, varid="CF", vals=CF.atlevelonly.DJF,
start=c(1,1,1,1), count=c(-1,-1,-1,-1), verbose=FALSE)
close(new.netcdf.file)
rm(list=c("new.netcdf.file", "netcdf.CF", "netcdf.lat", "netcdf.lon",
"netcdf.time", "netcdf.lev"))

#MAM

time.entries <- (grep("-03-01 00:00:00 GMT", ERA40.chrtimes) - 1)/4
source("~/Thesis/Scripts/NetCDF/create.netcdf.file.dimensions.R")

netcdf.time <- dim.def.ncdf(name="time",
units="days since 1957-09-01 00:00:0.0",
vals=time.entries, unlim=TRUE, create_dimvar=TRUE)

netcdf.CF <- var.def.ncdf(name="CF", units="none",
dim=list(netcdf.lon, netcdf.lat, netcdf.lev,
netcdf.time), missval=-1,
longname="Capacity Factor",
prec="double")

new.netcdf.file <- create.ncdf(filename="au_CF_democraft_MAM_925-600hPa.nc",
vars=list(netcdf.CF), verbose=FALSE)

put.var.ncdf(new.netcdf.file, varid="CF", vals=CF.atlevelonly.MAM,
start=c(1,1,1,1), count=c(-1,-1,-1,-1), verbose=FALSE)
close(new.netcdf.file)
rm(list=c("new.netcdf.file", "netcdf.CF", "netcdf.lat", "netcdf.lon",
"netcdf.time", "netcdf.lev"))

#JJA

time.entries <- (grep("-06-01 00:00:00 GMT", ERA40.chrtimes) - 1)/4
source("~/Thesis/Scripts/NetCDF/create.netcdf.file.dimensions.R")

netcdf.time <- dim.def.ncdf(name="time",
units="days since 1957-09-01 00:00:0.0",
vals=time.entries, unlim=TRUE, create_dimvar=TRUE)

netcdf.CF <- var.def.ncdf(name="CF", units="none",
dim=list(netcdf.lon, netcdf.lat, netcdf.lev,
netcdf.time), missval=-1,
longname="Capacity Factor",
prec="double")

new.netcdf.file <- create.ncdf(filename="au_CF_democraft_JJA_925-600hPa.nc",
vars=list(netcdf.CF), verbose=FALSE)

put.var.ncdf(new.netcdf.file, varid="CF", vals=CF.atlevelonly.JJA,
start=c(1,1,1,1), count=c(-1,-1,-1,-1), verbose=FALSE)
close(new.netcdf.file)
rm(list=c("new.netcdf.file", "netcdf.CF", "netcdf.lat", "netcdf.lon",
"netcdf.time", "netcdf.lev"))

# Export the seasonal 600-level-and-lower CFs to a netcdf file.
# SON
time.entries <- (grep("-09-01 00:00:00 GMT", ERA40.chrtimes) - 1)/4
CF.600below.netcdf <- array(NA, dim=c(dim(CF.600andlower.SON)[1],
    dim(CF.600andlower.SON)[2],
    1,
    dim(CF.600andlower.SON)[3]))
CF.600below.netcdf[, , 1, ] <- CF.600andlower.SON

old.pressure.levels <- pressure.levels
pressure.levels <- min(pressure.levels)
source("~/Thesis/Scripts/NetCDF/create.netcdf.file.dimensions.R")
pressure.levels <- old.pressure.levels
rm(list=c("old.pressure.levels"))

netcdf.time <- dim.def.ncdf(name="time",
    units="days since 1957-09-01 00:00:0.0",
    vals=time.entries, unlim=TRUE, create_dimvar=TRUE)

netcdf.CF <- var.def.ncdf(name="CF", units="none",
    dim=list(netcdf.lon, netcdf.lat, netcdf.lev,
        netcdf.time), missval=-1,
    longname="Capacity Factor",
    prec="double")

new.netcdf.file <- create.ncdf(filename=
    "au_CF_democraft_SON_600hPa_and_lower.nc",
    vars=list(netcdf.CF), verbose=FALSE)
put.var.ncdf(new.netcdf.file, varid="CF", vals=CF.600below.netcdf,
    start=c(1,1,1,1), count=c(-1,-1,-1,-1), verbose=FALSE)

close(new.netcdf.file)
rm(list=c("new.netcdf.file", "netcdf.CF", "netcdf.lat", "netcdf.lon",
    "netcdf.time", "netcdf.lev"))
rm(list=c("CF.600below.netcdf"))

# DJF
time.entries <- (grep("-12-01 00:00:00 GMT", ERA40.chrtimes) - 1)/4

CF.600below.netcdf <- array(NA, dim=c(dim(CF.600andlower.DJF)[1],
    dim(CF.600andlower.DJF)[2],
    1,
    dim(CF.600andlower.DJF)[3]))
CF.600below.netcdf[, , 1, ] <- CF.600andlower.DJF

old.pressure.levels <- pressure.levels
pressure.levels <- min(pressure.levels)
source("~/Thesis/Scripts/NetCDF/create.netcdf.file.dimensions.R")
pressure.levels <- old.pressure.levels
rm(list=c("old.pressure.levels"))

netcdf.time <- dim.def.ncdf(name="time",
    units="days since 1957-09-01 00:00:0.0",
    vals=time.entries, unlim=TRUE, create_dimvar=TRUE)

netcdf.CF <- var.def.ncdf(name="CF", units="none",
    dim=list(netcdf.lon, netcdf.lat, netcdf.lev,
        netcdf.time), missval=-1,
    longname="Capacity Factor",
    prec="double")

new.netcdf.file <- create.ncdf(filename=
    "au_CF_democraft_DJF_600hPa_and_lower.nc",
    vars=list(netcdf.CF), verbose=FALSE)
```r
put.var.ncdf(new.netcdf.file, varid="CF", vals=CF.600below.netcdf, 
            start=c(1,1,1,1), count=c(-1,-1,-1,-1), verbose=FALSE)

close(new.netcdf.file)
rm(list=c("new.netcdf.file", "netcdf.CF", "netcdf.lat", "netcdf.lon", 
            "netcdf.time", "netcdf.lev"))
rm(list=c("CF.600below.netcdf"))

# MAM
time.entries <- (grep("-03-01 00:00:00 GMT", ERA40.chrtimes) - 1)/4

CF.600below.netcdf <- array(NA, dim=c(dim(CF.600andlower.MAM)[1],
                        dim(CF.600andlower.MAM)[2],
                        1,
                        dim(CF.600andlower.MAM)[3]))

CF.600below.netcdf[, , 1, ] <- CF.600andlower.MAM

old.pressure.levels <- pressure.levels
pressure.levels <- min(pressure.levels)
source("~/Thesis/Scripts/NetCDF/create.netcdf.file.dimensions.R")
pressure.levels <- old.pressure.levels
rm(list=c("old.pressure.levels"))

netcdf.time <- dim.def.ncdf(name="time", 
                        units="days since 1957-09-01 00:00:0.0", 
                        vals=time.entries, unlim=TRUE, create_dimvar=TRUE)

netcdf.CF <- var.def.ncdf(name="CF", units="none", 
                        dim=list(netcdf.lon, netcdf.lat, netcdf.lev, 
                                netcdf.time), missval=-1, 
                        longname="Capacity Factor", 
                        prec="double")

new.netcdf.file <- create.ncdf(filename=
                                "au_CF_democraft_MAM_600hPa_and_lower.nc", 
                                vars=list(netcdf.CF), verbose=FALSE)

put.var.ncdf(new.netcdf.file, varid="CF", vals=CF.600below.netcdf, 
            start=c(1,1,1,1), count=c(-1,-1,-1,-1), verbose=FALSE)

close(new.netcdf.file)
rm(list=c("new.netcdf.file", "netcdf.CF", "netcdf.lat", "netcdf.lon", 
            "netcdf.time", "netcdf.lev"))
rm(list=c("CF.600below.netcdf"))

# JJA
time.entries <- (grep("-06-01 00:00:00 GMT", ERA40.chrtimes) - 1)/4

CF.600below.netcdf <- array(NA, dim=c(dim(CF.600andlower.JJA)[1],
                        dim(CF.600andlower.JJA)[2],
                        1,
                        dim(CF.600andlower.JJA)[3]))

CF.600below.netcdf[, , 1, ] <- CF.600andlower.JJA

old.pressure.levels <- pressure.levels
pressure.levels <- min(pressure.levels)
source("~/Thesis/Scripts/NetCDF/create.netcdf.file.dimensions.R")
pressure.levels <- old.pressure.levels
rm(list=c("old.pressure.levels"))

netcdf.time <- dim.def.ncdf(name="time", 
                        units="days since 1957-09-01 00:00:0.0", 
                        vals=time.entries, unlim=TRUE, create_dimvar=TRUE)
```
vals=time.entries, unlim=TRUE, create_dimvar=TRUE)

netcdf.CF <- var.def.ncdf(name="CF", units="none",
  dim=list(netcdf.lon, netcdf.lat, netcdf.lev,
    netcdf.time), missval=-1,
  longname="Capacity Factor",
  prec="double")

new.netcdf.file <- create.ncdf(filename=
  "au_CF_democraft_JJA_600hPa_and_lower.nc",
  vars=list(netcdf.CF), verbose=FALSE)

put.var.ncdf(new.netcdf.file, varid="CF", vals=CF.600below.netcdf,
  start=c(1,1,1,1), count=c(-1,-1,-1,-1), verbose=FALSE)

close(new.netcdf.file)
rm(list=c("new.netcdf.file", "netcdf.CF", "netcdf.lat", "netcdf.lon",
  "netcdf.time", "netcdf.lev"))
rm(list=c("CF.600below.netcdf"))
R Code for Calculating Downtime

# Thesis Results
# 03.08
# 03 Downtime
# 08 Analysis of downtime for the Roberts and Shepard (2003) example FEG,
# taking into account that the FEG might be able to find a lower pressure
# level with sufficient wind, by season.

# Load libraries/functions.
library(abind)

lessthan <- function(x, threshold) {
  100*length(x[x < threshold])/length(x)
}

allbelow <- function(x, nlevels) {
  100*length(x[x == nlevels])/length(x)
}

pressure.levels <- c(925, 850, 775, 700, 600)
ERA40.path <- "~/Thesis/Data/ERA-40/

molecular.weight <- 0.028966
gas.constant <- 8.3143

# Specify FEG parameters.
FEG.mass <- 520 # in kg.
rotor.area <- 4*pi*(5.35)^2 # in m^2.
tether.unit.mass <- 115/1000 # in kg/m.
g.0 <- 9.80665 # in m/s^2.
C.LWOP <- 0.615934 # Obtained from , when mu = and ac = .
tether.angle <- 40 # in degrees.

# Specify output NetCDF file names.
vmin.file.name <- "au_vmin_overall_DemoCraft.nc"
downtime.file.name <- "au_downtime_seasonal_DemoCraft_alllevels.nc"
rated.downtime.file.name <- "au_downtime_seasonal_DemoCraft_ratedlevel.nc"

# Calculate the minimum wind speed for autorotation for each pressure level.

# Calculate the mean air density and geopotential height for all the pressure
# levels below 300 hPa.
for (pressure.level in pressure.levels) {
  # Air Density.
  ERA40.filename <- paste("ERA-40_au_T", pressure.level,
                         "hPa_19570901-20020831.nc", sep="")
  cat("[", format(Sys.time(), format="%H:%M:%S", usetz=FALSE),
       "] Now opening ", ERA40.filename, ",...", sep="")
  ERA40.data <- OpenNetcdfFile("T", ERA40.filename, ERA40.path)
cat("done!\n", sep="")

  air.density <- (molecular.weight*pressure.level*100)/(gas.constant*ERA40.data)
  rm(list=c("ERA40.data"))

  mean.air.density <- apply(air.density, c(1, 2), mean)

  if (which(pressure.levels == pressure.level) == 1) {
    air.density.means <- array(NA, dim=c(dim(mean.air.density)[1],
                                        dim(mean.air.density)[2], length(pressure.levels)))
    air.density.means[, , 1] <- mean.air.density
  } else {
    air.density.means[, , which(pressure.levels == pressure.level)] <-
    mean.air.density
  }
}
rm(list=c("air.density", "mean.air.density"))

# Geopotential Height.
ERA40.filename <- paste("ERA-40-au_Z", pressure.level,
                        "hPa_19570901-20020831.nc", sep="")
cat("[", format(Sys.time(), format="%H:%M:%S", usetz=FALSE),
    "] Now opening ", ERA40.filename, " ... ", sep="")
ERA40.data <- OpenNetcdfFile("Z", ERA40.filename, ERA40.path)
cat("done!
", sep="")

geopotential.height <- ERA40.data/g.0
rm(list=c("ERA40.data"))
mean.geopotential.height <- apply(geopotential.height, c(1, 2), mean)
if (which(pressure.levels == pressure.level) == 1) {
  geopotential.height.means <- array(NA, dim=c(dim(mean.geopotential.height)[1],
                                                 dim(mean.geopotential.height)[2],
                                                 length(pressure.levels)))
  geopotential.height.means[ , , 1] <- mean.geopotential.height
} else {
  geopotential.height.means[ , , which(pressure.levels == pressure.level)] <-
    mean.geopotential.height
}
rm(list=c("geopotential.height", "mean.geopotential.height"))

# Calculate the autorotation threshold velocity for each pressure level.
tether.mass <- tether.unit.mass*geopotential.height.means/sin(pi*tether.angle/180) # in kg.
v.autorotation <- round(sqrt(((FEG.mass + tether.mass)*g.0/rotor.area)/
                           (0.5*air.density.means*C.LWOP)), 2)

export.autorotation.wind.speeds <- function

# Export the autorotation wind speeds to a NetCDF file.

# Create NetCDF dimensions.
longitudes <- seq(from=110, to=155, by=2.5)
latitudes <- seq(from=-10, to=-45, by=-2.5)

# Set up time and date index for the ERA40 datafiles.
ERA40.datetimes <- seq(from=ISOdatetime(1957, 9, 1, 0, 0, 0, "GMT"),
                        to=ISOdatetime(2002, 8, 31, 18, 0, 0, "GMT"),
                        by="6 hours")
ERA40.chrtimes <- format(ERA40.datetimes, format="%Y-%m-%d %H:%M:%S",
                           usetz=TRUE)
itime.entries <- (grep("2002-08-31 18:00:00 GMT", ERA40.chrtimes) - 1)/4
time.entries <- (c(grep("2001-09-01 00:00:00 GMT", ERA40.chrtimes),
grep("2001-12-01 00:00:00 GMT", ERA40.chrtimes),
grep("2002-03-01 00:00:00 GMT", ERA40.chrtimes),
grep("2002-06-01 00:00:00 GMT", ERA40.chrtimes)) - 1)/4

source("~/Thesis/Scripts/NetCDF/create.netcdf.file.dimensions.R")

netcdf.time <- dim.def.ncdf(name="time",
                           units="days since 1957-09-01 00:00:0.0",
                           vals=time.entries, unlim=TRUE, create_dimvar=TRUE)

# Create NetCDF variable(s).
overall.ncdf.array <- array(NA, dim=c(dim(v.autorotation)[1],
                                        dim(v.autorotation)[2],
                                        length(time.entries),
                                        length(pressure.levels)))
netcdf.time <- dim.def.ncdf(name="time",
                           units="days since 1957-09-01 00:00:0.0",
                           vals=time.entries, unlim=TRUE, create_dimvar=TRUE)
overall.ncdf.array <- array(NA, dim=c(dim(v.autorotation)[1],
                                        dim(v.autorotation)[2],
                                        length(time.entries),
                                        length(pressure.levels)))
dim(v.autorotation)[2],
length(pressure.levels),
length(time.entries)))

overall.ncdf.array[, , , 1] <- v.autorotation

netcdf.vmin <- var.def.ncdf(name="vmin", units="m s^-1",
    dim=list(netcdf.lon, netcdf.lat, netcdf.lev, netcdf.time), missval=-1,
    longname="minimum wind speed for autorotation",
    prec="double")

# Set the output folder for the NetCDF file by changing working directory.
setwd("~/Thesis/Data/Results/")

#new.netcdf.file <- create.ncdf(filename=vmin.file.name, vars=list(netcdf.vmin), verbose=FALSE)
#put.var.ncdf(new.netcdf.file, varid="vmin", vals=overall.ncdf.array, start=c(1,1,1,1), count=c(-1,-1,-1,-1), verbose=FALSE)
#close(new.netcdf.file)

# Clean up.
rm(list=c("new.netcdf.file", "overall.ncdf.array", "netcdf.vmin"))

# For each pressure level, count the occasions when the wind speed is below the threshold velocity.
for (pressure.level in pressure.levels) {
    # Wind Speed.
    ERA40.filename <- paste("ERA-40_au_v_", pressure.level, "hPa_19570901-20020831.nc", sep="")
    cat("[", format(Sys.time(), format="%H:%M:%S", usetz=FALSE), "] Now opening ", ERA40.filename, ", ... ", sep="")
    wind.speed <- OpenNetcdfFile("v", ERA40.filename, ERA40.path)
    cat("done!
", sep="")

    level.index <- which(pressure.levels == pressure.level)
    if (level.index == 1) {
        below.threshold <- array(NA, dim=c(dim(wind.speed)[1], dim(wind.speed)[2], length(pressure.levels), dim(wind.speed)[3]))
    }

    for (i in 1:dim(wind.speed)[1]) {
        for (j in 1:dim(wind.speed)[2]) {
            below.threshold[i, j, level.index, ] <- as.numeric(wind.speed[i, j, ] < v.autorotation[i, j, level.index])
        }
    }

    rm(list=c("wind.speed"))
}

# below.all.thresholds <- array(NA, dim=c(dim(below.threshold)[1],
# dim(below.threshold)[2],
# dim(below.threshold)[3],
# 4))
below.summary <- array(NA, dim=c(dim(below.threshold)[1],
                           dim(below.threshold)[2],
                           4))

below.vmin.ratedlevel <- array(NA, dim=c(dim(below.threshold)[1],
                                             dim(below.threshold)[2],
                                             4))

for (m in 1:4) {
  cat("\n[", format(Sys.time(), format="%H:%M:%S", usetz=FALSE),
       "] m = ", m, "\n\n", sep="")
  if (m==1) {
    # 1 = Spring
    season.index <- sort(c(grep("^-09-", ERA40.chrtimes), grep("^-10-",
                              ERA40.chrtimes), grep("^-11-", ERA40.chrtimes)))
  } else if (m==2) {
    # 2 = Summer
    season.index <- sort(c(grep("^-12-", ERA40.chrtimes), grep("^-01-",
                              ERA40.chrtimes), grep("^-02-", ERA40.chrtimes)))
  } else if (m==3) {
    # 3 = Autumn
    season.index <- sort(c(grep("^-03-", ERA40.chrtimes), grep("^-04-",
                              ERA40.chrtimes), grep("^-05-", ERA40.chrtimes)))
  } else if (m==4) {
    # 4 = Winter
    season.index <- sort(c(grep("^-06-", ERA40.chrtimes), grep("^-07-",
                              ERA40.chrtimes), grep("^-08-", ERA40.chrtimes)))
  } else {
    # Error
    season.index <- c(0)
  }

  # Count the number of occasions when the wind is below the threshold at all
  # pressure levels.
  cat("\n[", format(Sys.time(), format="%H:%M:%S", usetz=FALSE),
       "] Adding up downtime events across all pressure levels...
\n", sep="")
  below.all.thresholds <- apply(below.threshold[, , , season.index],
                                 c(1, 2, 4),
                                 allbelow, nlevels=length(pressure.levels))
  cat("\n[", format(Sys.time(), format="%H:%M:%S", usetz=FALSE),
       "] Finished adding up downtime events across all pressure levels.
\n", sep="")

  # Calculate the downtime as a percentage of the total ERA40 time period.
  cat("\n[", format(Sys.time(), format="%H:%M:%S", usetz=FALSE),
       "] Calculating percentage of total time...\n", sep="")
  below.summary[, , m] <- apply(below.all.thresholds,
                                 c(1, 2),
                                 allbelow, nlevels=length(pressure.levels))
  cat("\n[", format(Sys.time(), format="%H:%M:%S", usetz=FALSE),
       "] Finished calculating percentage of total time.\n", sep="")

  # Calculate the percentage of time the wind is below the autorotation wind
  # speed at the rated pressure level.
  below.vmin.ratedlevel[, , m] <- apply(below.threshold[, ,
                                         which(pressure.levels == min(pressure.levels)), season.index],
                                         c(1, 2),
                                         allbelow,
                                         nlevels=1)

  # Clean up.
rm(list=c("below.all.thresholds"))
}

# Export the time spent below autorotation wind speed at the rated pressure level to a NetCDF file.

# Create NetCDF dimensions.
# (Time dimensions does not need to be made, since it was created earlier.)

# Need to re-generate the pressure level object to contain only the highest pressure level (which is the lowest value).
old.pressure.levels <- pressure.levels
pressure.levels <- min(pressure.levels)
source("~/Thesis/Scripts/NetCDF/create.netcdf.file.dimensions.R")
pressure.levels <- old.pressure.levels
rm(list=c("old.pressure.levels"))

# Create NetCDF variable(s).
overall.ncdf.array <- array(NA, dim=c(dim(below.vmin.ratedlevel)[1],
                                                dim(below.vmin.ratedlevel)[2],
                                                1, length(time.entries)))
overall.ncdf.array[, , 1, ] <- below.vmin.ratedlevel

netcdf.down <- var.def.ncdf(name="p", units="%",
                             dim=list(netcdf.lon, netcdf.lat, netcdf.lev,
                                      netcdf.time),
                             missval=-1,
                             longname="Percentage of year below autorotation speed",
                             prec="double")

# Set the output folder for the NetCDF file by changing working directory.
setwd("~/Thesis/Data/Results/")
new.netcdf.file <- create.ncdf(filename=rated.downtime.file.name,
                                vars=list(netcdf.down), verbose=FALSE)
put.var.ncdf(new.netcdf.file, varid="p", vals=overall.ncdf.array,
             start=c(1,1,1,1), count=c(-1,-1,-1,-1), verbose=FALSE)
close(new.netcdf.file)

# Clean up.
rm(list=c("new.netcdf.file", "overall.ncdf.array", "netcdf.down"))

# Create an overall (entire time series) NetCDF file.

# Create NetCDF dimensions.
# (Time dimensions does not need to be made, since it was created earlier.)

# Need to re-generate the pressure level object to contain only the highest pressure level (which is the lowest value).
old.pressure.levels <- pressure.levels
pressure.levels <- min(pressure.levels)
source("~/Thesis/Scripts/NetCDF/create.netcdf.file.dimensions.R")
pressure.levels <- old.pressure.levels
# Create NetCDF variable(s).
overall.ncdf.array <- array(NA, dim=c(dim(below.summary)[1],
                                dim(below.summary)[2],
                                1, length(time.entries)))
overall.ncdf.array[, , 1, ] <- below.summary
netcdf.down <- var.def.ncdf(name="p", units="\%",
                            dim=list(netcdf.lon, netcdf.lat, netcdf.lev,
                                     netcdf.time),
                            missval=-1,
                            longname="Percentage of year below autorotation speed",
                            prec="double")

# Set the output folder for the NetCDF file by changing working directory.
setwd("~/Thesis/Data/Results/")
new.netcdf.file <- create.ncdf(filename=downtime.file.name,
                                vars=list(netcdf.down), verbose=FALSE)
put.var.ncdf(new.netcdf.file, varid="p", vals=overall.ncdf.array,
            start=c(1,1,1,1), count=c(-1,-1,-1,-1), verbose=FALSE)
close(new.netcdf.file)

# Clean up.
rm(list=c("new.netcdf.file", "overall.ncdf.array", "netcdf.down"))

R Code for Reading ERA-40 Data

This function is used to read in to R the ERA-40 data which is encoded in the NetCDF binary file format. The ncdf package (Pierce, 2015) was used for this purpose.

OpenNetcdfFile <- function(variable.type, file.name, folder.name) {
  require(ncdf)
  stopifnot(variable.type == "u" ||
            variable.type == "v" ||
            variable.type == "Z" ||
            variable.type == "d" ||
            variable.type == "P" ||
            variable.type == "T" ||
            variable.type == "S" ||
            variable.type == "U" ||
            variable.type == "V" ||
            variable.type == "P")
  full.path <- paste(folder.name, file.name, sep="")
  stopifnot(file.exists(full.path) == TRUE)
  raw.data <- open.ncdf(full.path, write=FALSE, readunlim=FALSE, verbose=FALSE)
  netcdf.data <- get.var.ncdf(raw.data, varid=variable.type)
  netcdf.data
}
D. R Code Used for Analysis
Author/s: Kambouris, Steven

Title: The Flying Electric Generator: evaluating the claims of a largely ignored proposal for generating electricity from high-altitude winds

Date: 2015

Persistent Link: http://hdl.handle.net/11343/91085

File Description: The Flying Electric Generator: Evaluating the claims of a largely ignored proposal for generating electricity from high-altitude winds