# Uninterrupted Power from Wind for an Off-grid Communication Setup

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# Abstract

This research aims to assess suitability of a micro wind turbine and energy storage for the task of providing uninterrupted power to a remote standalone communications setup. A literature study has been utilized to understand key theories and developments in the field. Remote micro-wind turbines have the potential to substantially reduce carbon emissions. Although larger wind installations and hybrid solar/wind applications have received a great deal of academic attention, micro-wind on its own is under-investigated. The study uses the initial SpaceX Starlink release parameters including location restrictions and power requirements to guide the scope of the research. Four locations within these guidelines are chosen in mainland Australia below -32 degrees latitude. Wind turbines of varying sizes and heights are then modelled for each location and an electrical load of less than 400W for 24hr and 12hr scenarios. The modelling shows reliable power generation even from a 2.5 metre diameter turbine coupled with Lead Acid storage, particularly in the South-West of the continent where a more significant wind resource exists. Costs and energy production are compared to photovoltaic solar and diesel generator. A Weighted Sum Model (WSM) Multi-Criteria Analysis (MCA) is used to view the results within the context of the modern energy landscape.

*Keywords*: wind turbines, WECS, communications, renewables, sustainability, Homer Pro, Starlink, MCA, WSM

Limitations of Use

University of Southern Queensland

Faculty of Health, Engineering and Sciences

ENG4111 & ENG4112

Research Project

# Limitations of Use

# Certification

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Tom Raymond

Student [redacted]

# Acknowledgements

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# 1 Introduction

## 1.1 Introduction

This study aims to ascertain the suitability of an off-grid Wind Energy Conversion System (WECS) to provide on-demand power for a communications setup. Having access to a reliable high-bandwidth, communication setup in remote areas enables a range of possibilities that may have been previously impossible. Automation utilising GPS navigation is increasingly popular for remote agriculture or mining however manual intervention is still necessary in many cases, for example, for enhanced safety management and navigation of a vehicle should it need to cross a public road. Increased bandwidth communications systems could help overcome these limitations thus inviting investigation of sustainable, reliable power sources. Higher bandwidth communications could allow increased complexity of data logging and sensor arrays for pursuits such as forestry or nature conservation, also prevalent in remote areas, or enable emergency infrastructure like VOIP highway phones or bushfire early warning systems. According to the Australian Renewable Energy Agency (ARENA), two percent of Australia's population live in off-grid areas however more than six percent of energy usage occurs there, indicating that the potential for renewable technologies to make an impact in these areas is not insignificant (Australian Renewable Energy Agency, 2021). Traditionally, in remote areas diesel has been used for power generation with the associated issues of carbon footprint, transport logistics and ongoing cost. Transmission of grid power to a limited customer base is less viable due to; (i) the initial expense of infrastructure and (ii) the ongoing expense of transmitting electricity over long distances as energy losses scale with the square of the current. In these areas, renewable technologies have potential to not only reduce emissions but provide a cheaper and simpler alternative to fossil fuels. Although hybrid standalone renewable power generation such as the use of both solar and wind energy generation combined with a battery is increasing in popularity, this study aims to ascertain whether the combination of wind energy and an appropriate storage medium alone is sufficient to provide constant power given the smaller scale of power required for a communication system. Although changing, it is accepted that when compared to grid-connected, invariable speed turbines there has been "insufficient review and comparative study on off-grid WECS" (Alnasir & Kazerani, 2013, p. 598).

The newly available Starlink model from SpaceX has been chosen as a communications system case study. Released in Australia in 2021, SpaceX's Starlink uses a grid of near-earth orbit satellites and steerable phased-array antennas specifically aimed at providing high-speed internet to remote customers (Purtill, 2021). The higher data speeds are attributable to the reduced distance of the near-Earth, satellite grid when compared with traditional geosynchronous orbit.

## 1.2 Project Brief

The overall aim of this study is to determine whether a micro wind turbine and some form of energy storage is **suitable** to power a Starlink communication setup in four potential remote Australian mainland locations below -32 degrees of latitude (as per the initial Starlink release location restrictions). Suitability is treated as a multifactorial concept including not only the technical ability to provide the requisite power but also factors such as environmental, social or lifecycle concerns that the responsible modern engineer must consider.

A literature study is used to situate this study within the existing body of knowledge. Particular emphasis is given to modern methods of qualitative infrastructure comparison such as Multi-Criteria Analyses. Modelling of the wind and turbine including sizing of the storage are completed using Homer Pro software and the method employed by Homer Pro explained with reference to established wind turbine theory.

## 1.3 Research Objectives

This study has the following objectives:

- To review available literature pertaining to the design requirements of modern, small Wind Energy Conversion Systems (WECS) and energy storage mediums
- To review available literature pertaining to qualitative, multifactorial assessment of renewable technologies and compare alternatives
- To analyse the system requirements for a simple Starlink communications setup and determine design goals with regard to load profile and hours of autonomy
- To choose 4 locations for which wind data will be analysed. Ideally these locations will represent a broad range of conditions that may affect wind energy conversion such as altitude and proximity to the coast. They will have at least 10 years of historic wind data available to produce an accurate model. The locations will need to correlate with the limited Starlink initial 2021 availability in Australia.
- To quantitively ascertain viability of micro-wind plus storage using Homer Pro. This process will take into account cost and technical fitness for purpose
- To qualitively assess suitability of the topology in comparison with alternatives using Multi-Criteria Analysis
- To give a definitive answer on whether a micro turbine and storage is a suitable power source for a remote communications setup in light of the Multi-Criteria Analysis and Homer Pro results

## 1.4 Consequential Effects of Study

It is desired that any effects that this study may have are of benefit to society and as such will be carried out in strict adherence to the Engineer's Australia Code of Conduct. Whilst it is acknowledged that the reception of this project will likely be limited, all due care has been taken to ensure that:

- the information presented here is honestly and professionally presented
- the research, facts and suppositions of the study are undertaken and tendered as competently as possible
- efforts were made to consult with peers, professionals and stakeholders alike, taking into account the reliance of others on engineering expertise
- safety is paramount in the scenarios considered
- the tenets of sustainability are at the core of the study

An increased need for engineering sustainability is one of the main motivations to carry out this study. The need to find carbon neutral alternatives to fossil fuels has been made clear with each successive IPCC (Intergovernmental Panel for Climate Change) report, the most recent describing the global warming situation as a Code Red for the planet (IPCC, 2021). The potential to replace diesel power generation in remote locations is worth investigating for this reason. Although solar panels are a cleaner alternative to diesel or coal and have demonstrated greater uptake than small scale wind, especially in Australia, there are concerns with toxicity and end of lifecycle disposal for photovoltaics (Xu, Li, Tan, Peters, & Yang, 2018). Given the inevitable popularity of the Starlink internet model, case studies such as illustrated here which explore scenarios on the use of wind generation to power a remote communications set up, ensure that information considered is at the cutting-edge of available information to inform and further empower decision-making regarding the use of cleanest power sources possible.

## 1.5 Safety Issues

A formal analysis of safety issues associated with the completion of this study has been carried out as per university guidelines and in accordance with the Work Health and Safety Act 2011(Federal Register of Legislation, 2018). A sample of the risk assessment is included (see Appendix A) in this document and has been lodged with the university via the Online Risk Management System.

The project scope has been selected for its low risk profile. Initial plans to build and test a physical prototype have been altered in favour of software modelling with a goal of risk minimization. There is no human research taking place and thus no ethics study.

The potential for damage to person and property from acting on the results or findings of this study are addressed in the Limitations of Use above and the author has striven to display the integrity required of a professional engineer as per the Engineers Australia Code of Conduct.

## 1.6 Resource Requirements

Resources required:

- Internet and library access for research and word processing
- Software including Homer Pro for simulation and calculation
- Access to online wind resources for further modelling. For wind records older than 14 months from the Bureau of Meteorology costs are accrued. Historical wind data of at

least ten years is preferred as the more wind data available, the more accurate the model

- An initial idea to construct a physical prototype from recycled materials has been discarded in the interests of risk mitigation and as the location parameters for the study have changed

## 1.7 Timeline

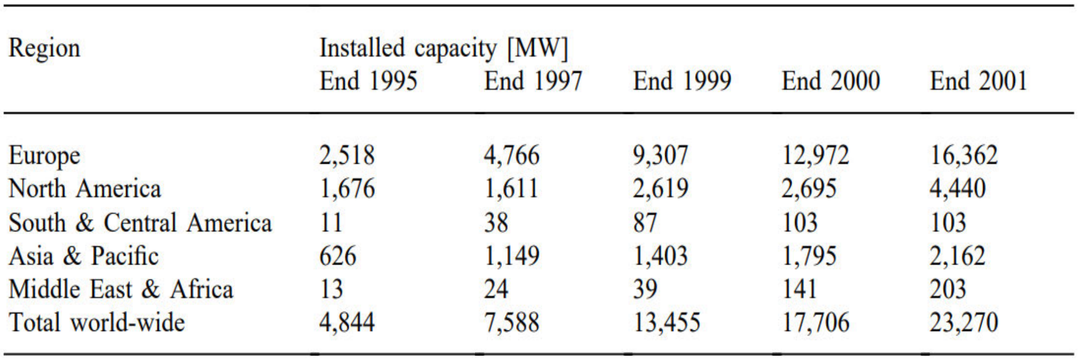
In keeping with university guidelines, this study has taken place over the course of a year. Project tracking including project scope, has been monitored to ensure that the project goals were achievable and delivered on time. All due care and attention has been accorded to the principles of organization and self-discipline. For a cascaded planning document please see Appendix B.

# 2 Literature Review

## 2.1 Historical Overview

Wind Energy Conversion Systems have existed for at least 3,000 years and experienced early popularity in the 1800s with as many as 20,000 units existing in France alone. With the introduction of steam power and industrialisation this popularity waned however concerns over oil scarcity in the 1970's prompted more serious investigation for the task of electricity generation. By the 1990s, wind power had become the fastest growing energy production technology and can now generally be considered a mature technology (Ackermann & Söder, 2002, p. 71).

Table 1: Installed wind capacity showing global industry growth throughout the 1990s



| Region | Installed capacity [MW]<br>End 1995 | End 1997 | End 1999 | End 2000 | End 2001 |
|---|---|---|---|---|---|
| Europe | 2,518 | 4,766 | 9,307 | 12,972 | 16,362 |
| North America | 1,676 | 1,611 | 2,619 | 2,695 | 4,440 |
| South & Central America | 11 | 38 | 87 | 103 | 103 |
| Asia & Pacific | 626 | 1,149 | 1,403 | 1,795 | 2,162 |
| Middle East & Africa | 13 | 24 | 39 | 141 | 203 |
| Total world-wide | 4,844 | 7,588 | 13,455 | 17,706 | 23,270 |

(Figures sourced from the Windpower Monthly industry publication (published since 1985) as per Ackermann & Soder (2002, p74)).

Turbine blades originally mimicked that of aeronautical aerofoils however have experienced much optimization to the current day (S. Larry Dixon & Hall, 2010, p. 362). Many of these designs are intellectual copyright however design particulars also exist in the public domain thanks to the efforts of organisations such as the US funded National Renewable Energy Laboratory or NREL (S. Larry Dixon & Hall, 2010, p. 363). The Homer Pro software used for analysis in this study is produced by the NREL and allows modelling using power curves specific to a range of commercially available turbines.

## 2.2 Wind Turbine Technology.

A great variety of wind turbine designs exist. As conditions at each prospective site can vary considerably, variations in design can maximise wind energy capture efficiency in each scenario. While aerofoil optimisation is not the goal of this study, an understanding of blade element theory and aerodynamics is necessary to inform judgement on wind power potential. This section will look at some of these variations and the strengths and weaknesses that they may offer.

### *2.2.1 Drag vs Lift.*

The basic principles of harvesting wind energy have been in use by humans for centuries. An example of this, the sailboat, can be used to illustrate two important concepts. In one configuration, a sailboat travelling in the direction of the wind with its spinnaker unfurled is using drag force and cannot exceed the speed of the wind. In the second configuration, with the sails placed at an optimum angle with respect to the approaching wind (the angle of attack, α, usually around 3-5 degrees) it is possible to exceed the speed of the wind powering the vessel despite travelling in the opposite direction. This principle of lift underpins the design of the aerofoil, a classic shape also utilised in aeroplane wings. It is also the reason that lift type turbine designs (these turbine blades are also called aerofoils) are the most common as the ability to rotate faster than the available wind correlates with the potential for more generated power.

Turbines can be categorised into those that use mainly lift or drag forces to propel their blades. While popular commercial turbines tend to utilise lift forces, there are designs that employ drag. A good example is that of the cup anemometer which is commonly used for measurements of wind speed using the drag force enacted on 3 cups on a vertical axis. This design is used for the nearly linear relationship between rotational frequency and wind speed.

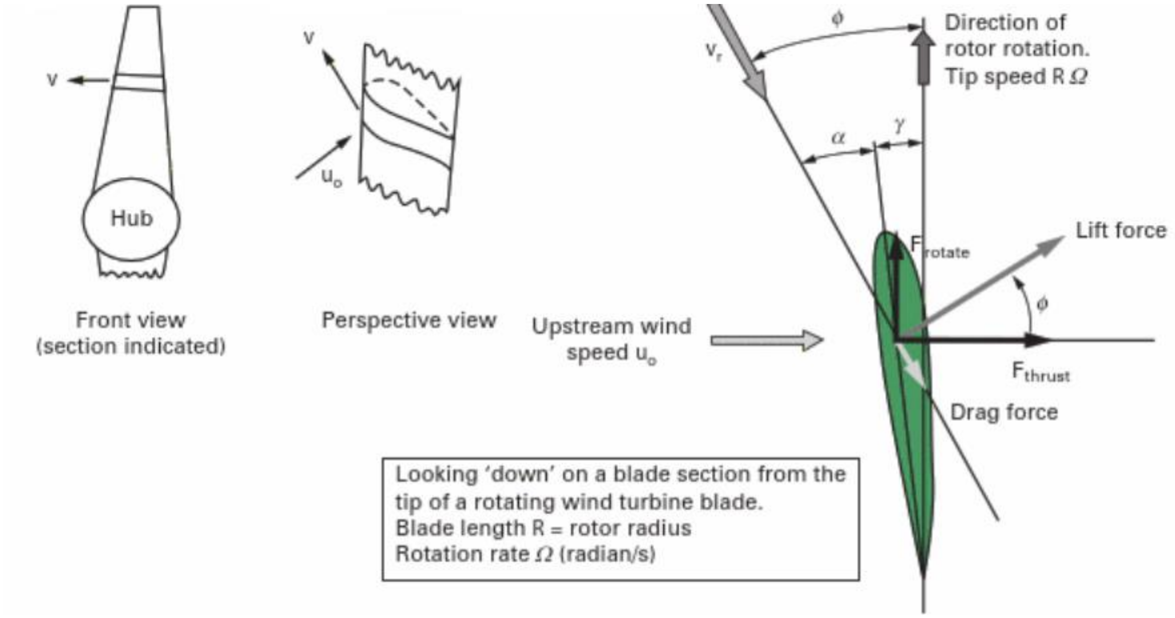


Figure 1. Drag vs Lift (Twidell & Weir, 2015)

### *2.2.2 Axis of Rotation*

Another element of categorization is the position of the axis of rotation. Turbines can be classed as either HAWT (Horizontal Axis Wind Turbines) or VAWT (Vertical Axis Wind Turbines). The predominance of commercial designs are HAWT however VAWT designs are sometimes used such as the Darrieus, Savonius or Musgrave type turbines, each with different strengths and weaknesses. The Savonius type uses mainly drag forces and has a high starting torque whilst the Musgrave rotor is designed with the ability to furl in high winds to prevent damage. Although VAWT turbines can operate consistently without regard for wind direction, a number of other disadvantages exist including torque fluctuations, poor self-start, poor speed regulation and the unequal vertical distribution of wind force (S. Larry Dixon & Hall, 2010, p. 326). These issues have led to their use declining since the 1980's (Ackermann & Söder, 2002).

### *2.2.3 Solidity and Tip Speed*

The reason for the high starting torque of the Savonius rotor is a high solidity. Solidity is defined as the ratio of the total area of the blades to the swept area. A higher solidity will give a lower tip speed however a greater startup torque and potentially earlier cut-in (the minimum wind speed at which the turbine can start generating power). For turbines with a design focus of constant power as opposed to maximizing capture of higher velocity winds (such as a water pump), a multi-bladed (ie high solidity) turbine design will often be preferred. A high tip speed can allow the most efficient rotational velocity of a generator to be reached using a lighter gearbox or direct drive (Ackermann & Söder, 2002, p. 86).

### *2.2.4 Steering*

For a HAWT turbine to capture the full strength of the available power in the wind, it must be facing directly into the oncoming airstream (not a problem for VAWT designs). There are three ways this steering might be accomplished; passively, actively or with power. Without a doubt, the passive design is the cheapest and simplest requiring only a vane/fan tail to turn the turbine into the wind. Active steering using another rotor or rotors or a gear driven rotation are also in existence however add cost and complexity. Active steering gives the option of steering out of high winds to protect the turbine. Positioning the blades downwind of the nacelle can be used to create passive steering without the need for a fan tail however an upwind design displays a lower noise level and does not suffer from the tower blocking the wind (S. Larry Dixon & Hall, 2010, p. 328)

### *2.2.5 Diffusers and Augmenters*

Finally, many studies show that the use of diffusers and augmenters can influence the range of operation wind speeds as well as the energy extraction efficiency. These types of concentrating structures are not generally used on large commercial type wind turbines due to the expense at that scale however may show promise for smaller installations. Using a combination of BEM (Blade Element Momentum Theory) and CFD (Computational Fluid Dynamics) for simulation as well as wind tunnel trial testing, Kesby et al have shown that efficiencies can be boosted using the addition of a diffuser (Kesby, Bradney, & Clausen, 2017). Joss Kesby and colleagues have since commenced operation with a company called Diffuse Energy (https://www.diffuse-energy.com/) that creates micro wind turbines (six bladed, horizontal axis, downwind style passive yaw with diffuser) for a variety of uses including communication systems in Australia. Their work is of considerable importance to this study.

### *2.2.6 Environmental Considerations, Materials and Lifecycle, Noise and Aesthetics*

Wind turbines can be made from completely recycled materials or sustainable materials such as laminated bamboo (especially at a smaller scale) and have a lifespan of over 30 years. They have zero carbon dioxide or particulate emissions in operation, they can be erected anywhere and do not interfere with most other land uses. Their utilization represents a reduction of transport costs, increased national energy security, a conservation of water, reduction of mining, shorter commissioning times and diversification of the power supply (Letcher, 2017, p. 8). Nevertheless, there are aspects of their installation and manufacture that can still be improved or that might be considered negative. Installing wind turbines in natural environments can be visually disruptive and larger windfarms often bring with them the problems of erosion and flooding from access roads (Weeks, 2003, p. 71). Another valid argument against wind power is that societally a focus on the reduction of consumption is as important as installing clean power, especially given the stringent timelines given by the latest IPCC report for emission reductions (IPCC, 2021).

The aesthetic merit has also been discussed regarding specific designs with reports that three bladed wind turbines are considered more aesthetically pleasing than two and deliver a lower noise level (Ackermann & Söder, 2002, p. 87). It must be noted here that by its nature, a wind turbine must protrude from the scenery whilst perhaps the closest clean energy competitor, photovoltaic panels, are far less obtrusive visually. Photovoltaic panels however have their own concerns environmentally both at point of manufacture and at end of life (Xu et al., 2018). Noise production and electromagnetic interference are also of concern with wind turbines and flying creatures such as birds and bats can be critically impacted.

Many of these issues are minimized by the small scale of the proposed wind turbine and most discussion of potential negative impacts refers to larger installations. A large windfarm is much more likely to have adverse effects visually, acoustically and on wildlife. Care with placement of small wind turbines is still recommended for the least impact to native fauna (Minderman, Gillis, Daly, & Park, 2017) and optimization of design for quiet operation is worthy of investigation.

### *2.2.7 Safety Engineering.*

#### ***2.2.7.1 Over-rotation Protection***

When designing a WECS, it is important to take into account peak wind velocity and design safeguards for high winds. These safeguards are not only for the safety of the turbine equipment but people in the vicinity as well. This is especially necessary given that a one in fifty year gale will be five to ten times the average wind speed (Twidell and Weir, 2015, p270). A wind turbine will be designed with certain specifications in mind including a rated wind speed (which is the maximum speed a turbine generator can rotate consistently without suffering heat damage) and a maximum wind speed (above which the turbine will almost certainly suffer catastrophic failure). Twidell and Weir (2015, p283) mention four options for avoiding damage to the turbine in high winds:

1. Yaw the rotor
2. pitch the blades or extend spoil flaps
3. design blades to be self-stalling in high wind
4. stop rotation by pitching or braking

The most common and cheap option of these four for a micro wind setup involves yawing the rotor. This is commonly achieved by furling which is where the angle of the sail is changed (sometimes automatically in high wind) thus yawing the turbine to a position relative to the wind that decreases rotation and captured wind. Furling can also be achieved vertically so that the furled rotor appears as a helicopter (Ackermann & Söder, 2002, p. 108). Self-stalling blades have the disadvantage that they may not be able to capture as much of the wind as possible (decreasing efficiency) whilst options such as active blade pitch control are cost prohibitive for smaller systems.

Being able to brake the turbine is a necessity when needing to maintain the system however adds complexity and weight. The turbine can be braked with a physical disc brake or electromagnetically depending on the generator and control setup. Braking the rotor can be achieved with a dump load.

#### *2.2.7.2 Maintenance and Monitoring*

Maintenance and monitoring of turbine operating conditions is critical over the life of the turbine. The advent of cold weather can produce blade icing and consequently ice throw, representing a personal safety hazard. Icing will also alter the aerodynamic qualities of the aerofoil reducing efficiency. Brittle fractures and insufficient lubrication are also possible and can result in the system being inoperable for extended periods if in a remote area. Correct choice of componentry and location as well as scheduled maintenance is essential.

#### *2.2.7.3 Electrical Safety*

The need for electrical safety and protections must also be considered. Preventing damage or injury from electrical fault requires careful consideration commensurate with the level of voltage/amperage that the system ends up employing. Installation to professional standards and legal requirements is mandatory. It is assumed that all effort is made to adhere to relevant safety standards and electrical danger is minimized.

#### *2.2.7.4 Forces acting on the turbine*

Understanding the forces acting on the turbine are important when attempting to create safe structures and prevent damage to person and property. The axial thrust on the turbine is presented in the following equation:

$$F_A = \left(\frac{1}{2}\rho A_1 u_0^2\right) C_F$$

where $A_1$ is the swept area of the turbine and another term is introduced, $C_F$, the axial force or thrust coefficient.

$$C_F = 4a(1 - a)$$

In accordance with the equation above, $C_F$ has a max of 1 when $a = 0.5$.

Completing the required force analysis to select a strong, safe tower structure with enough guy wires and correct materials and tensile strengths to survive all predicted wind speeds (including a decent safety factor) is a necessity. In this aspect, a remote location and the need to locate the turbine away from both turbulence-creating infrastructure and the Starlink dish (to avoid electromagnetic and line-of-sight interference) is a positive requirement. Although Australian government websites do not have a dedicated code for small wind turbines (https://www.yourhome.gov.au/energy/wind-systems), it is assumed that the turbine and structures would be built to all required standards and will not be the focus of this study.

## 2.3 Theory

### *2.3.1 Actuator Disc Approach*

The mathematical expressions used to describe capturing and converting wind energy into another form of energy are derived from linear momentum theory and thermodynamic concepts that are well understood and covered in multiple textbooks regarding renewable resources. The complete derivation of these expressions will be omitted, however important equations, variables and constants that will be used in creating the simulation are included below. The nomenclature used in this document is the same as that used in Twidell and Weir (Twidell & Weir, 2015).

A simple but common modelling technique is to imagine the turbine as an actuator disc within a laminar stream tube.

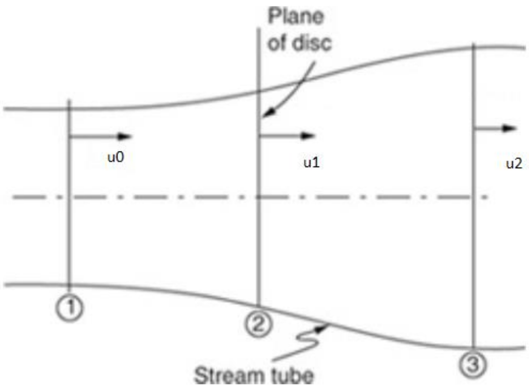


Figure 2. Diagram of Actuator Disc approach to turbine modelling (S. L. Dixon, 1998). Nomenclature as per Twidell & Weir (2015). The axial velocities are defined far upstream (u0) and far downstream (u2).

Using the actuator disc method, the power in the wind in Watts per unit area can be found using the following formula:

$$P_O(W) = \frac{1}{2}\rho {u_0}^3$$

where $u_0$ is the speed of the wind approaching the turbine and ρ is the designation for the density of air at the location. The power that a turbine can extract from this wind is given by:

$$P_T(W) = \frac{1}{2}\rho\big((\pi D^2)4\big)(\overline{u_0})^3 C_P$$

where D is the diameter of the wind turbine. $C_P$ is a term called the power coefficient. The power coefficient is a dimensionless term which describes "the efficiency of extracting power from the mass of air in the supposed stream tube" (Twidell and Weir, 2015, p280). It can be derived from another term, a, or the axial induction factor.

$$C_P = 4a(1-a)^2 = P_T/P_O$$

The axial induction factor is predicted by modelling theory and given by:

$$a = (u_0 - u_1)/u_0$$

where $u_0$ is the wind speed before the turbine and $u_1$ is the wind speed at the imaginary actuator disc. If using the speed of the wind after passing through the turbine ($u_2$):

$$a = (u_0 - u_2)/2u_0$$

It has been noted that for most practical, existent HAWTs, the value of $a$ rarely exceeds 0.6 (S. Larry Dixon & Hall, 2010, p. 337).

### *2.3.2 Betz Limit*

The introduction of a, the axial induction factor leads to an important limitation of all current WECS known as the Betz criterion or Betz limit. As the power coefficient ($C_P$) is dependent on the axial induction factor (a), it has a theoretical maximum of 0.593 or 59.3% which can be proven by differentiating the power coefficient with respect to the axial induction factor. The physical explanation for this limit is that air in the stream tube must have enough kinetic energy to leave the turbine region once energy is transmitted to the turbine blades. Turbine efficiencies are consequently often given relative to the Betz criterion. German physicist, Alfred Betz, used a simplified version of the actuator disc process to conceptualise this limit in 1926 (S. Larry Dixon & Hall, 2010, p. 330). In reality, a power coefficient approaching the Betz Limit is actually very hard to achieve with values above 0.45 being possible only with considerable engineering effort devoted to blade design.

### *2.3.3 Criticism*

The assumptions made here are that the flow is steady and uniform upstream and at the disc, there is no flow rotation produced by the disc, the flow remains within the stream tube and is incompressible. Whilst these simplifications are very useful, they disregard edge effects and turbulence, running the risk of oversimplifying data for more rigorous design investigation. The unavoidable swirl losses omitted by Betz can account for large irregularities especially in turbines exhibiting a low tip speed ratio (Ackermann & Söder, 2002, p. 84).

### *2.3.4 BEM*

The Blade Element method is typically used when designing the geometry of an aerofoil. The approach is well described by Dixon and involves iteratively evaluating the flow induction factors (S. Larry Dixon & Hall, 2010, p. 346). This type of analysis is an in-depth field outside the scope of this study typically involving the use of Computational Fluid Dynamics (CFD) and wind tunnels to prove hypotheses. Incremental improvements in blade design have contributed to increased efficiency in wind turbines and blade design can have a critical effect on a turbine's effective envelope of operation.

### *2.3.5 Tip Speed*

Tip speed (λ) is often mentioned in turbine specifications and is given by:

$$\lambda = \Omega R$$

Where Ω is the angular velocity in radians and R designates the radius of the turbine swept area. Tip speed is especially important when considering frequency control and designing the most efficient blades possible, often in conjunction with α, the angle of attack.

On high wind speed sites, it is common for smaller rotor diameters to be employed with an aerodynamic profile that will reach the maximum efficiency between 14–16 m/s whereas lower wind speeds will benefit from a larger diameter rotor with peak efficiency at a lower wind speed.

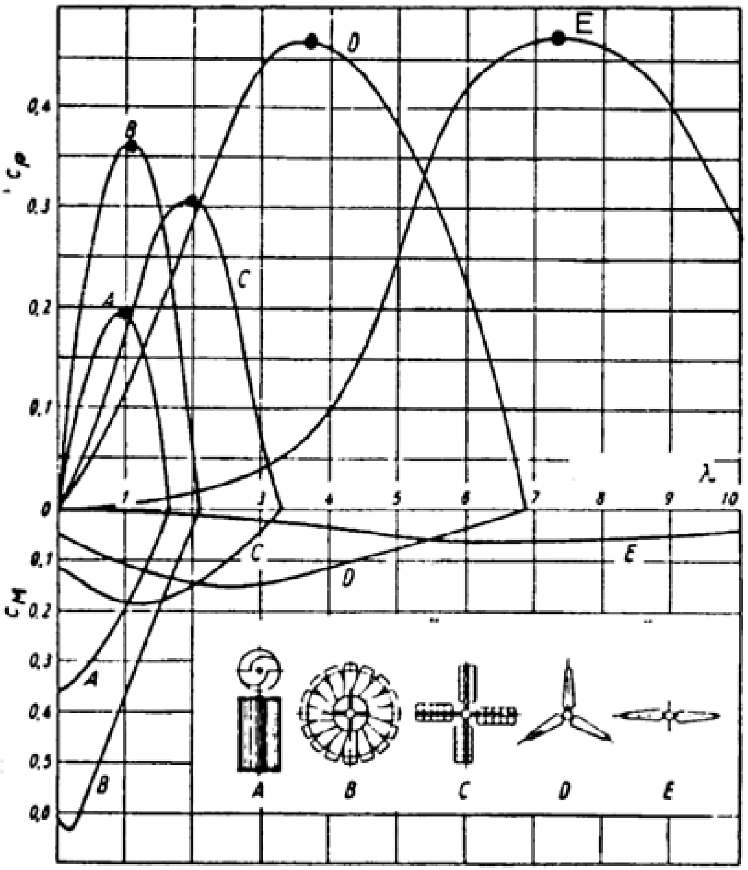


Figure 3: Tip Speed vs Power Coefficient for different blade configurations

Gasch (2002, p 163) gives this illustrative diagram which clearly indicates the relationship of solidity and the power coefficient to tip speed and how this effects the design envelope (Ackermann & Söder, 2002, p. 86). A high tip speed ratio is also less likely to suffer from misleading modelling as swirl losses are not as prevalent.

### *2.3.6 Location Aspects*

Wind shear refers to the considerable variation of wind speed with height. As weather stations typically measure at 10 metres ($u_s$), an estimate of wind speed at an alternative height can be attained if necessary with:

$$u_Z = u_s\left(\frac{z}{10m}\right)^{b'}$$

where z is the new proposed height above ground and b’ is an interference factor. For open sites with a good fetch and little obstruction, b’ will be a value of around 0.14. The more obstruction and the closer to ground the turbine is positioned, the more turbulence and less efficiency the WECS will experience. This formula is not a substitute for careful measurements taken at the correct height for prospective sites. Local topography and other variability in the local terrain such as surface roughness exert a major influence on wind speed and wind variability. Wind speed varies with height and with the shape and roughness of the terrain. Wind speed decreases with an increasingly rough surface cover, but can be accelerated over steep hills, reaching a maximum at the crest and then separating into zones of turbulent air flow. There are also thermal effects and funnelling which need to be considered when assessing wind resources. All of these effects impact on capacity factors (Coppin et al. 2003; ESIPC 2005).

### *2.3.7 Statistical Wind Model*

Although over longterm intervals the wind resource is generally stable, it is still very difficult to exactly predict, thus statistical calculations are necessary to try and ascertain the potential of prospective sites prior to any investment of capital. The two most common distributions are Weibull and Rayleigh. The formula for a Weibull distribution is:

$$\phi_u = \frac{k}{c}\left(\frac{u}{c}\right)^{k-1} \exp\left[\left(-\frac{u}{c}\right)^k\right]$$

where k is the dimensionless shape factor and c is the scale factor in metres per second. These two factors should be selected to closely represent recorded data in a location. Broadly speaking, the shape factor adjusts the slope of the curve while the scale factor impacts the amplitude of a distribution. Their specific usage for this study will be explained further in the methologody section. A Rayleigh distribution is in fact a Weibull distribution where the shape factor is 2 and the scale factor is $2\bar{u}/\sqrt{\pi}$. Distributions like this are useful when considering the most statistically likely wind speed in a given location, as simply averaging the measured wind speeds will not give results that best represent the available wind resource.

## 2.4 Generator Choice

### *2.4.1 Generator Types*

There are several options available for the conversion of mechanical, rotational force to electricity. Options include synchronous generators, induction machines and both AC and DC generation are possible. The most cost effective for small-scale wind generation will be determined in this study. For instance, as the output power will be around 200 watts, a DC generator may be possible (Shepherd, Shepherd, & Zhang, 2011). Alnasir & Kazerani (2013) have produced a comprehensive critical study comparing generator types for WECS. The major types covered are listed below in Table 1.

Table 2. Common types of generator used in wind turbines and their abbreviations

| | |
|---|---|
| WRIG | Wound Rotor Induction Generator |
| DFIG | Doubly Fed Induction Generator |
| BDFIG | Brushless Doubly Fed Induction Generator |
| SCIG | Squirrel Cage Induction Generator |
| WRSG/EESG | Wound Rotor or Electrically Excited Synchronous Generator |
| PMSG | Permanent Magnet Synchronous Generator |

Each of these options is perceived to have positives and negatives covered in some detail by Alnasir & Kazerani. A much briefer treatment will take place in this document. For the purposes of the design required by this particular study, extra weighting is given to high efficiency and low maintenance as efficiency will translate to a broader usage envelope in terms of available wind and low maintenance/ high reliability are critical for remote locations. These factors also have a direct influence on any economic forecasting for the installation.

### *2.4.2 Fixed Speed vs Variable Speed*

One factor heavily influencing generator choice in this study is the difference between fixed speed and variable speed turbine use. Of particular use when generating power in a grid connected role is the ability to match frequency to that of the attached network. This is often carried out by controlling rotor speed. In a standalone system such as that where batteries are being charged, the requirement for fixed speed is not an issue, therefore the speed can vary with the wind. Turbine blade designs have a maximum coefficient of power at a specific tip speed ratio, consequently allowing the rotor tip speed to vary with the speed of the oncoming wind can maximise efficiency. Whereas fixed speed turbines are often limited to generators like the SCIG, variable wind turbines can choose from a much greater range of generators and power converters

(Alnasir & Kazerani, 2013, p. 598). A variable speed wind turbine attracts 10-15% more energy, has lower mechanical stress and less power fluctuation (Kalantar & Mousavi G, 2010).

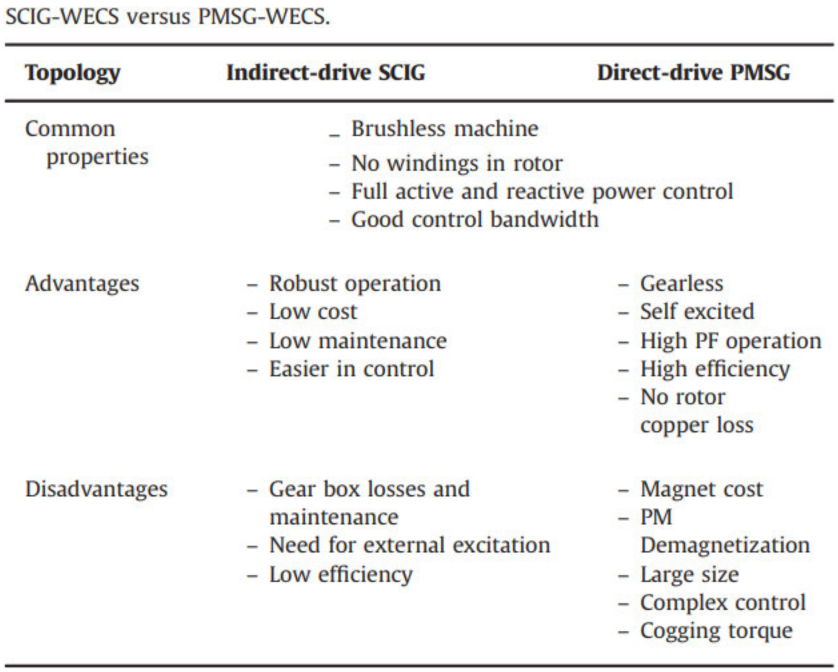
### *2.4.3 Gearing*

As larger wind turbines typically operate at a lower tip speed, gearing is often required to provide the rotational speed required to achieve maximum efficiency in the generator. Small turbines operating at higher tip speeds can afford to dispense with heavy gearbox components and added losses that they represent. Removal of the gearbox also means a decrease in complexity, failure points and maintenance.

### *2.4.4 Synchronous vs Asynchronous*

For standalone small scale wind generation, permanent magnet synchronous generators have typically been preferred. The permanent magnet means that there is no need to provide a magnetizing current to the stator hence only the stator current is responsible for creating torque. This means a PMSG can operate at a higher power factor than a SCIG leading to higher efficiency (Alnasir & Kazerani, 2013, p. 600). The reactive power requirement of induction generators is often compensated with capacitors, especially in grid connected turbines as a reactive power flow from the network is undesirable. A high current inrush is also found during startup due to the required magnetizing of the induction generator core (Ackermann & Söder, 2002, p. 96). The WRIG, BDFIG and DFIG layouts offer specific advantages in larger scale installations but for standalone, micro-scale generation add a level of complexity that does not make economic sense. A WRIG requires a VAR compensator, brushes and slip rings, soft starter and external variable resistance. The DFIG whilst giving the ability to save money on power converter and filter sizing in larger installations also uses brushes and slip rings requiring maintenance. The BDFIG whilst reliable and practically maintenance free is again more complicated than necessary in this instance. Table 2 below compares the two main choices, PMSG and SCIG.

Table 3: Comparison of two main generator choices, PMSG and SCIG (Alnasir & Kazerani, 2013, p. 607).



SCIG-WECS versus PMSG-WECS.

| Topology | Indirect-drive SCIG | Direct-drive PMSG |
|---|---|---|
| Common properties | – Brushless machine<br>– No windings in rotor<br>– Full active and reactive power control<br>– Good control bandwidth | |
| Advantages | – Robust operation<br>– Low cost<br>– Low maintenance<br>– Easier in control | – Gearless<br>– Self excited<br>– High PF operation<br>– High efficiency<br>– No rotor copper loss |
| Disadvantages | – Gear box losses and maintenance<br>– Need for external excitation<br>– Low efficiency | – Magnet cost<br>– PM Demagnetization<br>– Large size<br>– Complex control<br>– Cogging torque |

### *2.4.5 PMSG Drawbacks*

For the purposes of this study, permanent magnet synchronous generator turbines will be modelled. Although this is the most common arrangement for standalone micro wind turbines, it should be noted however that the topology is not without its criticisms. The magnet excitation cannot be varied for control and thus the voltage output will vary with load. The interaction of the magnets of the rotor and the slots of the stator causes vibration from a phenomena known as cogging torque which can affect reliability and power delivery. Perhaps most critically however is the global situation surrounding permanent magnet availability and price (40% of which is mined in China) as well as environmental questions surrounding their production (Jyothi, 2020). For a study focused on sustainability and low cost, these factors are of great import. The emission reductions and cost benefits offered by the change to renewables as well as the diminutive size of the turbines being investigated may offset these issues however they will need to be taken into account when assessing suitability post modelling.

## 2.5 Energy Storage and Management

### *2.5.1 Storage Types and Applicability*

Due to the inconsistent nature of the wind resource, it is anticipated that the systems in this project will require some form of energy storage both as a smoothing measure and for any prolonged periods without sufficient wind. Alnasir & Kazerani (Alnasir & Kazerani, 2013, p. 605) mention that lead acid batteries are a mature and established energy technology representing a low cost option for standalone WECS although they suffer from a lower power density and limited lifecycle than some other alternatives. Storage possibilities have proliferated during the increased uptake of renewables, however, as the type of energy created by a turbine is electric and therefore a higher form of energy (compared to something like heat), not all forms make sense to use in this context. For example, flywheels may be able to store the kinetic energy however over long periods of dormancy will lose energy and are thus suited better to constant charge and discharge cycles or load stabilization roles. Similarly, conversion to and from other forms of energy such as compressed air would result in losses that diminish viability. The chosen storage medium also must be of a cost that befits the small and inexpensive aim of the installation. Electrolytic hydrogen does not solve the problem of energy expenditure in transport if created somewhere else and the expense and losses do not make sense if an electrolytic converter were to be located onsite.

A deep-cycle battery makes sense here as there are many options already proven on the market in Ampere Hour capacities that are useful. There are plenty of options already on the market in this category with proven reliability, competitive price and a predictable lifespan. There are environmental issues surrounding the mining of lithium and the demand in coming years may make costs prohibitive. Choice of lead acid chemistry is therefore recommended as although power density may not rival lithium options, lead is the most efficiently recycled battery chemistry with 99% of lead batteries being collected and recycled in Europe and the USA (May, Davidson, & Monahov, 2018). Whilst the recyclable aspect is desirable, the power density offered by lead acid chemistry may not be sufficient in locations with a lower wind resource or where more autonomy is required.

### *2.5.2 Battery Management, Dump Load, Rectification, Regulation and MPPT*

A battery must be monitored to prevent overcharging and thus damage. Battery management systems are often included in the price of either turbine or battery purchases. Systems commonly employ the use of a dump load to absorb excess power when the batteries are full. This involves the Battery Management System directing excess current from the turbine via circuitry to an appropriately sized resistance capable of absorbing the excess flow. Battery Management systems often also handle regulation (ensuring the voltage remains within acceptable limits) and rectification (conversion of alternating, generally three-phase current from turbine generator windings to direct current required for charging batteries). Often Maximum Power Point Tracking (MPPT) is included in the functionality of the controlling microprocessor. MPPT maximises the power output of the system by allowing load resistance to be varied thus optimizing the relationship between voltage and current. This concept is much easier to implement in Induction Generators than permanent magnet generators due to the difficulties controlling synchronous generators. MPPT and other concepts such as Peukert's Law (governs the speed a battery can charge or discharge) are handled internally in the Homer Pro software and can be ignored for the purposes of this study however the advantages of MPPT for small WECS is an area that could benefit from more academic attention.

### *2.5.3 Inverter*

For operation with unmodified Starlink hardware, an inverter is required. Inverters typically have an efficiency of upwards of 90%, again calculated internally in Homer Pro with assumed proprietary values for the purposes of this study. Here again, there is the potential for further investigation as an increase in efficiency is possible if once converted from AC, the rectified direct current state was maintained. Although likely to void the Starlink warranty at this point, it might be beneficial for the company to consider the release of a DC alternative for their user terminal power supply given how many customers using the product are situated off-grid.

## 2.6 Prior Research in Wind Turbines

As evidenced by the history section above, wind turbines are considered a mature technology and consequently have benefitted from many years of research. Micro wind turbines and standalone wind power for communications setups or to charge batteries have received much less attention as larger turbines are more capable of effecting emissions reduction on a large scale. Solely relying on wind and battery as opposed to adding extra production mediums like photovoltaic solar experiences a similar lack of research due to the perceived cheap simplicity of solar PV and a commonly held belief that solar and wind are complementary. To achieve carbon neutrality in time however, it is necessary to consider all emission sources as even smaller sources are significant when considered together. This case study is aimed at the many smaller sources of emissions that exist that are often not considered by the research. Notwithstanding, there are still authors who have looked at similar topics within this realm.

Kesby (also based in Australia) modelled a complete micro wind turbine with combined CFD/ BEM and tested the design in a wind tunnel, claiming up to 50% more power with the addition of a diffuser (Kesby et al., 2017). This allows the turbine to be 50% smaller with the same output with a commensurate decrease in wildlife dangers and aesthetic impact. The team involved have since received grants to rollout their design for communication setups in remote areas under the company name Diffuse Energy. Their work focusses more on the blade/diffuser design element rather than an analysis of the wind resource in lower Australia but otherwise demonstrates a very similar ethos to this study. Their proprietary turbine is under 1 metre in diameter.

Although an older work, Drouilhet et al examine several ways of improving the battery charging capability of turbines under 10kW in capacity (De Broe, Drouilhet, & Gevorgian, 1999). The study uses permanent magnet generators and focusses on modelling actual turbine output under a variety of changing load conditions. Several possible implementations in the electronic makeup of small WECS are compared and analysed including optimizing battery storage size, adding capacitors inline with the generator, utilizing optimizing DC/DC voltage converters between rectifier and battery bank and a combination of the above. Substantial improvements to the traditional small battery charging WECS are outlined. Any increase in efficiency of capture has the power to profoundly improve wind generation potential and minimize inability to meet energy demand. The study makes the observation that the total output of turbine and energy capture often fall short of expectations, a statement that is intended to be tested in this paper.

Research from Kaldellis et al models wind output on the Greek Islands and compares wind and solar standalone systems for the electrification of remote consumers, also in the hope of supplanting diesel generator usage (Kaldellis, Kavadias, & Koronakis, 2007). This study makes excellent use of a Matlab iterative algorithm (see Figure 3 below) to size battery storage in a way that would be necessary without dedicated software like Homer Pro. The wind resource seems quite considerable (ie above 10m/s) giving wind generation a favourable outlook, in fact the study finds that in some cases wind generation is preferred over all alternatives. Differentiating this particular study, the loads used are primarily domestic and the turbines are sized accordingly.

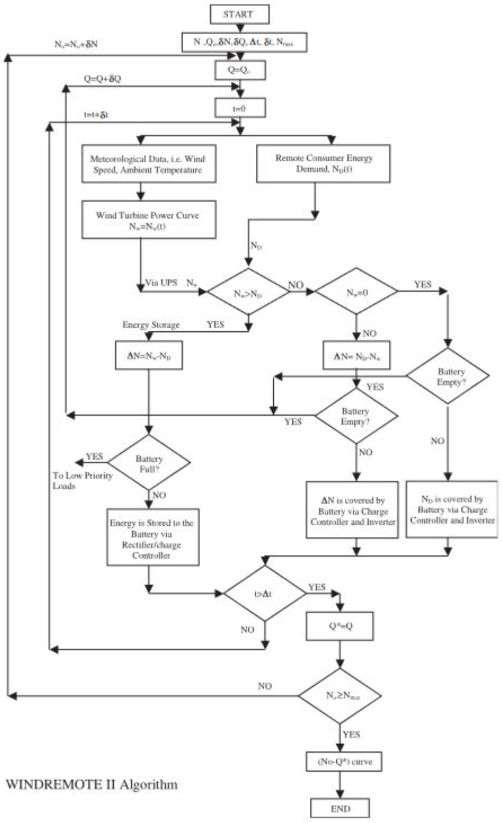


Figure 4. Algorithm used by Kaldelis to size battery storage

Hirahara et al also wind tunnel test a turbine with a very small diameter (500mm) but high solidity to ascertain viability in lower wind scenarios (Hirahara, Hossain, Kawahashi, & Nonomura, 2005). This study is of specific importance as it shows that ideally a turbine blade design should be matched to the available wind resource for maximum capture. The turbines available in Homer Pro and used in this study are all of the most common three blade design. In further studies, it would be desirable to test suitability of wind turbines of higher solidity. The Kesby turbine also demonstrates a higher solidity, giving more success in low wind density scenarios.

## 2.7 Multi-Criteria Analyses (MCA) or Multi-Criteria Decision Making (MCDM)

The question of how to make difficult infrastructure decisions when the factors separating competing options are not entirely clear or numerable is one that has been considered often in the literature. Aids to the decision-making process are often needed in government or industry as decisions are rarely clear-cut and often options demonstrate a complicated mix of positive and negative aspects. Likewise, the criteria used to judge an alternative can often often be in conflict, for instance, cost vs quality or in the context of engineering, cost vs environmental cost. Tools to help decision making often take the form of a Multi-Criteria Analysis (MCA). Decision-making in this fashion is often assisted by software with many different procedures existing due to the complex and varied nature of decision making in many fields. The process of MCA has also been regularly applied to problems in the energy infrastructure, sustainability and renewable energy fields. The different methods of MCA are almost too many to list. For this particular study, the MCA is desired to be quite simple as befits the narrow focus of the research. The literature study has allowed the alternatives to be narrowed down. Kaya et al have reviewed in detail fuzzy criteria MCA methodologies as applied energy policy (Kaya, Çolak, & Terzi, 2019). Although helpful in dealing with the lack of specificity in criteria associated with energy policy, fuzzy logic techniques introduce an unneeded level of complexity. Wang et al use MCDM to analyse renewable energy alternatives for Vietnam and preference solar above wind (Wang et al., 2021). Michal et al compare AHP and WSM finding that the results of each method were similar (Michał, Roman, & Norbert, 2016). The necessity to choose weightings and scales that adequately reflect the decision makers priorities is paramount. For the purposes of this study, it was deemed that the most common and simplest method, the weighted sum model (WSM) would be most appropriate.

# 3 Methodology

## 3.1 Locations

### *3.1.1 Influential Factors*

This study aims to ascertain whether on demand small-scale wind generation is suitable for a communication setup using the Starlink model as a case study. Starlink's release in Australia is initially restricted to the mainland below -32 degrees of latitude and only available in low density / remote areas; a scope that will also be adopted for the purposes of this study. As the proper design and size of a wind turbine depend on having wind of sufficient strength and duration, extended anemometric surveys lasting over at least a year for all locations under consideration are recommended (S. Larry Dixon & Hall, 2010, p. 323). Furthermore, predicting power levels based on average wind speed can result in large errors due to nonlinearity (Inoue et al., 2006, p. 52). Once a suitable length sample of the wind has been recorded however, variation of the mean power output has been estimated to have a standard deviation of 10% or less over a 20 year period giving sufficient economic confidence over the lifespan of the turbine (Ackermann & Söder, 2002, p. 83) .

Bureau of Meteorology weather stations record historical data for wind that will be used for creating modelling in 4 locations. Recordings give both gust and current wind speed with the last 14 months accessible in .csv format. Records further back may have charges for extraction. The measurements are all taken at a height of 10 metres using an anemometer. This raw data is to be used to supplement and crosscheck the NASA measurements at 50m which Homer Pro uses to create its wind model. The Homer Pro wind records are averaged over 10 years. The locations chosen have a BOM weather station present as this minimizes differences in location data and means that local records can be accessed for other influential factors like altitude, temperature or rainfall. The four locations have been chosen to give a spread of latitude and longitude across the mainland as well as variation between west facing and east facing coastlines. Two inland and two coastal locations have been used. The eastern coast of Australia has been avoided as it is likely too populous for the stipulated Starlink guidelines. The maps in Figure 3 and Figure 4 of major wind speed areas and land usage were also used to aid in deciding location.

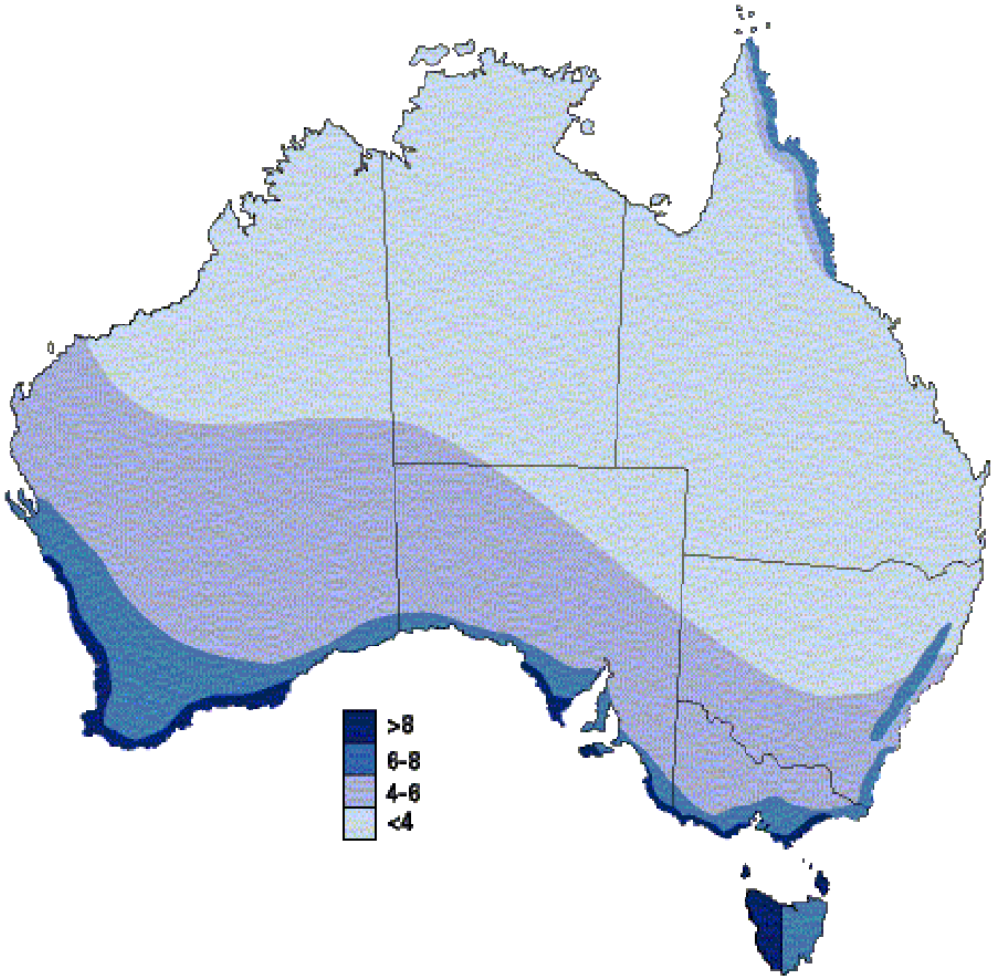


Figure 5. General background wind speeds (m/s) in Australia (Coppin et al, 2003)

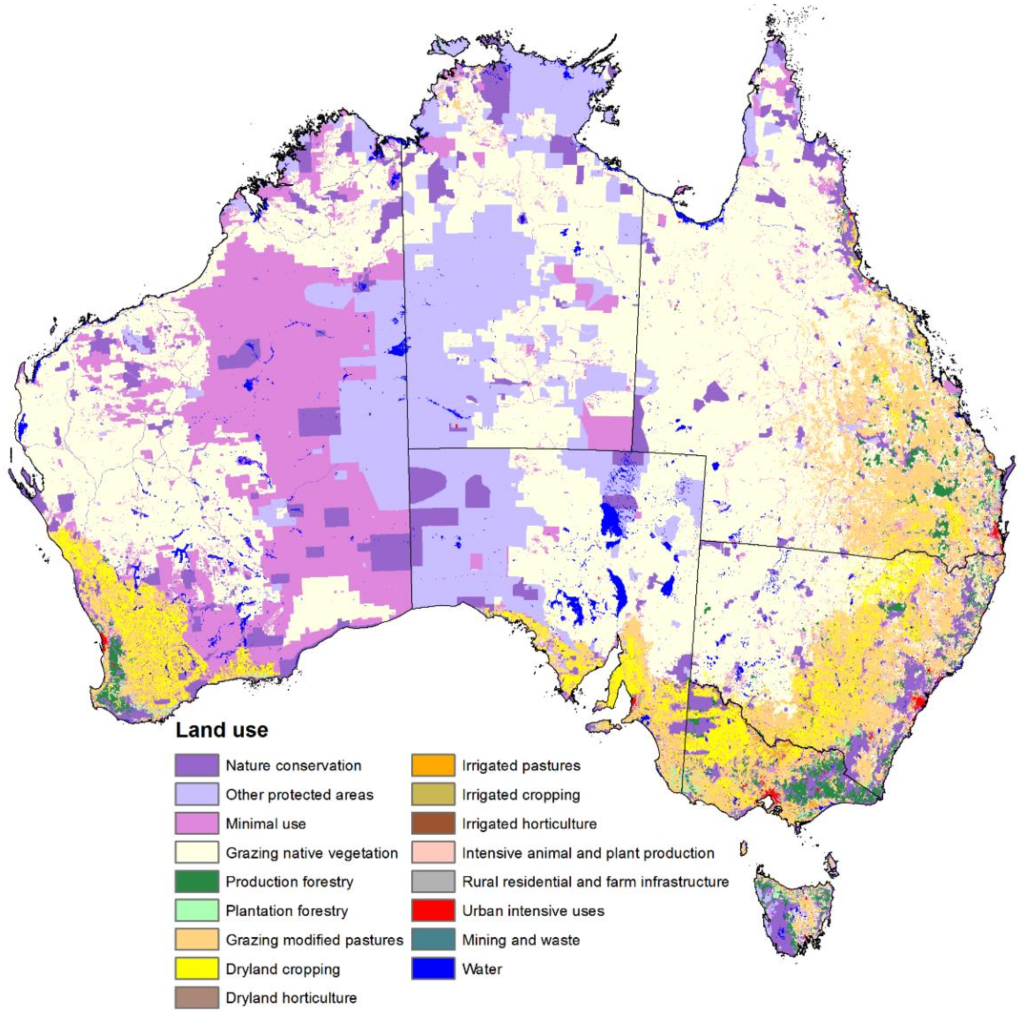


Figure 6. Australian land usage map (Australian Collaborative Land Use and Management Program, 2016)

### *3.1.2 Locations Chosen*

The four locations are displayed in Table 3 below. Cape Leeuwin is the most south-western location in Australia (although there are more southern areas). Port Lincoln sits on the eastern side of a promontory looking into the Spencer Gulf.

Table 4. Locations chosen for Homer Pro analysis

| Location Name | Latitude | Longitude | Altitude |
|---|---|---|---|
| Ivanhoe, NSW | 32.9ºS | 144.3ºE | 84m |
| Port Lincoln, SA | 34.72ºS | 135.86ºE | 4m |
| Katanning, WA | 33.7ºS | 117.5ºE | 320m |
| Cape Leeuwin, WA | 34.37ºS | 115.14ºE | 13m |

### *3.1.3 Air density*

Air density has a direct effect on the output of the turbine. Homer Pro extrapolates air density from altitude. As the four locations have a BOM weather station, the altitude of each location's weather station was used.

### *3.1.4 Survival wind speeds*

40 metres per second is a quite common 'survival' wind speed listed for wind turbines, although each turbine will have its own parameters. Above this speed, the wind turbine and components are likely to suffer critical damage. It was necessary to scan the maximum gusts for each site to ascertain if this survival wind speed was ever exceeded. Whilst some turbine tower designs allow lowering of the turbine to prevent damage, in remote areas this may not always be possible and to avoid damage to componentry and unnecessary cost of replacement, locations with excess wind are to be avoided where possible.

## 3.2 Power Requirements

The Starlink user terminal consists of a motor-driven, self-aligning dish, a wifi router and cabling including a PoE (Power over Ethernet) 56 Volt, 1.6 Ampere (x2) power supply. A maximum power draw of 179.2 Watts is possible yet early reports of power consumption during use have centred around an average of 100 Watts (Brodkin, 2021). It is acknowledged that different climate circumstances may produce different power usage figures, for instance the Starlink dish has a built-in heater that may activate in snow or icy conditions producing a much higher figure. Power usage is also likely to fluctuate when the self-aiming dish moves. To access this communication system, power must be allocated for a user interface for which an average laptop with an average power consumption of 60 Watts has been (somewhat arbitrarily) selected. Including a safety factor of 10%, one can expect a worst case scenario power draw peak of 263 Watts with an anecdotal average of around 176 Watts. The amount of hours of operation will be broken into two categories, constant 24 hour connection and a more realistic 12 hours of connection per day. Using the anecdotal average, this gives an Annual Energy Production (AEP) goal of 1541.8 kWh/yr for the 24 hr variant and 770.8 kWh/yr for the 12 hour load. Homer Pro will be used to create an electrical load that fluctuates around this anecdotal average (around 3.1kWh.day) with peaks occurring up to around 260 Watts.

### *3.2.1 Control Systems*

Control systems were assumed to be factored into the turbine cost.

### *3.2.2 Inverter*

Inverter efficiencies can vary depending on model however for the purposes of this study, the generic inverter in Homer Pro was used with the default efficiency of 95% and a lifetime of 15 years. Homer Pro assumes that this efficiency is constant despite most inverters being less efficient at very low loads.

## 3.3 Turbine Characteristics

### *3.3.1 Solidity*

One of the advantages of using Homer Pro is that proprietary information like the solidity and specific blade geometry of a turbine, its power coefficient and tip speed ratio is included in the software. It is possible to access the power curve of available turbines which give some indication of output at different wind speeds. These power curves are utilized by Homer Pro to model energy harvest.

### *3.3.2 Blade sizing*

It is possible to roughly estimate the required blade size using actuator disc theory and the following electrical power formula:

$$P_{el} = \frac{1}{2}\rho A_2 C_p \eta_g \eta_d (u_o^3)$$

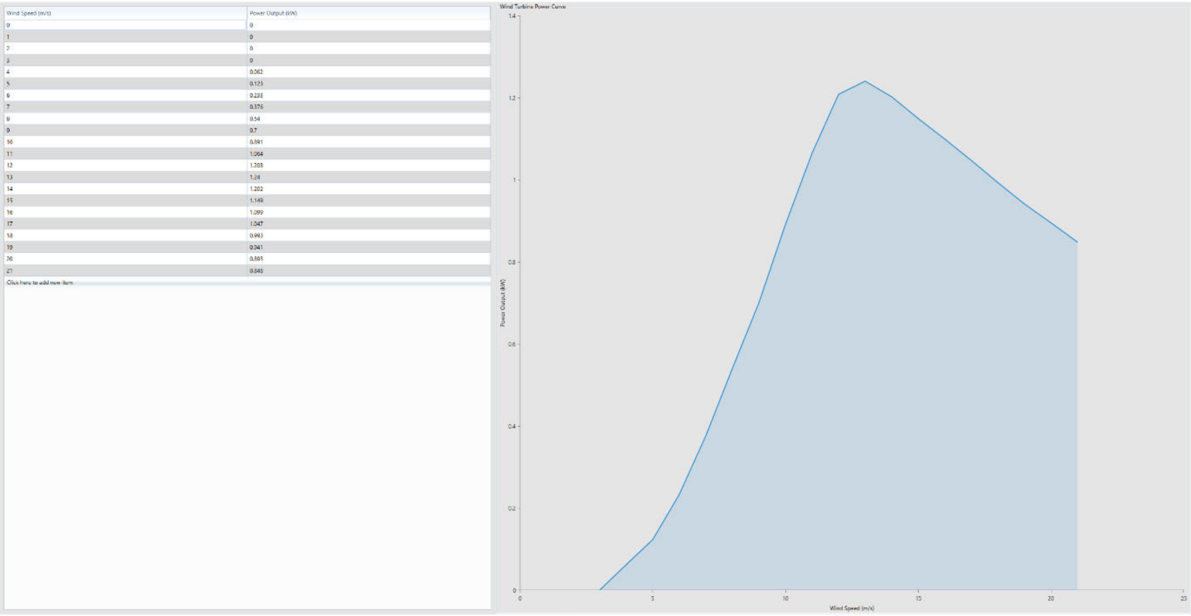
Using 200W electrical power, a direct drive, air density of 1.225kg/m^3, a power coefficient of 0.3, generator efficiency of 75% and a mean wind speed of 7.5m/s, a turbine radius of 0.98 metres was anticipated. Further modelling with Homer Pro would be able to show how accurate this method of estimation is for the purposes of this study. Clearly, the average wind in each location will differ.

### *3.3.3 Diffuser/shroud*

The turbines available in the Homer Pro database have no diffusers or shrouds. It is noted that as per the Diffuse Energy model (discussed in 2.6 - Prior Research) these alterations, if well designed, have the potential to provide significant output gains.

### *3.3.4 Turbines available in Homer Pro*

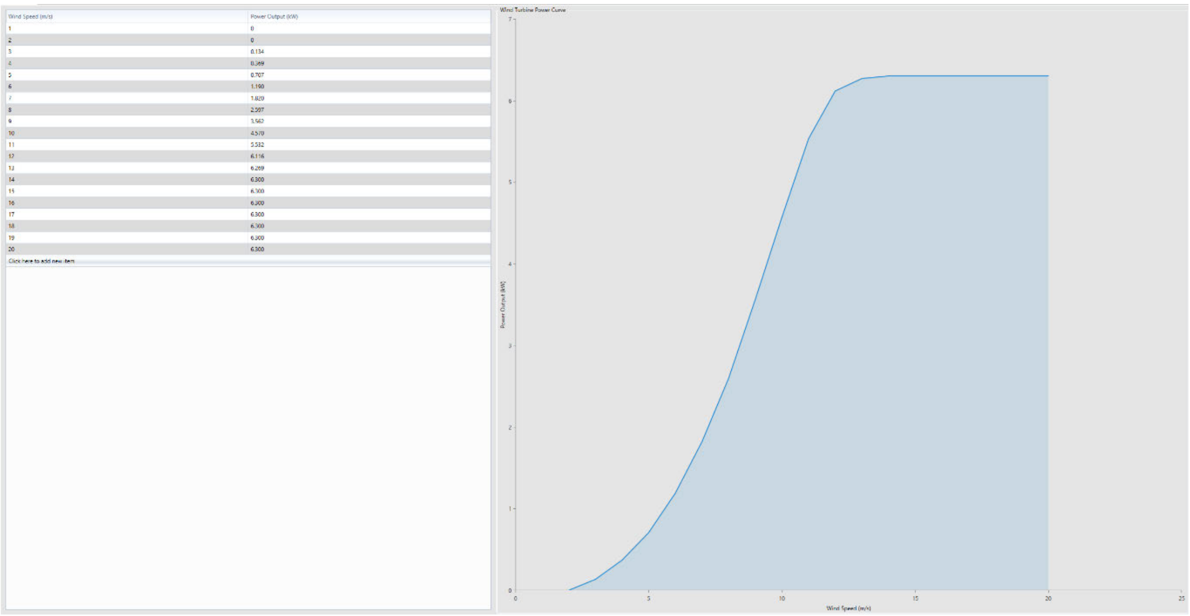
To answer the question of whether a microturbine and battery can provide sufficient power to a communication setup, it is necessary to define the scope of what is considered ‘micro’. Given that every year wind turbines grow in size with maximums now approaching 250 metres in height and blade lengths of around 120 metres, definitions are changing rapidly. In the Hirahara study, a microturbine is defined as one with a diameter below 1.25 metres (Hirahara et al., 2005, p. 1280). Drouilhet describes wind turbines of around 10kW output as small (De Broe et al., 1999) and Ackermann describes small turbines as being 5kW or less (Ackermann & Söder, 2002, p. 91) whilst Abraham counts anything beneath 100kW as small (Abraham & Plourde, 2014). For the purposes of this study, micro wind turbines will be considered to be up to 1.5 kW, small will be between 1.5kW and 6kW however using the smallest turbine possible is the goal of the study. A maximum of 10kW will be considered for extreme cases. Turbines in this range tested in Homer Pro are shown below (Figures 3-6), along with the price and power curve obtained from the software.



| Wind Speed (m/s) | Power Output (kW) |
|---|---|
| 0 | 0 |
| 1 | 0 |
| 2 | 0 |
| 3 | 0 |
| 4 | 0.062 |
| 5 | 0.123 |
| 6 | 0.233 |
| 7 | 0.376 |
| 8 | 0.54 |
| 9 | 0.7 |
| 10 | 0.891 |
| 11 | 1.064 |
| 12 | 1.208 |
| 13 | 1.24 |
| 14 | 1.202 |
| 15 | 1.149 |
| 16 | 1.099 |
| 17 | 1.047 |
| 18 | 0.993 |
| 19 | 0.941 |
| 20 | 0.895 |
| 21 | 0.848 |

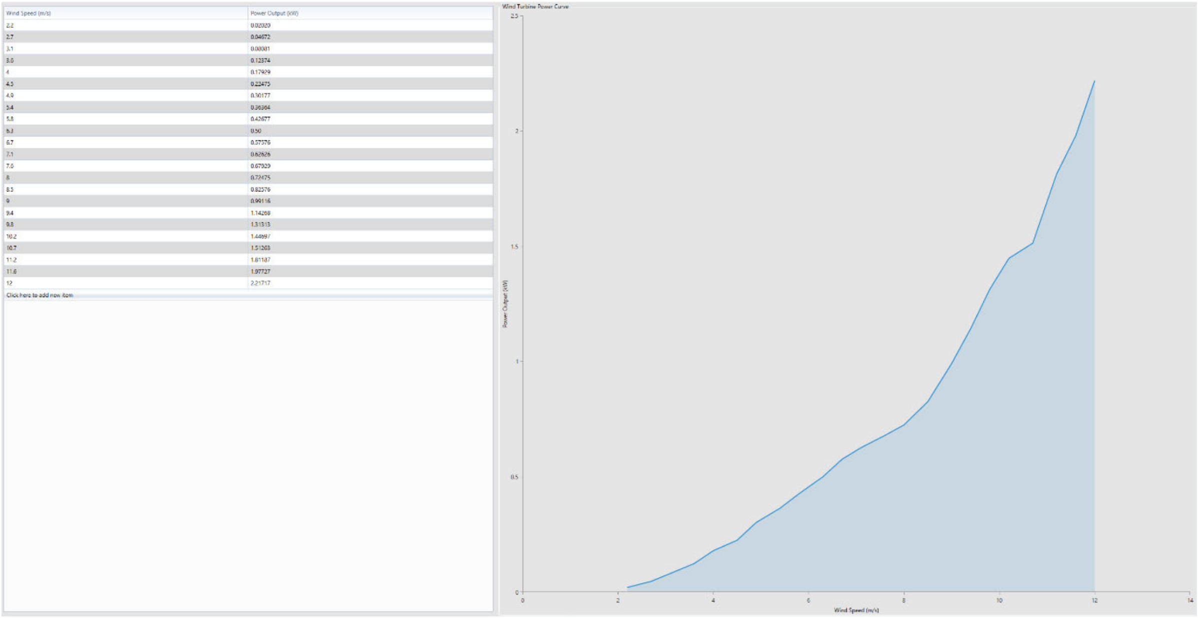
Figure 7.  Power curve for Bergey XL1, AUD$10,000, 1kW, 2.5 metre diameter

(<https://www.solaronline.com.au/bergey-xl-1-1000w-wind-turbine.html>)



| Wind Speed (m/s) | Power Output (kW) |
|---|---|
| 1 | 0 |
| 2 | 0 |
| 3 | 0.134 |
| 4 | 0.369 |
| 5 | 0.707 |
| 6 | 1.190 |
| 7 | 1.820 |
| 8 | 2.597 |
| 9 | 3.562 |
| 10 | 4.570 |
| 11 | 5.532 |
| 12 | 6.116 |
| 13 | 6.269 |
| 14 | 6.300 |
| 15 | 6.300 |
| 16 | 6.300 |
| 17 | 6.300 |
| 18 | 6.300 |
| 19 | 6.300 |
| 20 | 6.300 |

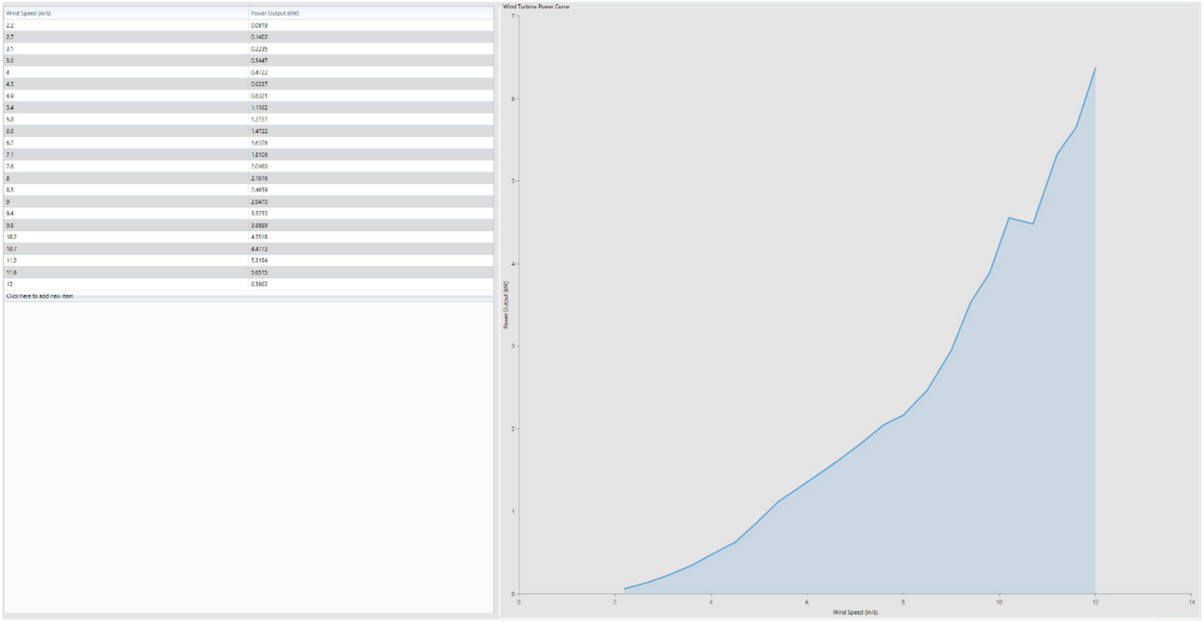
Figure 8. Power curve for Bergey XL6R - AUD$30,000, 6kW, 6.2 metre diameter



| Wind Speed (m/s) | Power Output (kW) |
|---|---|
| 2.2 | 0.02020 |
| 2.7 | 0.04672 |
| 3.1 | 0.08081 |
| 3.6 | 0.12374 |
| 4 | 0.17929 |
| 4.5 | 0.22475 |
| 4.9 | 0.30177 |
| 5.4 | 0.36364 |
| 5.8 | 0.42677 |
| 6.3 | 0.50 |
| 6.7 | 0.57576 |
| 7.1 | 0.62626 |
| 7.6 | 0.67929 |
| 8 | 0.72475 |
| 8.5 | 0.82576 |
| 9 | 0.99116 |
| 9.4 | 1.14268 |
| 9.8 | 1.31313 |
| 10.2 | 1.44697 |
| 10.7 | 1.51263 |
| 11.2 | 1.81187 |
| 11.6 | 1.97727 |
| 12 | 2.21717 |

Figure 9. Power curve for Australian Wind and Solar, AWS HC1.5, AUD$17,000, 1.5kW, 3.2metre diameter

(<https://www.australianwindandsolar.com/aws-hc-wind-turbines>)



| Wind Speed (m/s) | Power Output (kW) |
|---|---|
| 2.2 | 0.0619 |
| 2.7 | 0.1402 |
| 3.1 | 0.2235 |
| 3.6 | 0.3447 |
| 4 | 0.4722 |
| 4.5 | 0.6237 |
| 4.9 | 0.8321 |
| 5.4 | 1.1162 |
| 5.8 | 1.2727 |
| 6.3 | 1.4722 |
| 6.7 | 1.6376 |
| 7.1 | 1.8106 |
| 7.6 | 2.0480 |
| 8 | 2.1616 |
| 8.5 | 2.4659 |
| 9 | 2.9470 |
| 9.4 | 3.5253 |
| 9.8 | 3.8889 |
| 10.2 | 4.5518 |
| 10.7 | 4.4773 |
| 11.2 | 5.3194 |
| 11.6 | 5.6515 |
| 12 | 6.3662 |

Figure 10. Power curve for AWS HC5.1, AUD$34,000, 5.1kW, 5.24 metre diameter

## 3.4 Generator

All of the turbines modelled use Permanent Magnet Synchronous Generators (PMSGs).

## 3.5 Storage Types

### *3.5.1 Battery Chemistry*

Due to its recyclable nature and competitive price, it was attempted to use Lead Acid battery chemistry where possible. In some instances, the wind resource was not great enough to allow this and other chemistries with higher power density such as Lithium Ion have been investigated. The type of battery has been factored into the final Multi-Criteria Analysis as the environmental impacts differ.

### *3.5.2 Alternative storage types*

Due to the small scale of the installation being investigated, most other forms of energy storage are not suitable. For other types of usage, it might be possible to investigate other forms of storage such as flywheel or compressed air.

## 3.6 Hub Height

The installed hub height of the turbine was initially modelled at 10 metres. Where the turbine failed to adequately support the system, higher hub heights were investigated using a Logarithmic scale to extrapolate from existing wind resource data to account for the increase in average wind speed with increased height.

## 3.7 Local Placement Assumptions

It has been assumed that all due care has been taken to maximise the available wind resource in each location and avoid turbulence and interference resulting from geographical or other factors. The default settings in Homer Pro have been used, correlating with a Raleigh distribution.

## 3.8 Process

The research conducted will answer the question of suitability of wind and battery to support a Starlink communications system using two mechanisms:

(i) Quantitative analysis of technical and financial viability using Homer Pro including comparison to solar and diesel alternatives and,

(ii) Qualitative overall suitability analysis using fuzzy logic MCA

### *3.8.1 Model turbine output and size storage in four locations*

The chosen process for ascertaining technical and economic viability using Homer Pro is an iterative one. For each of the four locations, the following steps will be undertaken until a solution is found. A solution will be deemed successful when there are unmet power needs for less than 3 days a year. A successful solution will then be compared to generic solar and diesel solutions in terms of cost.

1. Test using the ideal setup (smallest turbine swept area possible and lead acid batteries) using 10 metre hub height and a **24hr load**.
2. If unsuccessful, retest using same setup but hub heights of 20 and 30 metres.
3. If unsuccessful, test with progressively larger size turbines and Lithium battery

4. If unsuccessful, test for **12hr load** using ideal setup at 10 metre hub height
5. If unsuccessful, retest using same setup but hub heights of 20 and 30 metres.
6. If unsuccessful, test with progressively larger size turbines and Lithium battery

### *3.8.2 Qualitative assessment - Conduct MCA including results of Homer Pro testing*

The resulting design topologies (if wind power is viable at the site) will be qualitatively compared to diesel and solar in four categories (price, ability to meet demand, reliability including maintenance, longevity, sustainability of materials, direct environmental impact, indirect environmental impact incl. emissions, social impact) using the WSM method.

Overall suitability will be assessed including any barriers to adoption.

# 4 Results and Discussion

## 4.1 Homer Pro Modelling

Table 5. Quick reference table for results of Homer Pro analysis

| Locations | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 | Scenario 6 |
|---|---|---|---|---|---|---|
| Ivanhoe | No | No | No | No | No | Yes |
| Port Lincoln | No | No | No | No | No | Yes |
| Katanning | No | No | No | No | No | Yes |
| Cape Leeuwin | No | No | No | Yes | Yes | Yes |

### *4.1.1 Cape Leeuwin, WA*

The results above in Table 4 at the very least show the wind resource at Cape Leeuwin to be impressive. The graph below (Figure 9) shows the turbine output (purple) in the top panel and the battery state of charge (orange) and unmet power (blue) in the bottom panel.

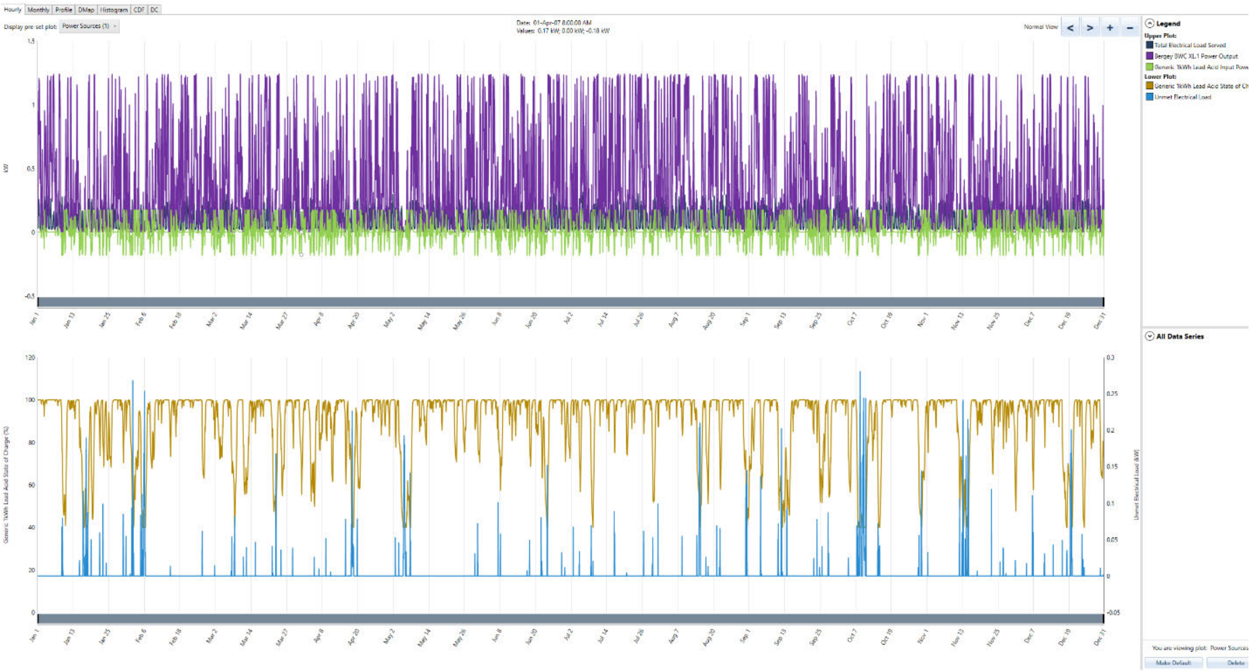
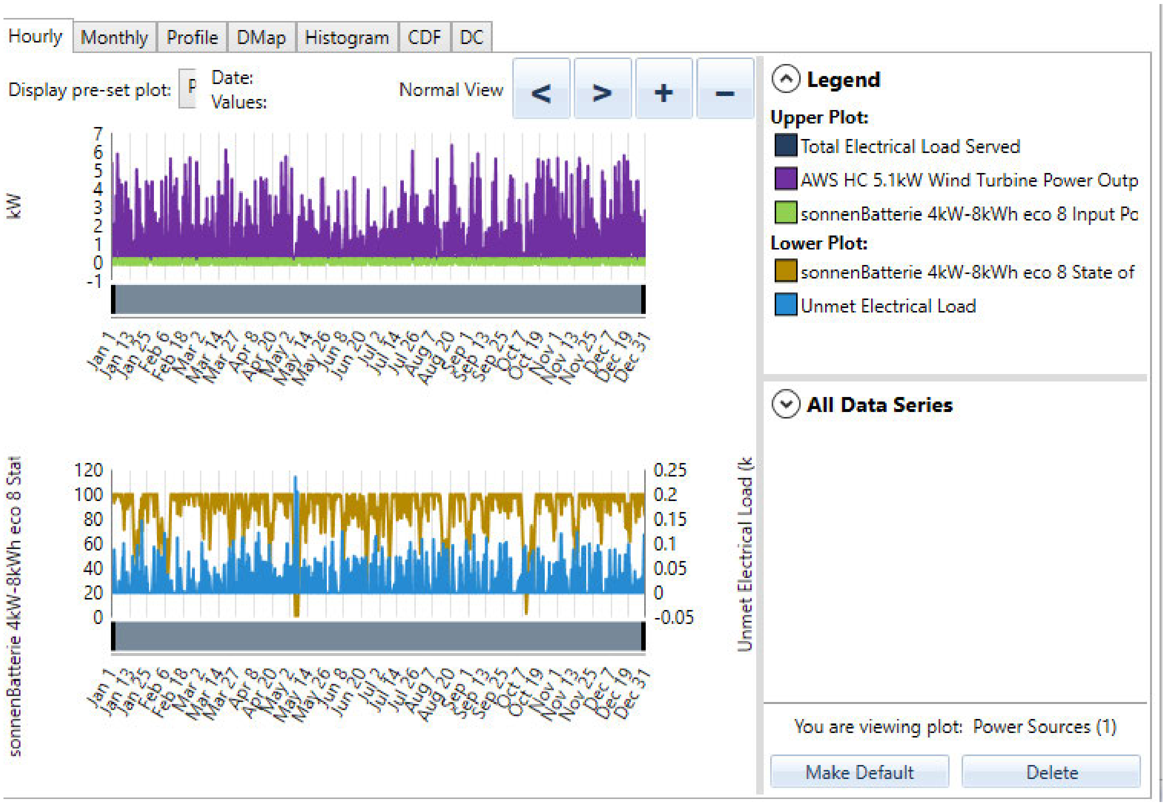


Figure 11. Cape Leeuwin modelling of 12hr load using 3kWh Lead Acid batteries and Bergey 1kW turbine at 10 metre hub height

There are roughly ten occasions throughout the entire year where the turbine and a mere 4kWh of lead acid batteries momentarily fail to meet the power needs of the communication setup. This is a pattern that will repeat (to a greater or lesser extent) throughout all locations and is a feature of wind variability. This is one of the first conclusions that we are able to draw from the data. The viability depends on the application of the communications setup. Some applications will suffer delays while others will not. Clearly, wind power alone would be hard to recommend for any full-time, real-time needs. Indeed, none of the setups tested were able to fully support the full 24 hour load. However, if the application was less time critical or able to be postponed to times of monitored battery high State of Charge, the potential for wind and battery alone is quite good, especially with a wind resource like that of Cape Leeuwin. In the instance shown, the setup is also very economical with a net present cost (NPC) of $13,411.00 over a 30 year period compared to a $5287.00 best case NPC for diesel generation not including maintenance. The NPC is the value of all lifetime costs minus any revenue earnt.

### *4.1.2 Ivanhoe, NSW*

For Ivanhoe and in fact all other locations, the wind resource in considerably reduced. This is not surprising given that it appears that the best winds on the mainland come from the South and the West. As evidenced by Figure 10, Ivanhoe was able to achieve consistent power with only one major interruption during the year however the size and cost of infrastructure increased dramatically. The next step down in turbine is also shown for comparison (Figure 11). Here we can see that retaining the $10,000 house-style Lithium Ion Sonnen Eco8 battery can allow a smaller 1.5 kW, 3.2 metre diameter turbine to be utilized however there is an increased associated risk of dropout. The roughly ten periods of unmet power seen here are more significant than in Cape Leeuwin, with some continuing for days on end.



You are viewing plot: Power Sources (1)

Figure 12. Ivanhoe best result using AWS 5.1kW turbine @ 12m hub height and Sonnen Eco8 4-8kWh Lithium Ion battery

Display pre-set plot: Power Sources (1)

Date: 31-Dec-07 11:00:00 PM

Values:

You are viewing plot: Power Sources (1)

Figure 13. Ivanhoe best result using AWS 1.5kW turbine @ 12m hub height and Sonnen Eco8 4-8kWh Lithium Ion battery

In the successful topography of Figure 10, the net present cost (NPC) of turbine and battery has increased to $39,877 and has ceased to be competitive with a solar and battery setup at $23,011. Figure 12 below shows that solar alone also has issues with intermittent outages especially in the winter months.

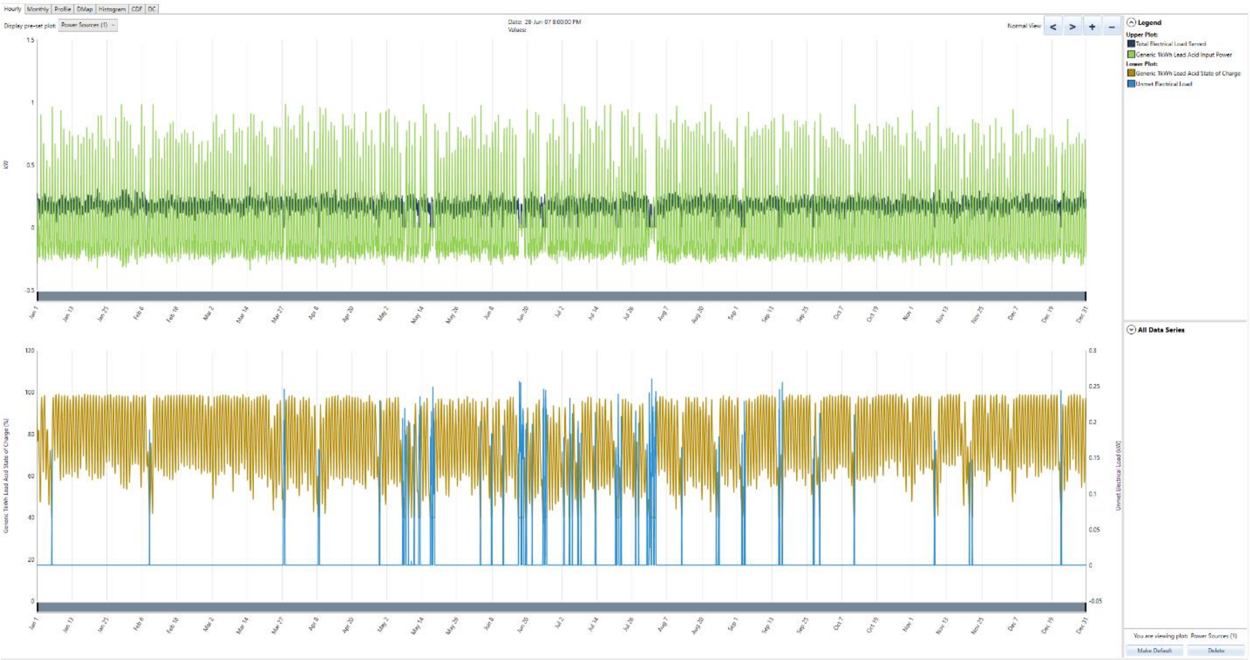


Figure 14. Ivanhoe solar and battery only

One question that arises from the modelling is that given that both wind and solar output suffer in the winter months, can the technologies really be described as complementary? On a daily basis, this commonly mentioned truism may hold up however over the course of the year, from this data set at least, both wind and solar output often appear to wane in the same season. This is perhaps more obvious in Figure 13 below which shows both the most capable setup tested (Bergey XL6-R turbine and Sonnen Eco8 battery) failing to output a 24 hour load in the Ivanhoe winter months.

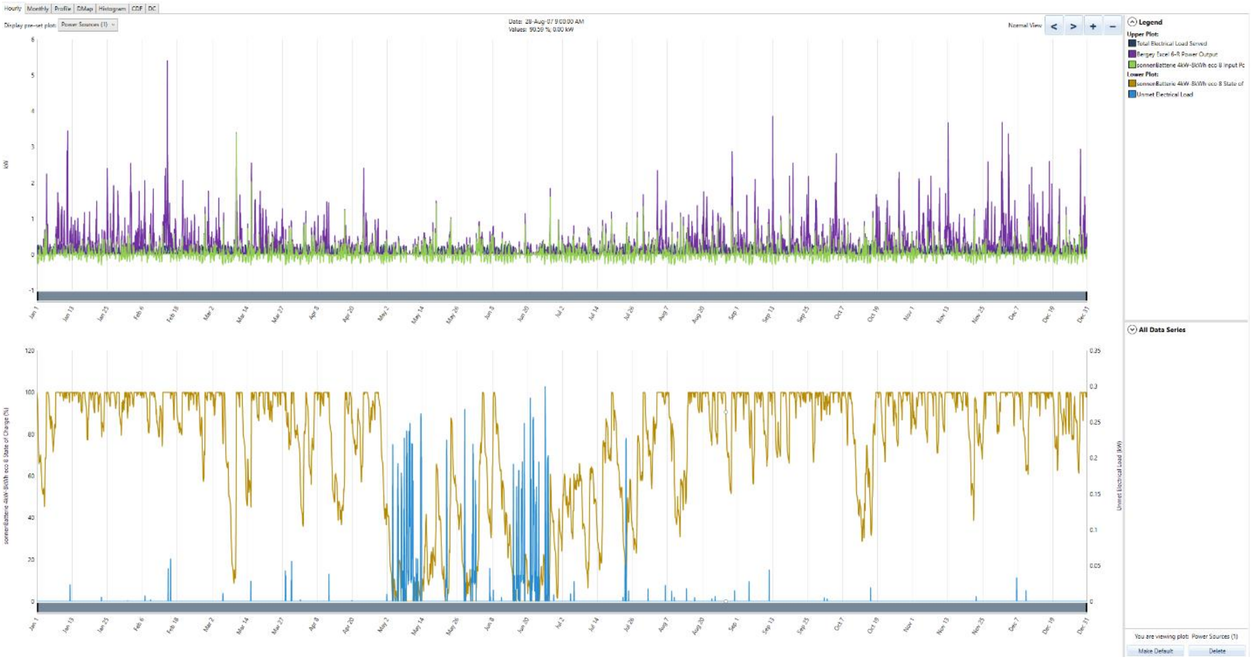
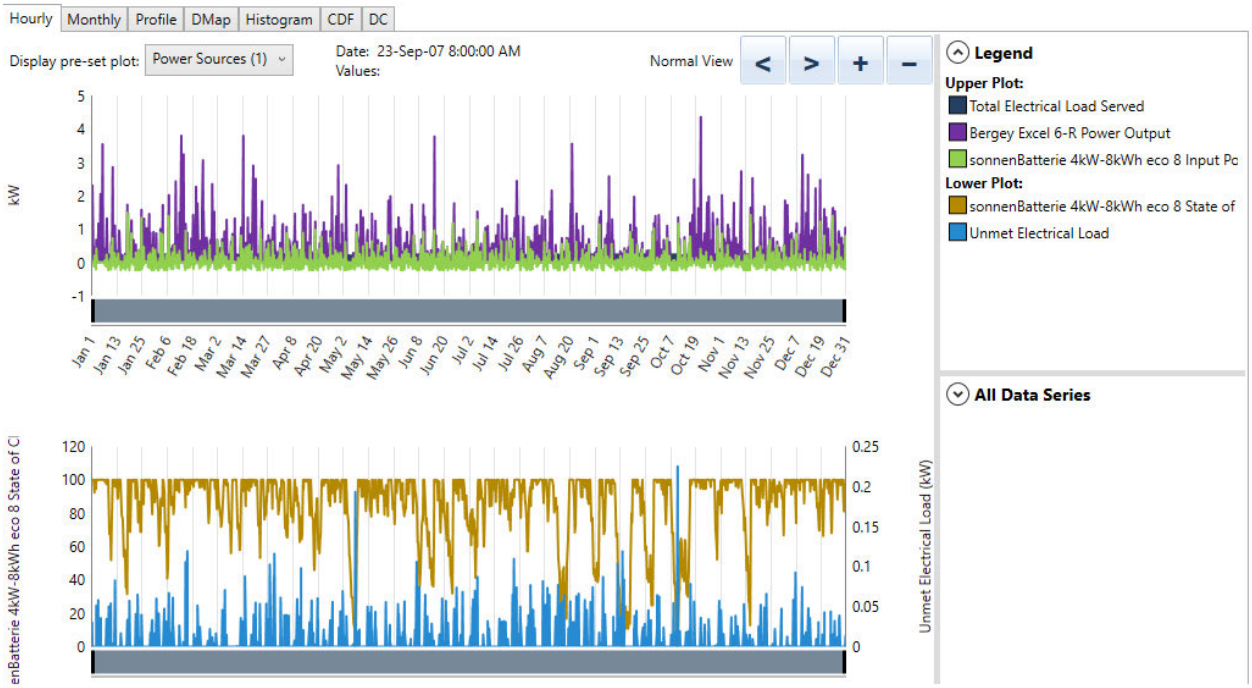


Figure 15. Ivanhoe 24hr load and the effects of winter months on wind output

### 4.1.3 *Katanning, WA and Port Lincoln, SA*

The Katanning and Port Lincoln locations exhibit a now familiar pattern (see Figures 14 and 15) with only the 6.2 metre turbine and Sonnen Eco8 4-8kWh battery able to guarantee decent reliability, both with only two dropouts during the year. Again, the NPC here for the turbine and battery are around $40,000 however an increase in insolation at these locations sees the price of solar (with the Sonnen battery) drop even further. Solar and battery at Katanning show an NPC of $19,729 whilst at Port Lincoln the NPC is $18,291. Solar and battery alone is again not viable (Figure 16) however the combination of both wind and solar, whilst expensive with an NPC of $58,351, seems to provide good stability (Figure 17).



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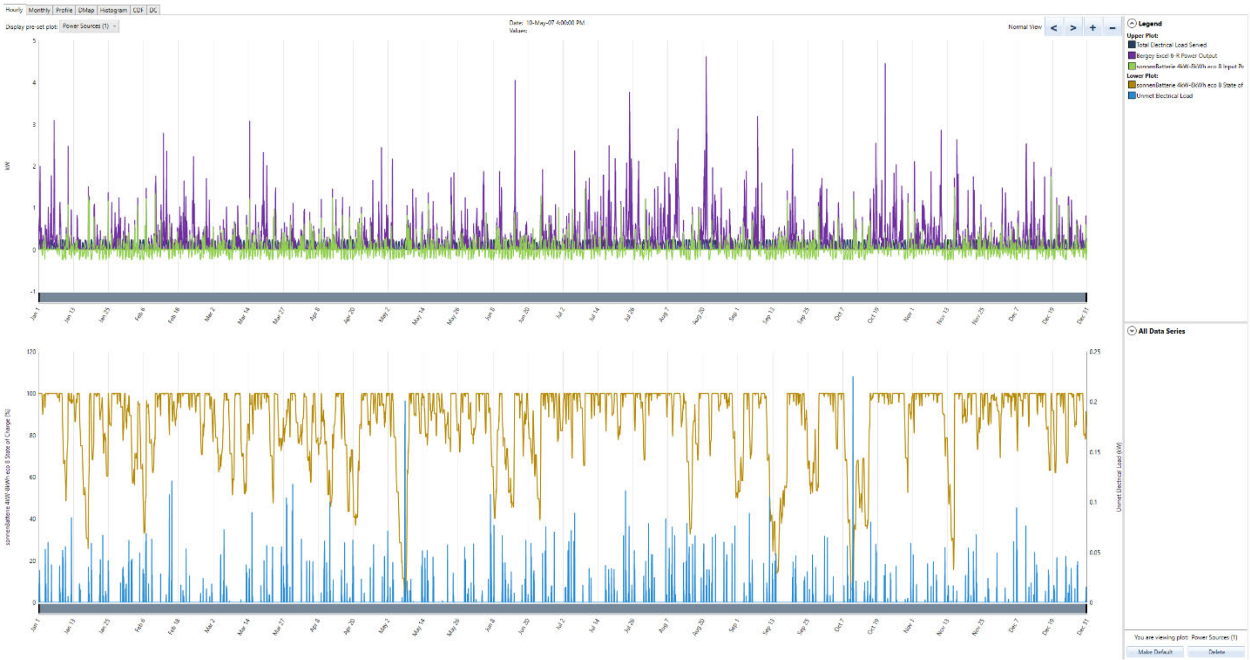
Date: 23-Sep-07 8:00:00 AM
Values:

Figure 16. Katanning yearly output with 12 hr load, XL6-R and Sonnen Eco8



Display pre-set plot: Power Sources (1)

Date: 10-May-07 4:00:00 PM
Values:

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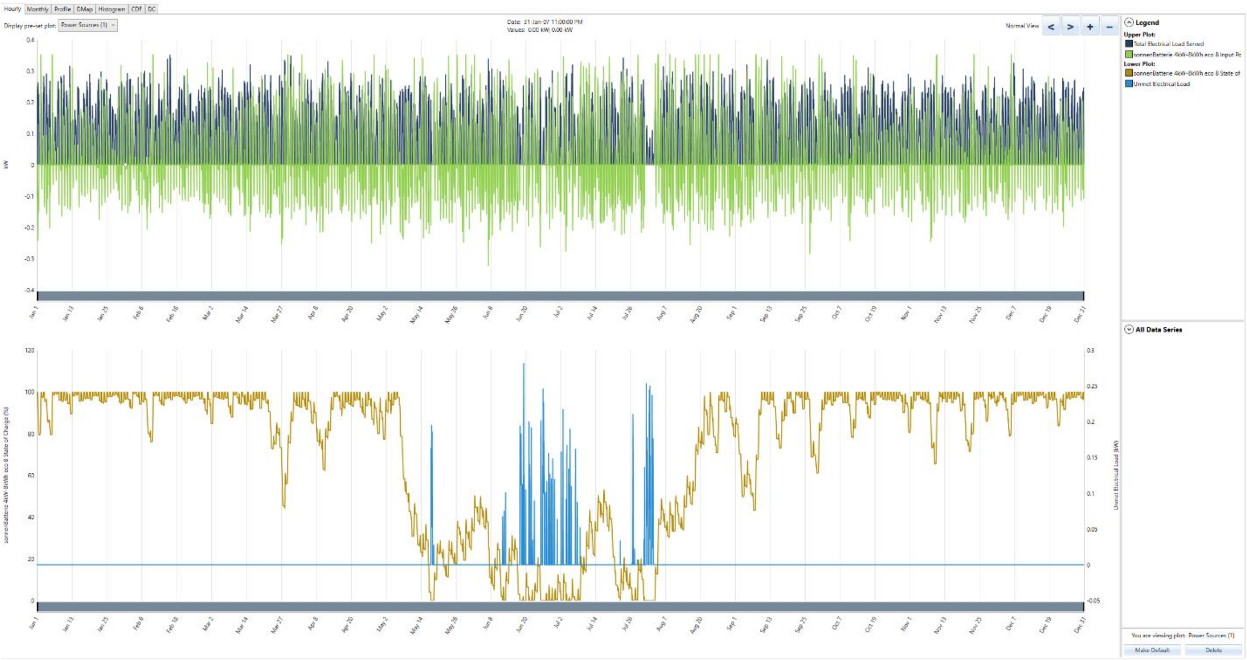
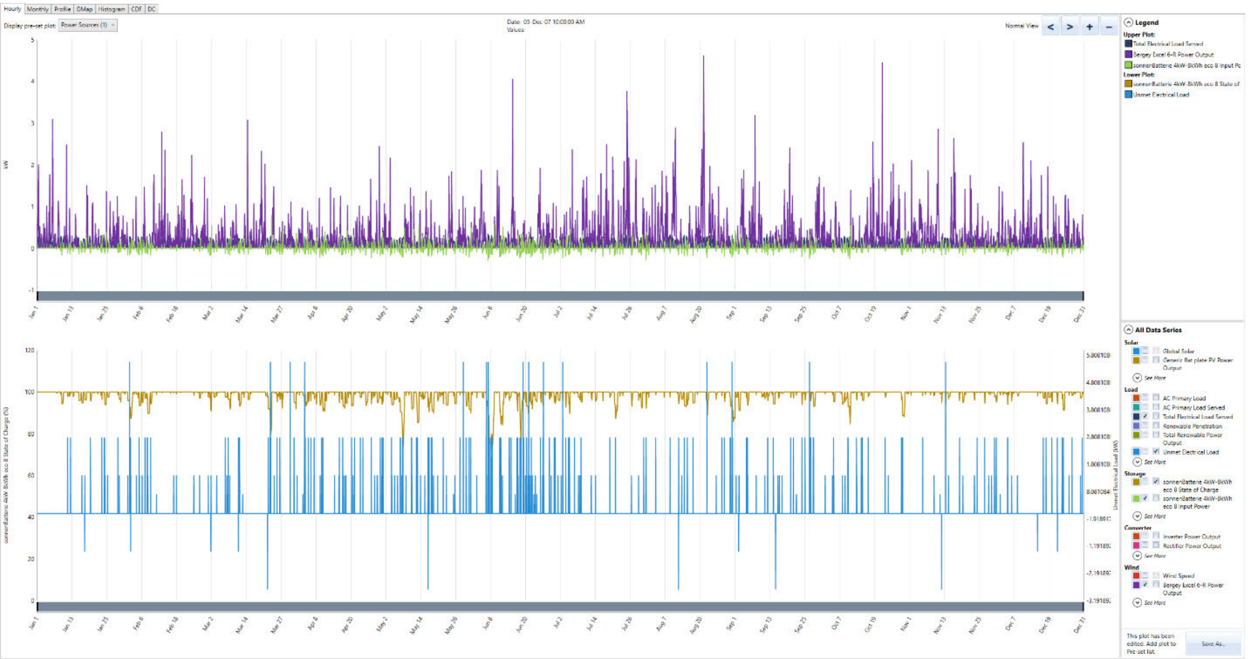
Figure 17. Port Lincoln yearly output with 12 hr load, XL6-R and Sonnen Eco8



Display pre-set plot: Power Sources (1)

Date: 31-Jan-07 11:00:00 PM
Values: 0.00 kW; 0.00 kW

Figure 18. Port Lincoln yearly output using solar only with Sonnen Eco8. Note failure of winter months.



Display pre-set plot: Power Sources (1)

Date: 05-Dec-07 10:00:00 AM
Values:

Storage:
☑ sonnenBatterie 4kW-8kWh eco 8 State of Charge
☑ sonnenBatterie 4kW-8kWh eco 8 Input Power

Load:
☑ Total Electrical Load Served
☑ Unmet Electrical Load

Wind:
☑ Bergey Excel 6-R Power Output

This plot has been edited. Add plot to Pre-set list.

Figure 19. Port Lincoln yearly output using solar and wind combination

These results also underline one of the reasons uptake of renewables at this size of installation might be more difficult to countenance. A $60,000 investment, albeit over the course of 30 years might be off-putting if one were not fully cognizant of the effects of anthropocentric climate change. The Multi-Criteria Analysis in the next section is designed to balance economic factors with other factors that might influence a decision as a purely economic analysis does not tell the whole story. We can also see that a 24 hour load is an ambitious requirement for a standalone renewables and battery setup given that wind speed generally diminishes overnight. Two technical aspects of the study that deserve further consideration are whether the Bergey XL6-R truly displays the power curve seen in Figure 6. This accounted for much of the success that was seen with this turbine. Secondly, many of the unmet power spikes apparent in the Homer Pro graphs (ie Figure 17) occur whilst there appears to be decent state of charge which deserves further investigation. Finally, the wear and tear on a battery especially of the Lead Acid type when reduced to a low state of charge has not been considered and could adversely affect outcomes through replacement costs.

## 4.2 Multi-Criteria Analysis

A very slight weighting has been used in the following multi-criteria analysis. The evaluation criteria have been mainly identified and discussed in the literature survey and are mostly self-explanatory. The lifespan, materials availability and end of life disposal criteria work together as although for instance wind turbines might need more copper, they can last for at least 30 years and are fully recyclable whereas PV cells use rare materials like Gallium, are difficult to recycle and have varying lifespans (10-20 years). Social impacts might be noise or visual pollution whilst ability to meet demand is the most important criterion. Subjectivity tends to be a problem with a method such as this however the decision maker and author in this instance has chosen to consider emissions reduction just as important, for reasons espoused in Section 1.4 Consequential Effects of Study. Scores for each criterion are either a 0, 1, or 2 to reduce any scoring bias.

Table 6. WSM MCA Evaluation using Cape Leeuwin case

| **Evaluation Criteria** | **Criteria Weights** | **Alternatives** | | |
|---|---|---|---|---|
| | | Wind and Battery | PV Solar and Battery | Fossil Fuel Generator |
| Ability to meet demand | 0.2 | 2 | 1 | 2 |
| Emissions Avoided | 0.2 | 2 | 2 | 0 |
| Cost Minimised/ yr | 0.1 | 1 | 1 | 2 |
| Lifespan | 0.1 | 2 | 1 | 1 |
| Materials Availability | 0.1 | 0 | 1 | 1 |
| End of life Disposal | 0.1 | 2 | 0 | 1 |
| Direct Environmental Impact Minimised | 0.1 | 1 | 1 | 0 |
| Social Impacts Avoided | 0.1 | 1 | 2 | 1 |
| | **WSM Score** | **1.5** | **1.2** | **1.0** |

In the case of Cape Leeuwin (Table 5), the costs are kept low compared to solar and the ability to meet demand is high. The battery is of the fully recyclable Lead Acid chemistry and the turbine size is only 2.5 metres in diameter, significantly reducing both aesthetic social impacts and potential impacts to bird and bat populations (although local placement plays a key role here and requires attention whenever considering potential sites). The turbine scores well here, edging out solar with diesel generation scores quite impacted by the emissions penalty. If we examine the case for wind at the other sites examined, the result is less clear-cut although the renewable technologies are still preferred over the fossil fuel generator. Wind has been impacted here due to reports of the negative aesthetic impacts of turbines for some people and otherwise would have been even with solar as preferred power source.

Table 7. WSM MCA Evaluation 3 sample locations except Cape Leeuwin

| **Evaluation Criteria** | **Criteria Weights** | **Alternatives** | | |
|---|---|---|---|---|
| | | Wind and Battery | PV Solar and Battery | Fossil Fuel Generator |
| Ability to meet demand | 0.2 | 1 | 1 | 2 |
| Emissions Avoided | 0.2 | 2 | 2 | 0 |
| Cost Minimised/ yr | 0.1 | 0 | 1 | 2 |
| Lifespan | 0.1 | 2 | 1 | 1 |
| Materials Availability | 0.1 | 0 | 1 | 1 |
| End of life Disposal | 0.1 | 2 | 0 | 1 |
| Direct Environmental Impact Minimised | 0.1 | 0 | 1 | 0 |
| Social Impacts Avoided | 0.1 | 1 | 2 | 1 |
| | **WSM Score** | **1.1** | **1.2** | **1.0** |

While this simple Multi-Criteria Analysis may seem subjective or unnecessary to some, it is a necessary component of decision making in today’s complex energy landscape and serves to illustrate how the cheapest, most capable technology is not always the correct choice.

# 5 Conclusion

This study sought to answer the question of whether micro-wind power and battery alone were suitable to power a stand-alone communications setup. Modelling in Homer Pro and a Multi-Criteria Analysis have been used to show that a wind turbine is indeed suitable for this task however the decision process is not straightforward, and the following observations have been made:

(i) The application of the communications setup is highly influential on whether wind and battery are a suitable power source. Although statistically calculated, a thoroughly modelled wind turbine will always be subject to variation in the wind resource and has the potential for dropouts if used as the only source of power.

(ii) 24 hour loads are an optimistic target and should be approached with caution

(iii) It is often said that wind and solar are complimentary however the addition of solar may only be helpful on a day-to-day basis and fail to improve reliability where seasonal macro-variations affect both solar and wind resources at the same time

(iv) Even for relatively small loads, as per Drouilhet, turbine power output often drastically underperforms estimation. Whilst micro-turbines are useful on their own in areas of excellent wind capacity, the results of this study support oversizing both turbine and battery as well as maximizing hub height wherever possible for increased capacity and reliability of supply

(v) Different decision-making processes and weightings are necessary to make informed decisions about energy concerns in today's emission conscious environment

Further research is recommended using high solidity turbine designs as the literature suggests potential increases in efficiency in lower wind density environments may positively affect small turbine applications. It is also clear from the literature study performed, that although photovoltaic solar is an excellent low cost, low emission technology, improvements need to be made to life expectancy and end-of-life disposal for PV panels. The ability to reclaim the rare materials used in production of these panels would at least ease one aspect of the standalone energy decision-making process. In summary, micro wind turbines have enormous potential for small-scale, standalone power needs and will likely become an important piece of society’s emission-free energy puzzle going forward. The correct choice of power generation technology type and size, however, involves a solution specifically tailored to its intended use.

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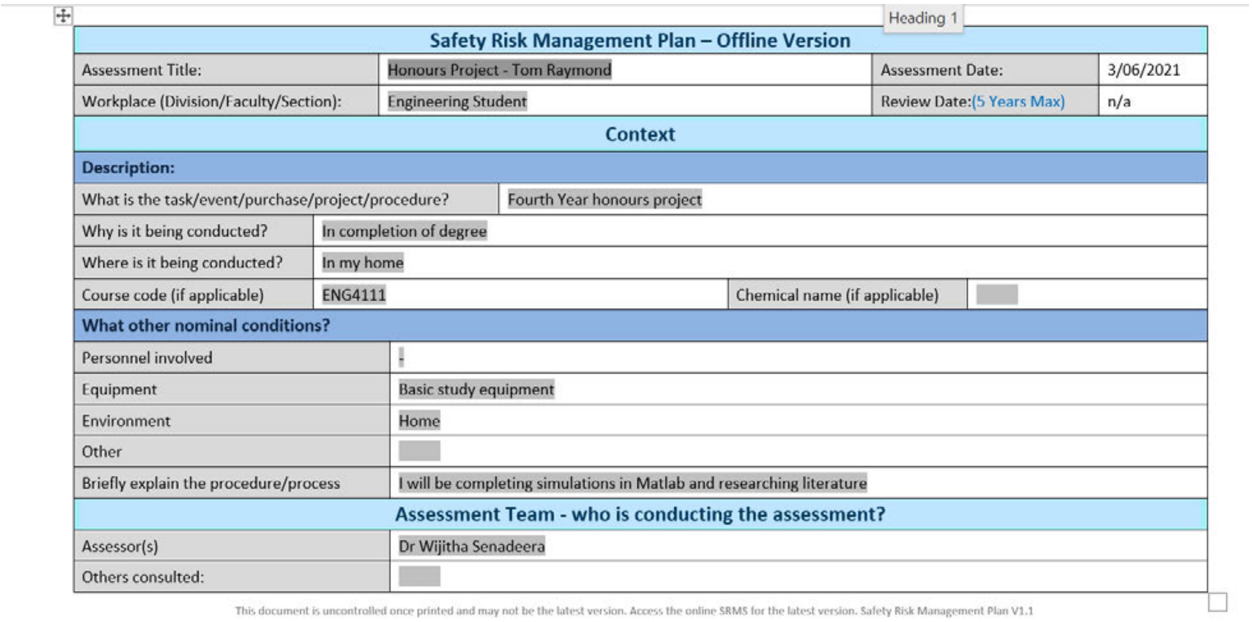
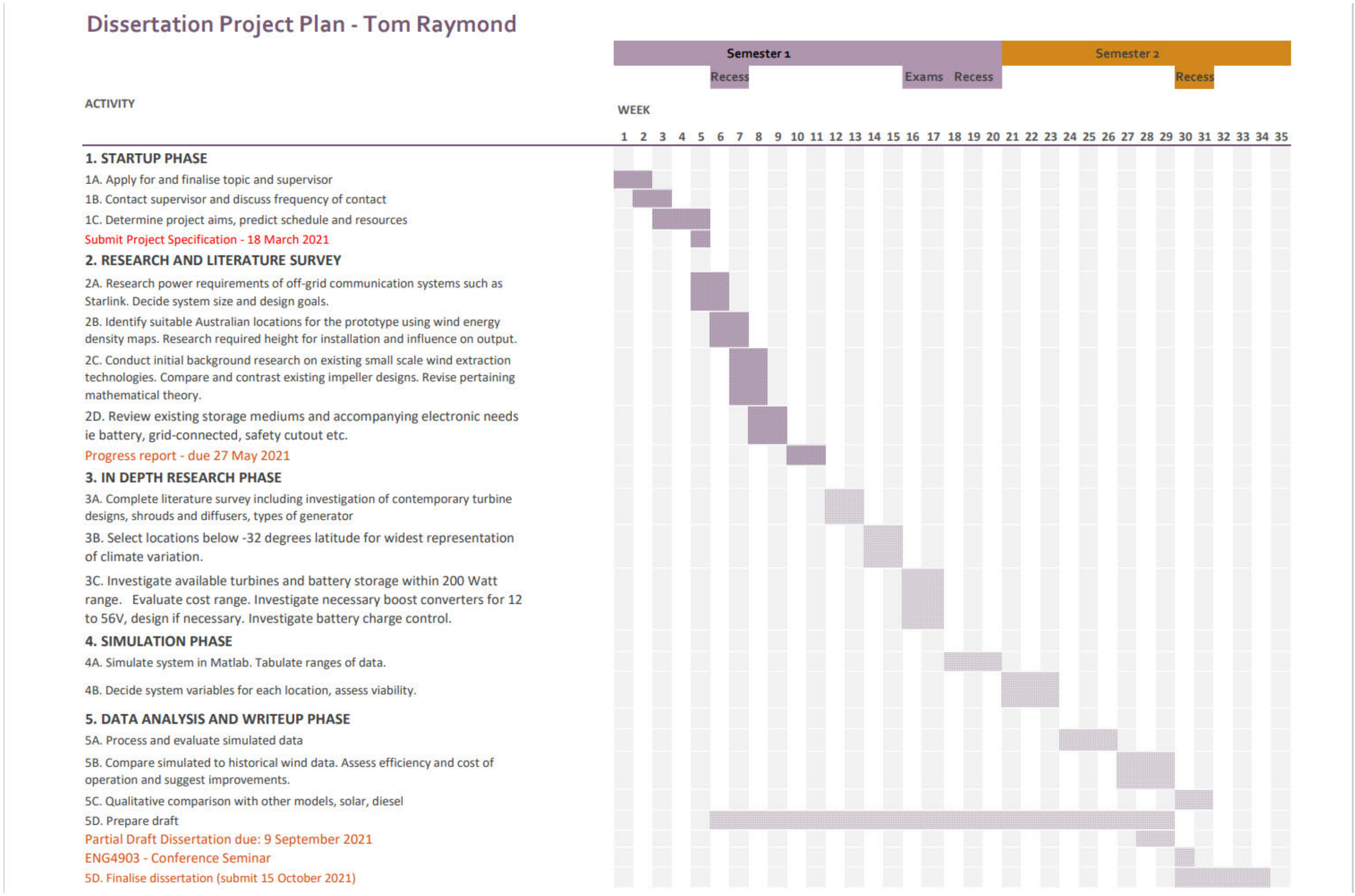
# 7 Appendices

## Appendix A: Risk Assessment Excerpt



| | | | |
|---|---|---|---|
| **Safety Risk Management Plan – Offline Version** | | | |
| Assessment Title: | Honours Project - Tom Raymond | Assessment Date: | 3/06/2021 |
| Workplace (Division/Faculty/Section): | Engineering Student | Review Date:(5 Years Max) | n/a |
| **Context** | | | |
| **Description:** | | | |
| What is the task/event/purchase/project/procedure? | Fourth Year honours project | | |
| Why is it being conducted? | In completion of degree | | |
| Where is it being conducted? | In my home | | |
| Course code (if applicable) | ENG4111 | Chemical name (if applicable) | |
| **What other nominal conditions?** | | | |
| Personnel involved | - | | |
| Equipment | Basic study equipment | | |
| Environment | Home | | |
| Other | | | |
| Briefly explain the procedure/process | I will be completing simulations in Matlab and researching literature | | |
| **Assessment Team - who is conducting the assessment?** | | | |
| Assessor(s) | Dr Wijitha Senadeera | | |
| Others consulted: | | | |

Appendix B: Cascaded Planning Schedule for project as at 27 May 2021



Dissertation Project Plan - Tom Raymond

ACTIVITY

1. STARTUP PHASE
1A. Apply for and finalise topic and supervisor
1B. Contact supervisor and discuss frequency of contact
1C. Determine project aims, predict schedule and resources
Submit Project Specification - 18 March 2021

2. RESEARCH AND LITERATURE SURVEY
2A. Research power requirements of off-grid communication systems such as Starlink. Decide system size and design goals.
2B. Identify suitable Australian locations for the prototype using wind energy density maps. Research required height for installation and influence on output.
2C. Conduct initial background research on existing small scale wind extraction technologies. Compare and contrast existing impeller designs. Revise pertaining mathematical theory.
2D. Review existing storage mediums and accompanying electronic needs ie battery, grid-connected, safety cutout etc.
Progress report - due 27 May 2021

3. IN DEPTH RESEARCH PHASE
3A. Complete literature survey including investigation of contemporary turbine designs, shrouds and diffusers, types of generator
3B. Select locations below -32 degrees latitude for widest representation of climate variation.
3C. Investigate available turbines and battery storage within 200 Watt range. Evaluate cost range. Investigate necessary boost converters for 12 to 56V, design if necessary. Investigate battery charge control.

4. SIMULATION PHASE
4A. Simulate system in Matlab. Tabulate ranges of data.
4B. Decide system variables for each location, assess viability.

5. DATA ANALYSIS AND WRITEUP PHASE
5A. Process and evaluate simulated data
5B. Compare simulated to historical wind data. Assess efficiency and cost of operation and suggest improvements.
5C. Qualitative comparison with other models, solar, diesel
5D. Prepare draft
Partial Draft Dissertation due: 9 September 2021
ENG4903 - Conference Seminar
5D. Finalise dissertation (submit 15 October 2021)