University of Southern Queensland

Faculty of Engineering and Surveying

Design of a Small Wind Turbine for a Rural Community in Australia

A dissertation submitted by

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ABSTRACT

The health and the very survival of humanity are dependent on the health of the planet, which is deteriorating rapidly due to the burning of fossil fuels. Renewable energy is of paramount importance to humanity for this reason. Wind turbines are an environmentally friendly power generation option for the sustainable future of our planet and of humanity.

The Australian Government has a Renewable Power Percentage target of 6% for 2010, increasing to 20% in 2020. Financial incentive schemes have recently been introduced in the form of Renewable Energy Certificates to encourage small power generation unit installations. The Australian wind power market is almost doubling annually and is expanding far quicker than the global market. The appetite and potential for Small Wind Turbine innovation in Australia is enormous.

This project aims to design a lightweight, durable and economical wind turbine (~ 1 kW) using commercially available parts and composite structural materials. The target market is farmers in rural Victoria, and paramount to the concept is that two farmers are able to erect the Small Wind Turbine and also pull it down for maintenance using only typical farming machinery such as a light truck.

The conceptual design evaluates the horizontal axis, three bladed, rigid hub, upwind configuration with passive control and tilt-up tower to be the most suitable for the application. The detailed design requires the Small Wind Turbine to be divided into six systems – rotor, drive train, nacelle, tower, machine controls and electrical system. The six systems are further divided into sub-components which are then designed as per the design load calculations for the target market. All components are freely available in component form in a variety of materials including composites.

The dissertation aims to make a positive contribution to the ethical, financial and environmental potential of the rural community in Australia. The research is expected to result in an SWT design which is viable for use by the rural community, economical to produce due to its simplicity and reliance on commercially available modular components.

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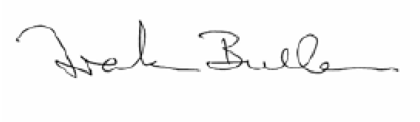

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I certify that the ideas, designs and experimental work, results, analysis and conclusions set out in this dissertation are entirely my own efforts, except where otherwise indicated and acknowledged.

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.

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NOMENCLATURE

The following abbreviations have been used throughout the text and bibliography:

AC	Alternating Current
BOD	Basis of Design
CFRC	Carbon Fibre Reinforced Composites
DC	Direct Current
DN	Nominal Diameter
ERET	Expanded Renewable Energy Target
EWM	Extreme Wind Model
GFRC	Glass Fibre Reinforced Composites
HAWT	Horizontal Axis Wind Turbine
MRET	Mandatory Renewable Energy Target
MVAWT	Magnetic Vertical Axis Wind Turbine
NTM	Normal Turbulence Model
NWP	Normal Wind Profile
PMG	Permanent Magnet Generator
REC	Renewable Energy Certificates
RPP	Renewable Power Percentage
SGU	Small Generating Unit
SWT	Small Wind Turbine
USQ	University of Southern Queensland
VAWT	Vertical Axis Wind Turbine
VRET	Victorian Renewable Energy Targets

GLOSSARY OF TERMS

The following terms have been used throughout the text and bibliography:

Angle of attack

A variable of blade property used to estimate HAWT performance.

Furling

A passive overspeed control mechanism by means of reducing the projected swept area.

Horizontal Axis Wind Turbine

Wind turbine whose axis is substantially parallel to the wind flow.

Hub

Fixture for attaching the blade or blade assembly to the rotor shaft.

Hub height

Height of the centre of the wind turbine rotor above the terrain surface.

Nacelle

Housing which contains the drive-train and other elements on top of a horizontal axis wind turbine tower.

Swept area

Projected area perpendicular to the wind direction that a rotor will describe during one complete rotation.

Small Wind Turbine

A system of 200 m^2 rotor swept area or less that converts kinetic energy in the wind to electrical energy.

Teetering

The wind turbine hub is mounted on bearings and can rock back and forth, in and out of the plane of rotation.

Topology

Overall layout of the wind turbine.

Tower shadow

Blocking of the airflow by the tower results in regions of reduced wind speed both upwind and downwind of the rotor.

Vertical Axis Wind Turbine

A wind turbine whose rotor axis is vertical.

Yaw mechanism

Mechanism used to turn the wind turbine rotor into the wind as the wind direction changes.

TABLE OF MATHEMATICAL SYMBOLS

The following mathematical symbols have been used throughout the text and bibliography:

a	Axial flow induction factor
a	Dimensionless slope parameter to be used in NTM calculations
A	Resource availability of system [hours per annum]
A	Area of rotor swept area [m^2]
AAR	Average annual return [$]
A_{proj}	Component area in its most unfavorable position [m^2]
$A_{proj,B}$	Planform area of the blade [m^2]
B	Number of blades
C_c	Installed capital cost [$]
C_d	Drag coefficient
C_f	Force coefficient
C_P	Coefficient of power
C_T	Coefficient of thrust
D	Deeming period [years]
D_i	Inside diameter [m]
D_o	Outside diameter [m]
F	Force on each component [N]
F_{total}	Total axial force [N]
$F_{x\text{-}shaft}$	Axial shaft / thrust load [N]
F_{zB}	Centrifugal load in the blade root [N]
g	Acceleration due to gravity [9.81 m/s^2]
I	Moment of inertia of the section [m^4]
I_{15}	Characteristic value of hub height turbulence intensity at 15 m/s
k	von Karman’s constant [0.4]
L	Length [m]
L_{lt}	Distance between the lifting point and the top of the tower [m]
m_B	Blade mass [kg]
$m_{overhang}$	Mass of the tower between the lifting point and the tower top [kg]
$m_{towertop}$	Mass of the rotor and nacelle combined [kg]
M	Bending moment [Nm]

M_{tower}	Bending moment of the tower at the lifting point attachment [Nm]
MV	Multiplied value
n_{design}	Design rotational speed [RPM]
N	Number of REC entitlements
P	Rated power output [W]
P_{design}	Design power [W]
P_r	Rotor power [W]
Q_{design}	Design shaft torque [Nm]
R	Rotor radius [m]
R_{cog}	Radius to the rotor centre of gravity [m]
REC	Value of the Renewable Energy Certificates [$]
SP	Simple payback period [years]
$U(z)$	Wind speed [m/s]
U^*	Friction velocity [m/s]
U_∞	Free stream velocity [m/s]
V_{ave}	Annual average wind speed at hub height [m/s]
V_{design}	Design wind speed [m/s]
$V_{e1}(z)$	1 year extreme wind speed [m/s]
$V_{e50}(z)$	50 year extreme wind speed [m/s]
V_{hub}	Air velocity at the hub [m/s]
V_{ref}	Reference wind speed [m/s]
$V(z)$	Average wind speed as a function of height z [m/s]
y	Distance from the neutral axis [m]
z	Height [m]
z_{hub}	Hub height of the wind turbine [m]
z_0	Surface roughness length [m]
α	Power law exponent [0.2]
λ	Tip speed ratio
λ_{design}	Design tip speed ratio
ρ	Density [kg/m^3]
σ	Maximum stress [Pa]
ω_{design}	Design rotational speed [rad/s]
$\omega_{n,\text{design}}$	Design rotor speed [rad/s]
Ω	Rotational speed [rad/s]
η	Drive train efficiency

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CHAPTER 1 – INTRODUCTION

1.1 Outline of Study

The transition from fossil based energy systems to one based on renewable energies is of paramount importance to humanity for the following three reasons:

- The health and the very survival of humanity are dependent on the health of the planet, which is deteriorating rapidly due to the burning of fossil fuels.
- Energy independence and security of energy supplies for all countries would enhance and stabilise global security and peace.
- The economic potential for the development of new markets, technologies and industries is enormous.

There are many viable alternatives to fossil fuel based energy, including nuclear, heliostat, biomass, wind, solar, hydro, tidal, wave, ocean thermal and marine current. Wind turbines are one of the more environmentally friendly options and can be summarised as a modular renewable energy technology which attracts moderate cost, has minimal environmental impact and has varying degrees visual impact depending on the design. Unfortunately the energy source (wind) is not entirely predictable, is inconsistent & cannot be stored.

1.2 Introduction

Globally the wind generated power has been doubling every three years since 1992. In Australian the wind power market grew slowly up until 2007, however sharp increases in installed capacity are still expected by almost doubling annually until well beyond 2010. This means the Australian wind market was expected to expand far quicker than the global market during 2010.

China was the world’s largest manufacturer Small Wind Turbines (SWT) at the time of reporting in 2008, with roughly 170,000 SWTs installed totalling 42 MW generating capacity (ABS Energy Research 2008). This equated to roughly 0.33% of the installed capacity in China in 2008 coming from SWTs. China's total energy generating capacity from wind power was 12,906 MW in 2008 compared to 1,503 MW for Australia, or roughly nine times that of Australia (ABS Energy Research 2009).

In Australian the primary government framework for the transition to renewable energy is the Commonwealth Government's Expanded Renewable Energy Target (ERET) which includes the Renewable Power Percentage (RPP) target, set at 5.98% for 2010 and increasing to a 20% share of renewable in Australia's electricity supply by 2020 (Australian Government Office of the Renewable Energy Regulator 2010). The ERET provides both large and small power generation unit installations (including SWT) with a financial incentive through the creation and trade of Renewable Energy Certificates (REC). Each REC created from a renewable energy source can be sold for a negotiated price and transferred in a market based online system called the REC Registry.

1.3 The Problem

Because SWT design is an area of enormous economic potential, most research and development has been carried out by individual companies and is rigorously protected by privacy laws and copyright protection. There is a large body of literature available for large wind turbine design, however very little literature is available relating to SWT innovation and design.

The common three bladed Horizontal Axis Wind Turbine (HAWT) is the industry standard for SWT design due mainly to its simplicity and high efficiency. More research is required in the marketplace relating to the suitability of various design options with an emphasis on the growing trend towards mechanical simplicity. Future SWT designs are likely to trend towards reduced mechanical complexity and overall simplification. More refined mechanical designs, the introduction of magnetic levitation designs and improvement of electrical sub-systems are likely be major areas of research and development in upcoming years.

1.4 Research Objectives

The project aim is to design a lightweight, durable and economical wind turbine (~1 kW) using commercially available parts and composite structural materials. The project objectives to achieve the aim can be summarised as follows:

1. Research background information of wind turbine design specifically relating to SWTs.
2. Critically evaluate past, current & emerging wind turbine component technologies to assess their usefulness in this application.
3. Obtain wind energy availability data for regional locations in Victoria and identify suitable data.
4. Carry out engineering design & analysis of mechanical components with an emphasis on development of innovative alternatives.
5. Evaluate alternative material selection including composite structural materials SWT based on their commercial suitability for this application.
6. Design a SWT assembly including rotor, drive system, generator and tower using commercially available parts.

As time permits:

7. Evaluate the manufacturing requirements, cost and benefits associated with the selected design.
8. Produce a set of manufacturing drawings for the selected assemblies.

The target market is farmers in rural Victoria, and paramount to the concept is that two farmers are able to erect the Small Wind Turbine and also pull it down for maintenance using only typical farming machinery such as a light truck or tractor.

1.5 Project Methodology

The project is divided into six chapters:

- Chapter 1 – Introduction
- Chapter 2 – Literature Review
- Chapter 3 – Design and methodology overview
- Chapter 4 – Detailed design and validation
- Chapter 5 – Results and discussion
- Chapter 6 – Conclusion

Chapter 1 introduces the project and justifies the need for the SWT being designed.

Chapter 2 is the Literature Review which aims to establish the importance wind turbines in the modern world and in particular SWTs. It also aims to justify the need for new SWT designs and to provide some background to the development of such designs.

Chapter 3 section explores some theory relevant to SWT design and discovers how to apply relevant theory to the specific design aims of the project. It also develops a methodology for designing the various components as sub-systems and combining the entire system as a feasible commercial package. Identification of suitable design data and standards is established.

Chapter 4 applies the theory to specific component design to develop the SWT package. Different options and overall layout (topology) features are compared and assessed for suitability and specific designs are chosen to suit the project aims and objectives. Where possible different commercially available components and materials are assessed and chosen for the design.

Chapter 5 evaluates performance data relating to the design chosen and the manufacturing requirements are assessed, and also the financial performance expectations and cost benefit study.

Chapter 6 delivers overall conclusions to the design of the SWT, as well as an assessment of the completeness and adequacy of the project. Suggestions are made regarding the direction of further research and design for the work in the future.

1.6 Consequential Effects

The challenge is to make the SWT design viable for Australian farmers. In remote areas this could have positive effects on the farmers and the community in the following ways:

- Enhance the quality of life of the farmers by providing a source of electricity where none existed before, thus easing their hardship.
- Offer a sense of achievement and increased self-esteem by creating 'something from nothing', by generating electricity from the wind.
- Contribute to the farmer's commercial success by expanding their infrastructure for business activities and providing new opportunities.
- Contribute to long term financial success by generating electricity from a free resource instead of paying for electricity consumption per kWh. This is especially relevant after the initial capital payback period of the SWT installation.
- Provide a means of earning money from the government through current and future renewable energy incentives (currently the REC scheme).
- Promote the use of renewable energy to the community thus making a positive contribution to reducing the environmental degradation of the planet due to burning fossil fuels.
- Contribute to the growth of an emerging industry in ethically sound sectors of renewable energy and wind turbines.

The negative effects must also be considered:

- Capital cost of the SWT installation may strain the financial resources of the owner.

- Environmental impacts introduced such as avian interaction, visual disturbance, noise pollution and land usage.
- Safety hazards (albeit minimal) associated with rotor blade breakage.
- Future cost associated with dismantling and removal of SWT installation when its operating life expires.

Overall the positive consequential effects far outweigh the negative effects from ethical, environmental and financial perspectives.

1.7 Summary

The dissertation aims to make a positive contribution to the ethical, financial and environmental potential of the rural community in Australia. It promises to be a worthwhile contribution to society as a whole and to the promotion of renewable energy. The economic, moral and environmental incentives are enormous for establishing a wind turbine manufacturing base in Australia. This is a new industry which is undergoing enormous growth and is almost doubling annually. Australia has a huge potential to contribute to the growth of this industry but must act swiftly to claim some of the market from the dominant manufacturing bases of China and USA.

The research is expected to result in an SWT design which can be further refined for installation in the rural community, and is economical to produce due to its simplicity and reliance on commercially available modular components. Although time constraints do not allow a full design to be completed, or the assembly of a prototype for testing, the design offered is expected to be sufficiently researched and developed to provide an excellent base for more detailed design and testing.

CHAPTER 2 - LITERATURE REVIEW

2.1 Introduction

This literature review aims to establish the importance wind turbines in the modern world and in particular SWTs. It also aims to justify the need for new SWT designs and to provide some background to the development of such designs. After examining the importance of renewable energy in today's society, the incentives for developing renewable energy and some of the current policies and objectives are discussed at the State Government, Federal Government and global level. The role of wind power and how it compares to other renewable energy options are also examined, as well as the trends for renewable energy on both the national and global platforms.

The historical development of wind turbines is discussed, leading into the first attempts at generating electricity and then the development of modern SWT including the evolution of some design features we see in current SWTs. Various SWT configuration options are presented as well as evaluations of some popular configurations in the current commercial market. Some of the latest developments in small wind turbine configurations are also investigated along with their advantages and disadvantages.

The performance criteria necessary in the design of SWT are examined, as well as some of the theory and calculations necessary to develop such performance criteria. Also an investigation into the associated design standards and a discussion of how they relate to performance criteria are presented. Finally the environmental and safety aspects relating to small wind turbine design and implementation are examined. The conclusion to this chapter is a summary of the topics discussed and an evaluation of the project direction.

2.2 The Renewable Energy Situation

2.2.1 The Importance of Renewable Energy

Mendonca (2007) revealed that the transition from fossil based energy systems to one based on renewable energies is of paramount importance to humanity for the following three reasons:

- The health and the very survival of humanity are dependent on the health of the planet, which is deteriorating rapidly due to the burning of fossil fuels.
- Energy independence and security of energy supplies for all countries would enhance and stabilise global security and peace.
- The economic potential for the development of new markets, technologies and industries is enormous.

The obstacles and challenges relating to the transition from fossil fuels to renewable energy are massive and were summarised by Mendonca (2007) as follows:

- Feed in Tariff Laws
- Renewable support for other sectors such as heating and transport
- Differing economic models of different countries
- Technicalities of integrating renewable into the grid
- Kyoto Protocol
- Emissions trading
- Carbon capping
- Political energy policy decision making
- Ecological tax reform
- Peak oil
- Issues relating to the emerging economies of India, Brazil & China
- Research into the dangers of fossil fuels and nuclear energy
- Liberalisation of energy markets
- Creation of an international treaty on accelerated deployment of renewable.

2.2.2 Incentives for Renewable Energy

Australian and global policies relating to renewable energy have had a varied and turbulent history. Some recent highlights are:

- The senate rejection of Kevin Rudd's emission trading scheme on December 2, 2009.
- The failure of the 2009 Copenhagen summit of 190 governments to agree on carbon cutting targets to combat global warming.

On 15 June, 2004, the Australian Government reconfirmed its commitment to the Mandatory Renewable Energy Target (MRET) scheme as 9,500 GWh by 2010. At that time Victoria had the Victorian Renewable Energy Target (VRET) scheme in which 10% of all retail electricity sales were to be sourced from renewable energy by 2016 (ABS Energy Research 2008). However the VRET scheme was to be phased out by transitioning it in stages in 2010 to the Commonwealth's Expanded Renewable Energy Target [ERET] (Essential Service Commission 2010).

The ERET scheme was amended in March 2010 to include the Renewable Power Percentage (RPP) target, set at 5.98% for 2010 and increasing to a 20% share of renewable energy in Australia's electricity supply by 2020 (Australian Government Office of the Renewable Energy Regulator 2010). The transition from MRET to ERET is shown in figure 2.1:

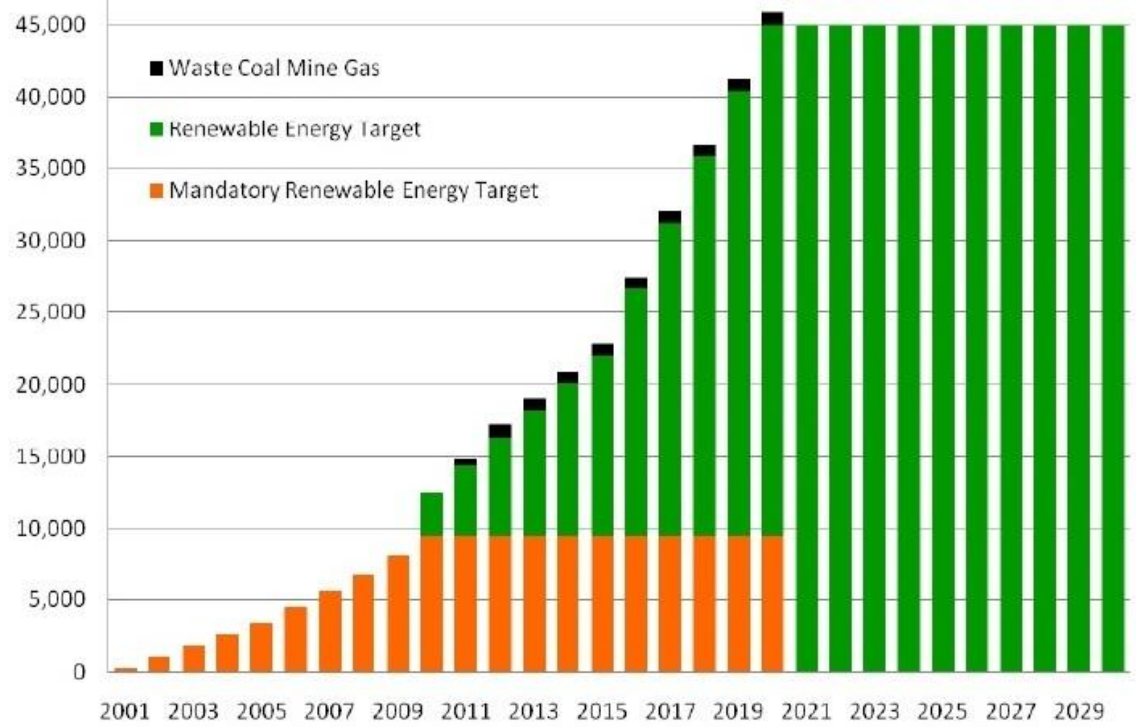


Figure 2.1: Annual Renewable Energy Targets (GWh) (Australian Government Office of the Renewable Energy Regulator 2010)

The ERET provides both large and small power generation unit installations (including SWT) with a financial incentive through the creation and trade of Renewable Energy Certificates (REC). Each REC created from a renewable energy source can be sold for a negotiated price and transferred in a market based online system called the REC Registry.

SWTs are classed as a Small Generating Unit (SGU) if they have a system capacity below 10 kW and a total annual electricity output less than 25 MWh. Solar Credits are a mechanism by which the number of RECs eligible are multiplied for the first 1.5 kW of capacity installed. The Australian Government Office of the Renewable Energy Regulator (2009) provided the following guidelines for calculating RECs for SWTs:

$$N = 0.00095 \times P \times A \times MV \times D \tag{2.1}$$

where N is the number of REC entitlements
P is the rated power output [kW]
A is the resource availability of system [hrs/annum]; default 2000
MV is the multiplied value from table 4 [solar credits]
D is the deeming period [years]

For example, if you wished to calculate RECs on a 5 year basis for a system with a rating of 1.0 kW, installed in 2011 and with the default wind resource availability of 2000 hours:

$$\begin{aligned} N &= 0.00095 \times P \times A \times MV \times D \\ &= 0.00095 \times 1.0 \times 2000 \times 5 \times 5 \\ &= 47 \end{aligned}$$

The owner of these 47 RECs could either:

- Assign the RECs to an agent in exchange for financial benefit in the form of delayed payment or upfront discount.
- Become registered in the online REC register and sell then to a registered agent at any time during the life of the scheme.

Because the REC register is an open market the spot price is subject to fluctuations, evident in figure 2.2, which shows that the price in May 2010 was approximately $45 per REC. The calculated incentive for installing a 1 kW SWT in 2011 for a five year period based on May 2010 spot price was thus calculated:

$$\$45 \times 47 \text{ RECs} = \$2115$$

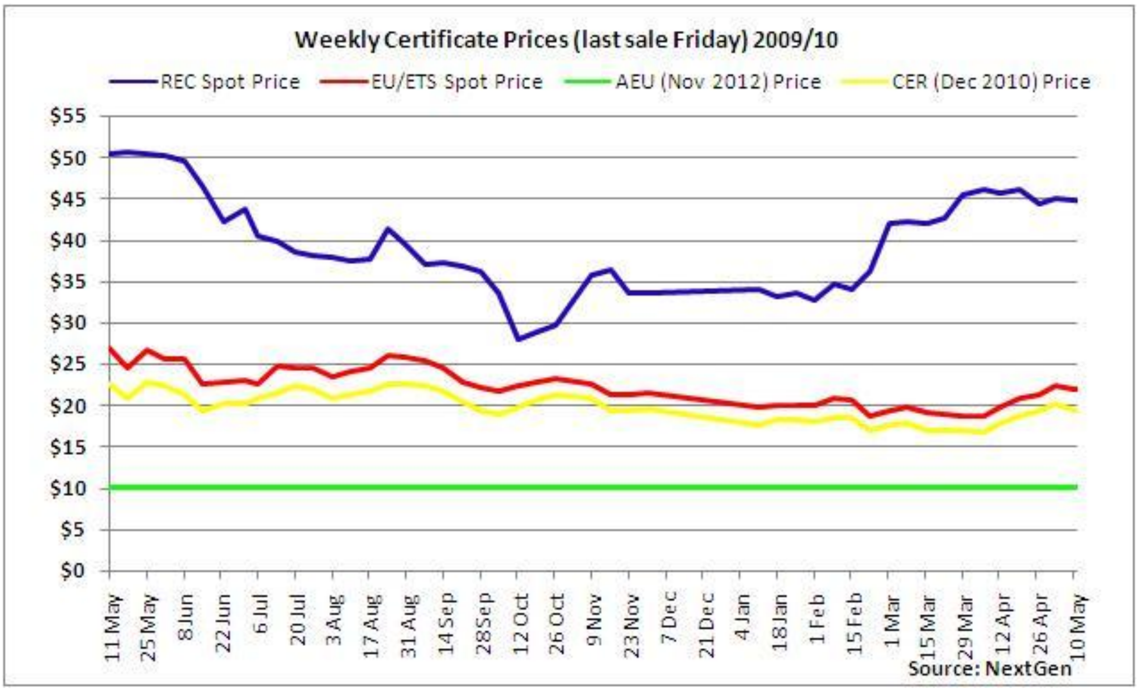


Figure 2.2: Weekly REC prices (Green Energy Markets 2010)

There are various incentive models in use around the world for the promotion of renewable energies, the main ones being:

- The Feed-in Model
- The Quota Model
- The Tendering System
- Net Metering

Mendonca (2007) claimed that when comparing the incentives used worldwide, the Feed-in Laws have produced the quickest, lowest cost deployment of renewable technologies in countries which have implemented them. The basic Feed-in model comprises of a set of laws in which producers of renewable energy are paid a set rate for their electricity generated, which is defined by the technology used and the size of the installation. This is somewhat different to the REC model now operating under the Australian Government.

2.2.3 Advantages of Wind Power

Wind is not the only attractive solution to renewable energy targets. Table 2.1 illustrates the various options available and shows the comparable advantages and disadvantages of wind power. This table appears to be more relevant to large wind turbines due to the claim that wind energy involves large capital cost, which is not the case with small wind turbines.

	Renew-able	Low capital cost	Low running cost	Lower/Minimal environmental impact	Predictable	Minimal visual impact	Modular	Base load
Fossil (basic)	×	✓	×	×	✓	×	×	✓
Fossil (advanced)	×	×	×	✓	✓	×	×	✓
Nuclear	×	×	✓	✓✓	✓	×	×	✓
Biomass	✓	×	×	✓✓	✓	×	×	✓
Wind	✓	×	✓	✓	×	×	✓	×
Solar	✓	××	✓	✓✓	×	×	✓	×
Hydro	✓	××	✓	✓	✓	×	×	×/✓
Tidal	✓	×	✓	✓	✓	×	×	×
Wave	✓	×	✓	✓✓	✓	✓	✓	✓
Ocean Thermal	✓	×	✓	✓✓	✓	✓	✓	✓
Marine Current	✓	×	✓	✓✓	✓	✓	✓	✓

Table 2.1: Advantages and disadvantages of different types of renewable energy (ABS Energy Research 2008)

SWTs can be summarised as a modular renewable energy technology which attracts moderate cost, has minimal environmental impact and has varying degrees visual impact depending on the design. Unfortunately the energy source (wind) is not entirely predictable, is inconsistent & cannot be stored.

2.2.4 National & Global Wind Energy Trends

Globally the wind generating power doubled between 2005 & 2008 as can be seen in figure 2.3. It was estimated to reach 236 GW by the end of 2012, almost double the 2008 level (ABS Energy Research 2009).

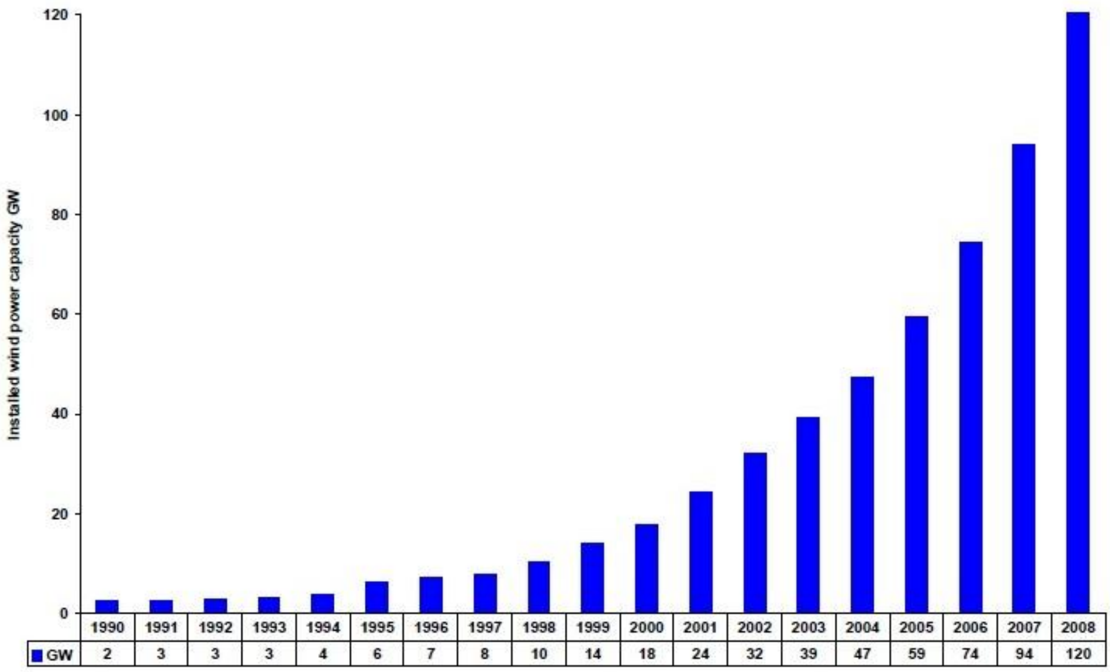


Figure 2.3: Global wind power installed capacity GW 1990-2008 (ABS Energy Research 2008)

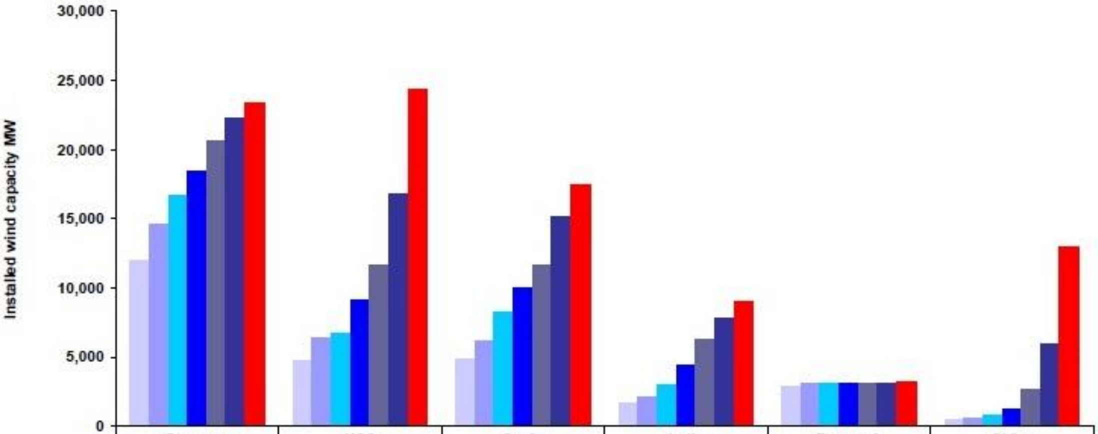
The Australian wind power market grew slowly, from 746 MW of installed capacity in 2005 to 824 MW in 2007. After 2007 sharp installed capacity increases were expected by almost doubling annually until beyond 2010. This meant the Australian wind market was expanding far quicker than the global market in 2010.

1990	1995	2000	2005	2006	2007	2008*	2009*	2010*
0	2	33	746	817	824	1,503	2,741	5,000

*Predicted

Table 2.2: Australian wind power installed capacity MW 1990-2010 (ABS Energy Research 2008)

The world wind energy industry was dominated by five countries until 2004: Denmark, USA, Germany, Spain and India. In 2006 China became significant and surged forward in 2008, as did USA. China was the world’s largest manufacturer of SWTs at the time of reporting in 2008, with roughly 170,000 SWTs installed totalling 42 MW generating capacity (ABS Energy Research 2008). This equated to roughly 0.33% of the installed capacity in China in 2008 coming from SWTs.



	Germany	USA	Spain	India	Denmark	China
Dec 2002	11,994	4,685	4,825	1,702	2,880	468
Dec 2003	14,609	6,374	6,202	2,110	3,123	568
Dec 2004	16,629	6,750	8,263	3,000	3,117	764
Dec 2005	18,428	9,149	10,027	4,430	3,122	1,260
Dec 2006	20,622	11,603	11,614	6,270	3,136	2,604
Dec 2007	22,247	16,818	15,145	7,845	3,125	5,906
Dec 2008	23,320	24,319	17,500	9,039	3,198	12,906

Figure 2.4: Installed wind power capacity of the six leading countries, 2002 to 2008 (ABS Energy Research 2008)

2.3 Historical Development of Wind Turbines

2.3.1 Ancient Windmills

Windmills first appeared for the sole purpose of grinding/milling grain. Stone windmills may have originated in Egypt some 3000 years ago (Hau 2000), but the first reliable information indicated 644 AD around the Persian-Afghan Border. Manwell, McGowan & Rogers (2003) argued that the first windmills on record were built by the Persians in approximately 900 AD which were vertical axis drag type devices.

2.3.2 The Middle Ages and European Windmills

During the Middle Ages wind energy was used for a wide variety of mechanical tasks including water pumping, grinding grain, wood sawing and powering tools. The first windmill with horizontal axis of rotation first appeared in the year 1119 in northwest

Europe (Hau 2000). Windmills then spread quickly all over Europe with numerous post windmills found in Germany in the 13th century.

The European windmills were divided into five broad categories (Hau 2000):

1. Post windmill.
   The entire mill-house revolved around a post or trestle, used to mill grain. The mill house was manually turned into the wind direction with the help of the so-called tail fixed at the back wall.

2. Hollow post windmill
   Introduced in the 15th century, a fixed base was introduced which housed a water pump drive. These were mainly used for draining water but were later adapted to milling grain and sawing wood. A vertical shaft was fed through a hollow post to connect the mill-house to the pump base, so it could be yawed into the wind.

3. Tower windmill
   These incorporated a round stone tower and were popular in the Mediterranean regions. Initially it could not be yawed but was later developed so that the wind shaft could be manually repositioned.

4. Dutch windmill
   A larger and more powerful windmill which had a firm base to house various auxiliary machines. These were the dominant windmill design by the mid 19th century. The base was fixed with only the upper roof and the rotor being the yawing components.

5. Paltrock mill
   Similar to the post windmill, except the entire mill house turned on a wooden or iron bearing which was set into the ground. These were developed in Holland in the 16th or 17th century as wood sawing mills

Wind was a major source of mechanical energy in Europe right through until the industrial revolution (1760 to 1850), when coal powered steam engines took over. The economic significance of windmills increased in Europe until the mid 19th century when

Netherlands had more than 9,000 windmills, Germany had 20,000, and there were a total of about 200,000 in Europe. After the introduction of the steam engine and the electrification of the rural areas the count declined to 1,400 windmills in Holland in 1943 (Hau 2000). Prior to the industrial revolution, some of the major design achievements were listed as follows:

Drive Train

- Greased hardwood obtuse-angle bevel gear set with replaceable teeth.
- Wooden shoe or band brake.
- Tapered main shaft.
- Tilted back main shaft.

Rotors

- Tapered rotor blade stocks.
- Airfoil blade shape including some twist.

Rotor speed control

- Fixed pitch varying solidity blades.
- Slats which were regulated by a continuous control system.

Load Control

- Automatic stone-clearance control using a fly ball governor.
- Power adjustment by an automatic control system.

Yaw Control

- The majority of the mill was stationary, only the top would be moved to face the wind.
- Fan tail rotor system and small side rotor.

Some of the early European windmills operated for 400-600 years. The basic design principles in these mills were simple – easily replaceable parts were designed to fail first, protecting the major assemblies from destruction.

2.3.3 American Wind Turbines

In the early 19th century the settlers in rural USA used windmills to pump water up from wells using European windmill designs. In 1850 Daniel Halladay invented a new type of windmill which was self regulating and was safe from destruction in storms (Hau 2000). Using the controls used in steam engines which opened a safety valve in the case of overspeed, he invented a windmill which incorporated the following design features:

- Blades were loosely suspended on a ring.
- The blades were connected such that a movement of the collar ring effected an alteration of the blade pitch angle, triggered by centrifugal forces.
- The wind wheel was divided into six sections.
- A wind vane took care of the yawing.
- The water pump was driven by a crank gear.

In 1929 Reverend Leonhard R.Wheeler came up with a new design called Eclipse (Hau 2000), which became the new standard of the American wind turbine. Instead of dividing the wind wheel into sections, Wheeler mounted an additional wind vane which positioned at right angles to the wind direction. With the help of this vane the entire wind wheel was turned out of the wind. The vane was connected to a weight so that then the wind speed declined, the wheel turned back to its original position. The Eclipse wind turbine was of enormous commercial significance, and by 1930 more than six million American wind turbine units had been manufactured (Hau 2000). In the 21st century the estimate is 150,000 remaining units.

Figure 2.5: The Eclipse wind turbine (source unknown)

2.3.4 Early Wind Generation of Electricity

The first recorded electricity generating wind turbine was in 1891 when Professor P.LaCour installed an experimental wind turbine in Denmark with a 22.8 m diameter rotor and four twisted, constant chord blades with remotely controlled slats. It was an upwind machine winded by two small fantails which drove two 9 kW generators (Eggleston & Stoddard 1987).

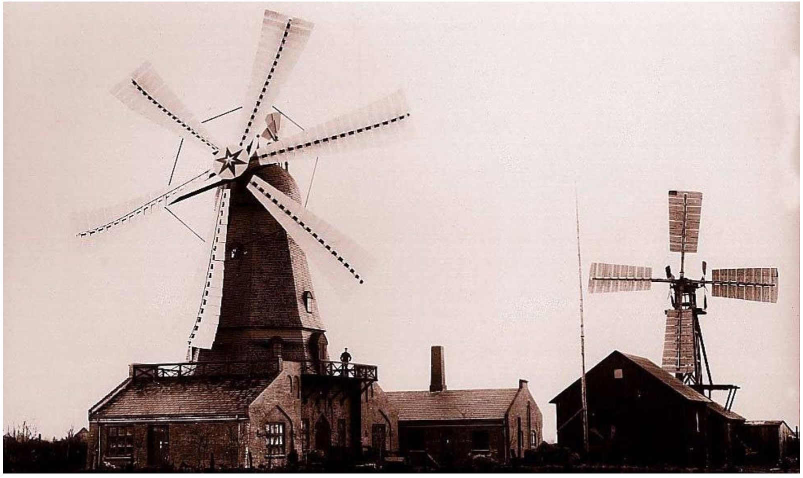


Figure 2.6: Two of LaCour's test wind turbines in 1897 in Denmark (Danish Wind Industry Association 2003)

LaCour and the Likkegard Company had built 72 electricity generating wind turbines by 1908 and 120 by 1918 (Hau 2000). Power outputs ranged from 10 to 35 kW, rotors were four shutter blades up to 20m diameter, and yawing was carried out by two fan tails. The electrical generator was housed at the base of the latticed steel tower and was driven by the rotor via a long shaft and intermediary gearbox. Electricity was fed into the grid via a buffer battery and efficiency was rated at about 22%; at a good site energy yield amounted to about 50,000 kWh.

2.3.5 Development of Small Wind Turbines

In 1922, the brothers Marcellus and Joseph Jacobs started to develop a small wind turbine named the Jacobs Wincharger. This was in essence the birth of the SWT. Initially they tested two bladed aircraft propellers and then moved onto a three bladed rotor with a 4m diameter which directly drove a DC generator. From 1920 to 1960 tens of thousands of these were produced and sold in various versions from 1.8 to 3 kW rated power. They were extraordinarily reliable, with one taken by the American Admiral Byrd on his Antarctic expedition which operated without maintenance for 22 years from 1933 until l955 (Hau 2000).

Figure 2.7: Jacobs 2.5 kW unit – 1940's (Jacobs Wind Energy Systems 2010)

2.4 SWT Topology

2.4.1 Wind Turbine Concepts

A wind turbine is a machine which converts power from the wind into electricity. It generally does this by using the basic aerodynamic force of lift to produce a net positive torque on a rotating shaft, resulting in the production of mechanical power. This power is then transformed to electricity in a generator. The production of energy is inherently fluctuating due to the fact that the wind turbine can only produce energy in response to the wind that is immediately available; it is not possible to store the wind and use it at a later time.

There are two basic wind turbine types: Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT). The main configurations for HAWTs are illustrated in figure 2.8, which all rely on aerodynamic lift forces. Large turbines usually have a powered yaw system to turn the rotor into the wind, but most small turbines rely on a simpler tail fin.

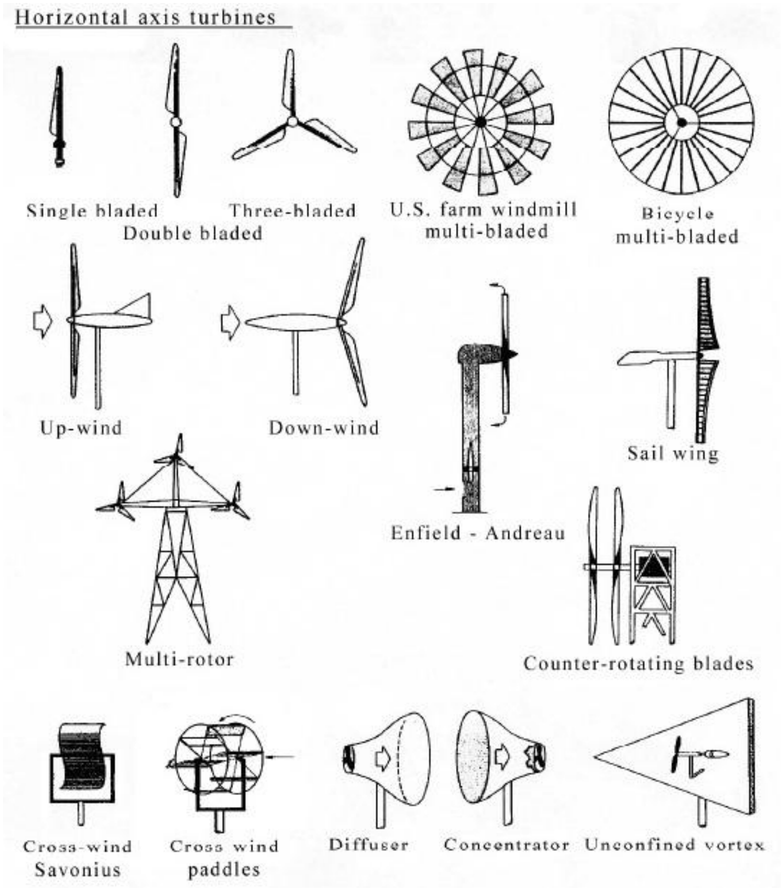


Figure 2.8: Various concepts for Horizontal Axis Wind Turbines (Manwell, McGowan & Rogers 2003)

The modern HAWT can be summarised into a series of systems and components as illustrated in table 2.3:

System	Component
Rotor	Blades
	Supporting Hub
Drive Train	Shafts
	Gearbox
	Coupling
	Mechanical Brake
	Generator
Nacelle & Main Frame	Wind Turbine Housing
	Bedplate
	Yaw System
Tower & Foundation	
Machine Controls	
Electrical Systems	Cables
	Switchgear
	Transformers
	Electronic Power Converters

Table 2.3: Major systems & components of a Horizontal Axis Wind Turbine (Manwell, McGowan & Rogers 2003)

Various other non HAWT configurations are possible as per figure 2.9, which embody the VAWT family of wind turbines. Of all these configurations the Savonius and the Giromill are currently the most popular VAWTs available in the commercial sector.

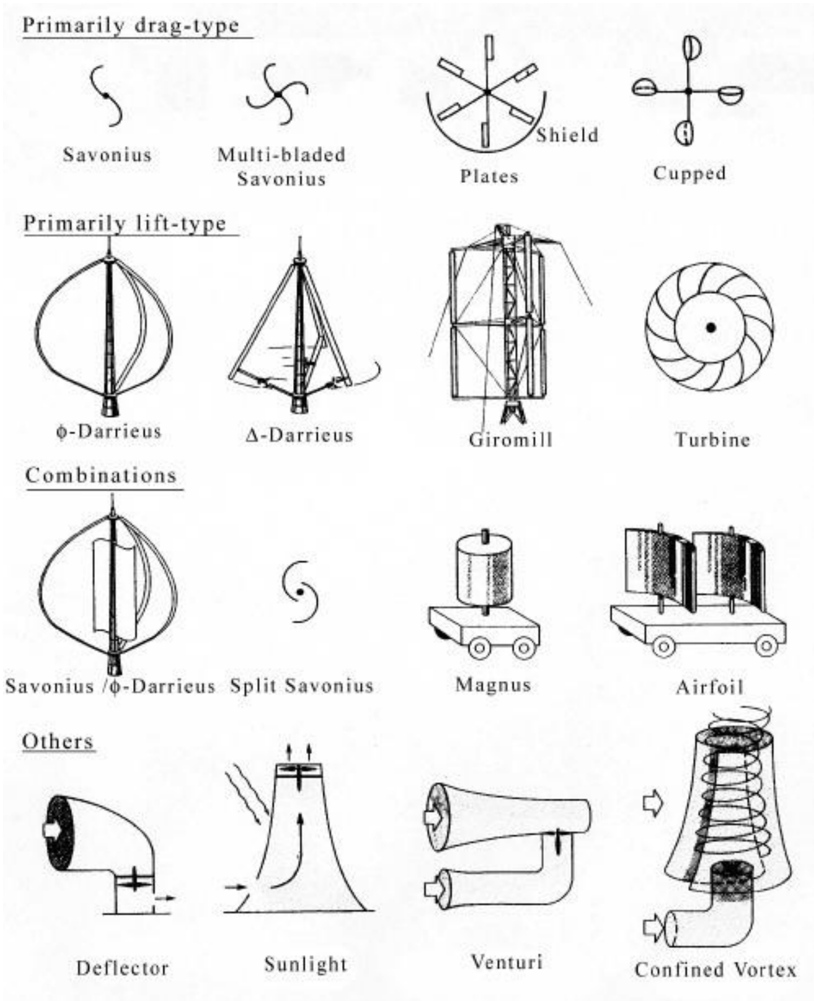


Figure 2.9: Various concepts for Vertical Axis Wind Turbines (Manwell, McGowan & Rogers 2003)

The main advantages of VAWTs are as follows:

- Quieter than HAWTs and are thus more suitable for locations near people and animals.
- Do not require a yaw mechanism and immediately respond to changes in wind direction.
- Reduce mechanical failures due the yaw mechanism.
- Have the generator at the bottom allowing for easier maintenance.

The major disadvantages of VAWTs are as follows:

- The wind passes through or by the rotor twice, adding resistance and making them less efficient than the HAWTs.

- Power coefficient is much less than HAWTs meaning that VAWTs are much less efficient (refer to figure 2.19).

Both HAWTs and VAWTs continue to undergo continual development. The newest advances in SWTs are evidently in the area of control, gradually evolving to contain fewer moving parts. This means less contact, less wear and longer life (consider the solar panel with very few moving parts). The ultimate goal is to figure out how to extract energy from the wind with zero moving parts.

2.4.2 Current Trends

A survey was carried out by the author examining 18 manufacturers of SWTs to attempt to establish current trends for commercially available SWT topology in the vicinity of 1 kW power output rating. The trend was clearly in favour of three bladed HAWTs in this bracket. In the 2-3 kW bracket there was a higher presence of VAWTs and related design variations, however 1 kW VAWTs appeared less popular due to cost restrictions necessitating simpler designs and thus favouring HAWTs. Results of the survey are summarised in table 2.4 and detailed in Appendix B.

SWT Configuration	Count	Percentage
HAWT three blade	11	61%
HAWT 5 blade	2	11%
VAWT	5	28%

Table 2.4: Survey of SWT configurations (Authors own table)

The following observations were made regarding the SWTs surveyed:

- All HAWTs were upwind design.
- All HAWTs incorporated wind vane yaw systems.
- All SWTs used brushless permanent magnet alternators.
- All SWT towers were steel construction, offered in guyed and free standing.

- 28% of all SWTs used fibreglass & 16% used carbon fibre reinforced fibreglass rotor blades.
- Speed control designs were varied with microprocessor, passive pitch control and passive sideways furling each being the most popular and each accounting for 14% of all SWTs.

2.4.3 Recent Innovative Designs

Bergey Windpower's 1 kW BWC XL1 is a good example of the conventional HAWT three bladed upwind design, which was the predominant configuration on the market survey. The rotor blades are 2.5 m diameter protruded fibreglass, the overspeed control is passive furling, the yaw control is via the wind vane, and the tower is tubular steel tilt-up.

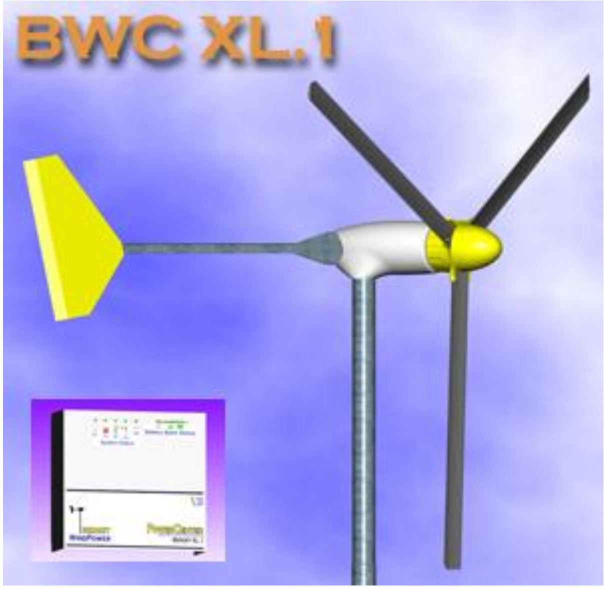


Figure 2.10: BWC XL.1 wind turbine (Bergey Windpower Co. 2010)

Southwest Wind Power market another three blade upwind HAWT, the Whisper 200, with an innovative side-furling angle Governor. This is possibly a similar passive furling mechanism as the Bergey XL.1; the action of the furling mechanism is clearly illustrated in figure 2.11.

Figure 2.11: Whisper 200 side furling angle-governor by Southwest Wind Power (South West Wind Power 2010)

Enviro Energy market one of the most innovative wind turbine designs in the Magnetic Vertical Axis Wind Turbine (MVAWT), a breakthrough wind turbine system aimed at the rooftop market. The key technology breakthrough focuses on magnetically levitated, virtually frictionless, low RPM wind turbine with high torque power output. It is difficult to imagine how the magnetic levitation concept can be applied to HAWT design however it appears to be a promising concept for VAWT design.

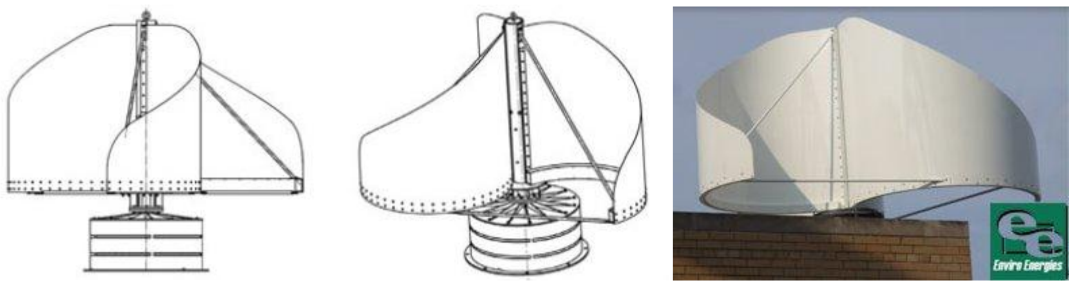


Figure 2.12: Enviro Energies 2.5kW MVAWT (Enviro Energies 2010)

Honeywell market a gearless wind turbine which generates all the power at the blade tips rather than the sometimes complicated gearing of conventional turbines. Windtronics (2010) claimed that the new design of the blade system cuts in at 3km/h wind speed and can generate electricity at a third the kWh cost of any other SWT in class and size. This HAWT has found an innovative way to eliminate the conventional permanent magnet generator coupled to the rotor drive shaft.

Figure 2.13: Honeywell wind turbine blade tip power system (Windtronics 2010)

French company Nheowind has developed a revolutionary blade design which was released for commercial distribution in 2010. The innovative blade form amplified the strength of the wind impinging on the blade, thus increasing rotor efficiency. The optimised blade deflection angle lead to a much more efficient use of kinetic air flow (Nheolis 2010).

Figure 2.14: 3D 100 CP Nheowind (Nheolis 2010)

Broadstar Wind Systems marketed a new concept in 2010 called the AeroCam. Although initially marketed in a 7 kW version this was seen as a potential for smaller designs. Broadstar (2010) claimed it featured breakthrough technology that easily adapted to changes in wind direction and extreme wind speeds, and can easily handle turbulent wind environments. This appears to be a refinement of the 'cross wind paddles' concept illustrated in figure 2.8.

Figure 2.15: The science behind the AeroCam system (Broadstar Wind Systems 2010)

Leviathan Energy market the Wind Tulip, an aesthetically pleasing VAWT design claiming quiet and vibration free operation, hazard free for birds and able to produce electricity at wind speeds of less than 2 m/s. It targets the rooftop market and is obviously targeted at urban installations where customers may require more fashionable designs and less noise.

Figure 2.16: Leviathan Energy Wind Tulip (Leviathan Energy 2008)

2.4.4 Performance

International Electrotechnical Commission (2005) stated that:

> "The wind turbine power performance characteristics are determined by the measured power curve and the Annual Energy Production (AEP)."

The standard IEC 61400-12-1:2005(E) - Wind turbines – Part 12-1: Power performance measurements of electricity producing wind turbines (International Electrotechnical Commission 2005) outlined the methodology used to establish these two performance criteria as follows:

- The measured power curve is collated by measuring wind speed and power output at a test site for a pre-determined period of time.
- The AEP is then calculated by applying the measured power curve to the reference wind speed distributions.

Manwell, McGowan & Rogers (2003) explained that the power performance curve incorporates three key points as shown in figure 2.17:

- Cut in speed – the minimum wind speed which will produce useful power.

- Rated wind speed – the wind speed at which the rated power is produced.
- Cut out speed – the maximum wind speed at which the wind turbine is allowed to produce power.

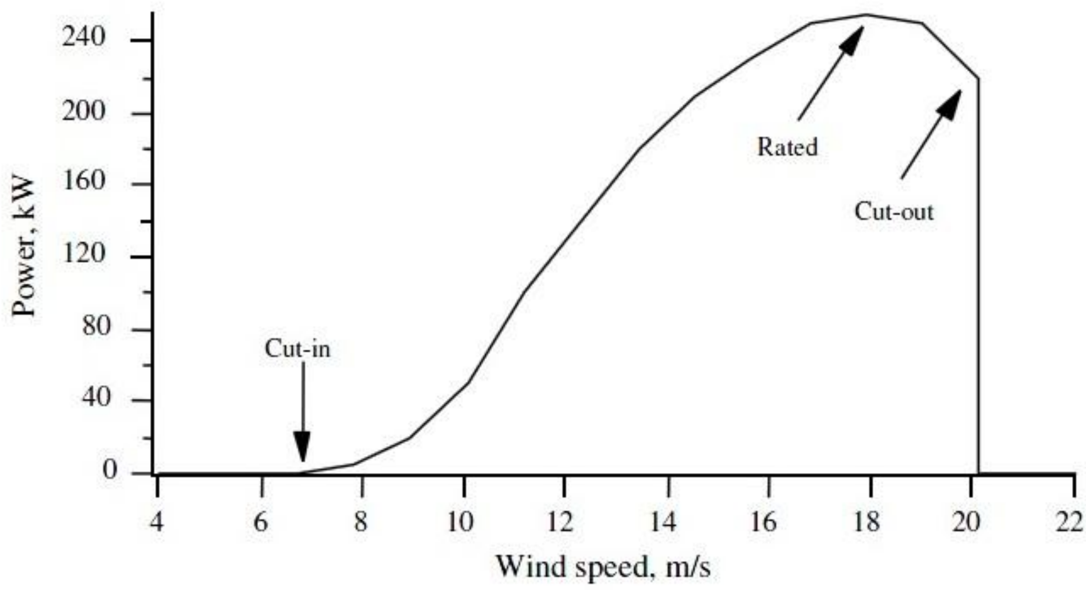


Figure 2.17: Typical wind turbine measure power curve (Manwell, McGowan & Rogers 2003)

Burton et al. (2001) related wind turbine performance to a different set of criteria, stating that the performance of a wind turbine is summarised by examining how three main indicators – power, thrust & torque – vary with wind speed.

C_P – λ (Power coefficient – tip speed ratio) performance curve

The C_P – λ graph is useful for comparing the effect on power extracted by varying parameters on a wind turbine. For example, the effect of varying the solidity (number of blades) on a HAWT can be seen in figure 2.18:

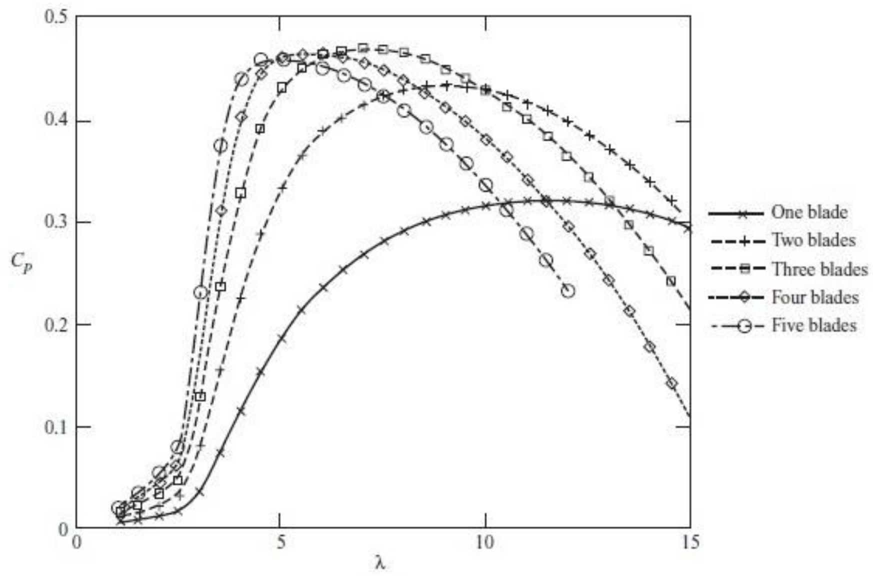


Figure 2.18: Effect of changing solidity (Burton et al. 2001)

Burton et al. (2001) showed that:

$$C_P = 4a(1-a)^2 \quad (2.2)$$

where C_P is the coefficient of power
a is the axial flow induction factor

and

$$\lambda = \Omega R / U_\infty \quad (2.3)$$

where λ is the tip speed ratio
Ω is the rotational speed of rotor [rad/s]
R is the blade tip radius [m]
U_∞ is the free stream velocity [m/s]

The power coefficient is essentially a ratio of the power extracted to the power available. The maximum achievable value of the power coefficient is 0.593 and is known as the Betz Limit (Burton et al. 2001). The C_P – λ graph in Figure 2.19 compares different wind turbine configurations and shows that the three bladed HAWT has the highest power coefficient of all popular configurations.

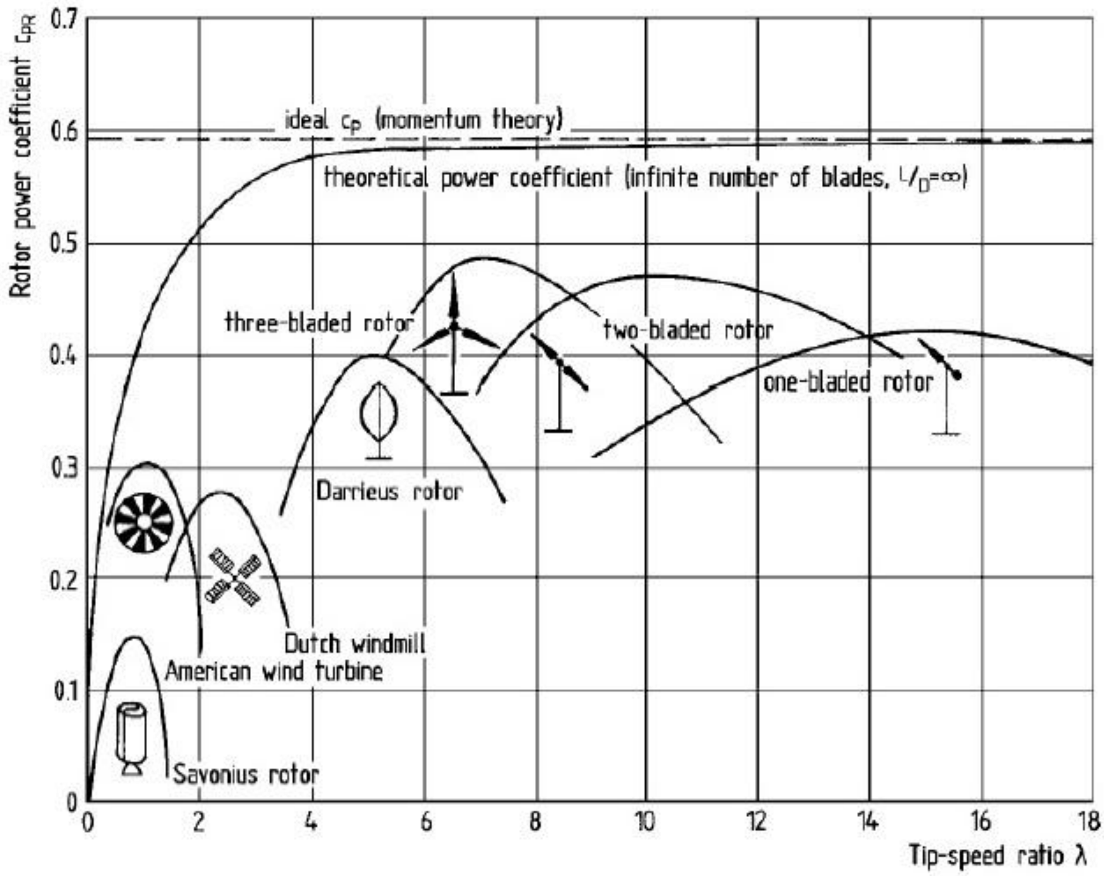


Figure 2.19: Power coefficient vs. tip speed ratio (Hau 2006)

$C_Q - \lambda$ (Torque coefficient – tip speed ratio) performance curve

Burton et al. (2001) revealed that the torque coefficient C_Q is derived from the power coefficient C_P simply by dividing the tip speed ratio λ. The $C_Q - \lambda$ performance curve is used for torque assessment purposes when the rotor is connected to a gearbox and generator.

$C_T - \lambda$ (Thrust force – tip speed ratio) performance curve

The thrust force curve is used to determine the structural design requirements of the tower. Generally the thrust force is heavily influenced by the solidity of the rotor.

Burton et al. (2001) showed that:

$$C_T = 4a(1-a) \tag{2.4}$$

where C_T is the coefficient of thrust

a is the axial flow induction factor

2.4.5 Justification for Use of Standards

The Engineering Code of Ethics (The Institute of Engineers, Australia 2000) stipulated that members must:

> "Work in conformity with accepted engineering and environmental standards and in a manner which does not jeopardise the public welfare, health or safety"

It would therefore seem reasonable that designers of SWTs must refer to and comply with the accepted engineering standards. The chief organisations which publish engineering standards relevant to SWT design are the International Organisation for Standardisation (ISO), the International Electrotechnical Commission (IEC) and the Australian Standards (AS). The series of standards which relate to wind power are the series 61400 standards. There were two AS 61400 standards and ten IEC 61400 standards in existence, which are listed in table 2.5. The AS standards should generally be used in preference to IEC standards, however in the case of AS 61400-2 (Int) this was an interim version which expired in 2008 so it is debatable whether this should be used in preference to the IEC version.

Standard Reference	Standard Title
AS 61400-2 (Int) (2006)	Wind turbines - Part 2: Design requirements for small wind turbines
AS 61400-21 (2006)	Wind turbines – Measurement and assessment of power quality characteristics of grid connected wind turbines
IEC 61400-1 Ed.3.0 (2005)	Wind turbines - Part 1: Design requirements
IEC 61400-11 Ed.2.1 (2006)	Wind turbines generator systems – Part 11: Acoustic noise measurement techniques
IEC/TC 61400-13 Ed.1.0 (2001)	Wind turbines generator systems – Part 13: Measurement of mechanical loads
IEC/TC 61400-14 Ed.1.0 (2005)	Wind turbines generator systems – Part 14: Declaration of apparent sound power level and tonality values
IEC 61400-2 Ed.2.0 (2006)	Wind turbines - Part 2: Design requirements for small wind turbines
IEC 61400-21 Ed.2.0 (2008)	Wind turbines - Part 21: Measurement and assessment of power quality characteristics of grid connected wind turbines
IEC/TS 61400-23 Ed.1.0 (2001)	Wind turbine generator systems – Part 23: Full scale structural testing of rotor blades
IEC/TR 61400-24 Ed.1.0 (2002)	Wind turbine generator systems – Part 24: Lighting protection
IEC 61400-25 Ed.1.0 (2006)	Wind turbines – Part 25: Communication for monitoring and control of wind power plants
IEC 61400-3 Ed.1.0 (2009)	Wind turbines – Part 3: Design requirements for offshore wind turbines

Table 2.5: Summary of AS & IEC 61400 series wind turbine standards (Authors own table)

2.5 Safety & Environmental Issues

2.5.1 Environmental Aspects

Wind turbines are associated with both positive and negative environmental impacts, however they are generally regarded as environmentally friendly. The major reason for this is evident when wind turbines are compared to large scale conventional power plants for electrical generation, whose environmental effects are summarised in table 2.6.

Pollutant	Conventional coal w/ Controls	Conventional gas w/ controls	Wind
Sulphur oxides	1.2	0.004	0
Nitrogen oxides	2.3	0.002	0
Particulates	0.8	0.0	0
Carbon dioxides	865	650	0

Table 2.6: Stack emissions of coal, gas, and wind power [kg/MWh] (Manwell, McGowan & Rogers 2003)

Negative impacts of wind energy can be divided into the following categories for both a single wind turbine and for a large scale wind farm (Manwell, McGowan & Rogers 2003):

- Avian interaction with wind turbines.
- Visual impact of wind turbines.
- Wind turbine noise.
- Electromagnetic interference effects of wind turbines.
- Land-use impact of wind power systems.
- Other impact considerations.

Interestingly Standards Australia (2006) mandated requirements regarding the safety aspects of wind turbines in AS 61400-2, but did not mandate requirements for environmental aspects.

2.5.2 Safety Aspects

The main safety hazards associated with wind turbines are parts of the rotor being hurled off. Hau (2000) revealed that experience has identified two distinct causes of rotor blade breakage:

- Overspeed, which is the most frequent cause of rotor blade breakage. This is likely to occur when all braking systems fail and the rotor speed approaches its critical aerodynamic speed.
- Material fatigue in the rotor blades, which can result in fatigue cracks and rotor blade breakage without being exposed to abnormal loading.

Hau (2000) also claimed that a wind turbine structure toppling over is not considered as a major safety hazard as it is no more of a risk than any other building toppling over. There are three main design considerations with respect to wind turbine safety:

- Robust overspeed protection systems.
- High material strength of rotor blades.
- Structural design of wind turbine & structure.

Standards Australia (2006) mandated guidelines to ensure the safety of the structural, mechanical, electrical and control systems of wind turbines, which include:

- Active and/or passive protection systems are included in the design to prevent overspeed.
- Partial safety factor for loads is loaded into ultimate strength analysis, fatigue failure design and critical deflection analysis.
- Mandatory testing including static blade tests, safety & function test, and duration test.

- Routine maintenance inspections

2.6 Summary

This literature review highlighted some large gaps in the body of literature studied. It was evident that most research and data related to large turbine installations and very little data was available for SWT installations. For instance there was abundant data available to identify the trends in wind power generation capacity and to accurately predict future generation growth, but little could be found to indicate the growth and trends of the SWT sector.

Also noteworthy was the Australian Governments seemingly fluid policy relating to renewable energy incentives. The absence of the most productive model – the feed-in tariff model – seems to leave Australia behind world's best practice, and seems to reduce the commercial opportunities for the success of wind turbines in Australia. The discussion seems to suggest further changes may be afoot in the not too distant future.

Various configurations were briefly examined however comparative assessments of SWT suitability or performance remained undiscovered. Several companies were found to market innovative and attractive concepts however the comparison between these new innovative designs and traditional VAWTs or HAWTs were not obvious. It was interesting to see such a wide variety of exciting new concepts, which suggest an exciting future for SWT development.

The common three bladed HAWT, although popular, did not appear to be an obvious winner as the best solution for an SWT design. More research is required into the suitability of various design options with an emphasis on the growing trend towards mechanical simplicity. Future SWT designs could show more positive innovation if they continue the trend towards simplification and endeavour to reduce mechanical complexity in favour of more refined mechanical designs, the introduction of magnetic designs and improvement of electrical sub-systems.

CHAPTER 3 – DESIGN & METHODOLOGY OVERVIEW

3.1 Introduction

This chapter aims to lay down the ground rules for this SWT design project by adopting a design procedure for execution throughout the design task. Basis of Design guidelines are introduced to align the design procedure with the project aims and objectives. The conceptual design is then developed by examining various topology options suitable for SWT design. The conceptual design does not aim to develop actual component designs but rather to offer general guidelines for the selection and design of individual components in the following chapter.

The appropriate design standards are briefly examined to identify the preliminary design data requirements throughout the component design process. The wind resource for the target market is examined in detail, and the design requirements highlighted. Once again this involves aligning the available wind resource data with the aims and objectives of the project, and identifying which sections of the data are useful for subsequent component design. The chapter concludes with a summary of the conceptual design leading into detailed component selection and design in the following chapter.

3.2 Design Procedure

The SWT design process combines various electronic and mechanical components into a machine which converts wind power, which is variable and often unpredictable, into a user friendly form of electrical power. The process must consider environmental, safety and cost implications to come up with a commercially suitable design. A useful SWT design procedure was summarised by Manwell, McGowan & Rogers (2003) as follows:

1. Determine application.
2. Review previous experience.
3. Select topology.

4. Preliminary loads estimate.
5. Develop tentative design.
6. Predict performance.
7. Evaluate design.
8. Estimate costs and cost of energy.

Chapter three focuses on steps one through four, whilst steps five through eight are dealt with in subsequent chapters. Further to the design procedure outlined above there are still more design tasks required for a typical commercial SWT design project. These include the detailed design and testing of machine software and hardware, and form a much larger proportion of the complete SWT design than those covered in this project. Although these extra tasks are beyond the scope of this project they are still worthy of mention and are summarised here:

9. Refine design.
10. Build prototype.
11. Test prototype.
12. Design production machine.

3.3 Application

3.3.1 Basis of Design

The project aim was to design a lightweight, durable and economical wind turbine (~1 kW) using commercially available parts and composite structural materials.

The key target market for the Basis of Design (BOD) was rural Victoria, and in particular the demographic sector of primary producers, or farmers. Rather than focusing on the high wind regions of Victoria, the project focused on the average wind speed regions representing typical farmland. This means the design should appeal to a wider range of farmers who do not live in high wind zones or have access to above average wind speeds. Paramount to the design concept was that two farmers are able to erect the SWT and also pull it down for maintenance using only typical farming machinery such as a light truck or tractor. To satisfy the project aim, objectives and target market the following BOD key points have been formulated, which effectively formed the rule-book for all subsequent SWT design work in this project:

1. SWT design must be in compliance with Australian safety and design regulations and standards.
2. Capital cost and payback periods must be competitive with existing markets.
3. Environmental impacts are to be minimised and/or optimised.
4. SWT assembly must be highly transportable to make it attractive to remote area installations.
5. SWT installation must be possible using minimal resources and not require heavy machinery like cranes.
6. SWT rotor, drive system, generator and tower can be assembled using commercially available parts as much as practicable.
7. Development of innovative alternatives are encouraged especially those which reduce wear on mechanical components.
8. Reliability is paramount to cater for remote installations.
9. Maintenance requirements must be minimal and inexpensive.
10. Composite structural materials should be considered based on their commercial suitability for this application.
11. Manufacturing requirements, costs and benefits should be considered.

3.3.2 BOD Rating System

In order to make unbiased topology assessments a BOD rating system was utilised to correlate the BOD requirements with previous experience, found throughout a wide range of literary resources. For large wind turbines there were many reliable literary resources available to review past experience, however information relating to SWT design was not as readily available. The BOD rating system used the following guidelines:

1. Each key BOD point was assigned a BOD weighting out of ten, to represent its importance to the SWT design as a whole, as shown in table 3.1.
2. A BOD weighting of ten meant it was of the highest importance to the design.

3. A BOD weighting less than ten meant it carried less importance, proportionally rated on a scale out of 10.
4. Each conceptual design option was assigned a score out of ten signifying how well it complied with the corresponding key BOD point.
5. The BOD weighting was multiplied by the conceptual design option score for each line, which gave a weighted score.
6. The weighted scores were totalled to give a total weighted score for each conceptual design option.
7. The highest total weighted score was assessed as the most suitable conceptual design option to satisfy the basis of design requirements and was thus the preferred option.

BOD #	Description	BOD Weighting	Description
1	Standards	10	Compliance with regulations & standards
2	Costs	10	Costs competitive with existing markets
3	Environmental	10	Environmental impacts minimised/optimised
4	Transportability	8	To be transportable to remote locations
5	Installation	8	Installation not too machinery intensive
6	Components	8	Assembled using commercially available parts
7	Innovation	7	Innovative alternatives available
8	Reliability	7	Good level of reliability
9	Maintenance	6	Maintenance is minimal & inexpensive
10	Materials	5	Composite structural materials available
11	Manufacturing	4	Manufacturing requirements, costs & benefits

Table 3.1: BOD rating system (Authors own table)

3.4 Topology Selection

3.4.1 Topology Overview

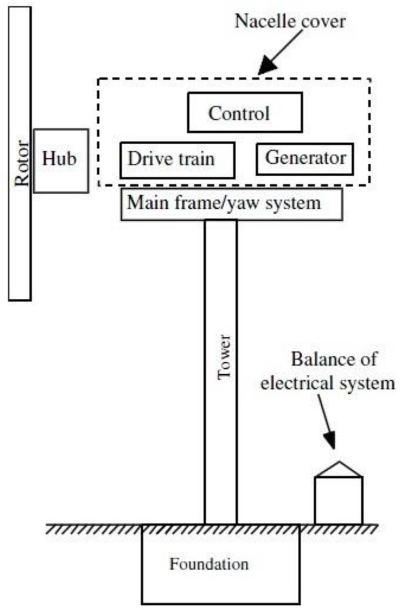


Figure 3.1: Major systems & components of a HAWT (Manwell, McGowan & Rogers 2003)

The modern SWT is summarised into a group of systems as follows:

- Rotor – converts the kinetic energy of the wind into torque.
- Drive train – transmits the torque to usable electrical energy through a generator.
- Nacelle and main frame – the structure used to house the rotor, drive train and yaw system.
- Tower and foundation – elevates the rotor to a sufficient height to access higher wind speeds whilst providing stability for the SWT in high wind speeds.
- Machine controls – includes overspeed and lighting protection.
- Electrical systems – transmits the generated electrical power to a storage system or grid connection.

The SWT systems can be further broken down into groups of components as illustrated in table 3.2. Generally the conceptual design carried out in this chapter fell into the systems category, whilst component design in subsequent chapters fell into the component category.

System	Component
Rotor	Blades
	Supporting Hub
Drive Train	Drive shaft
	Mechanical Brake
	Generator
Nacelle & Main Frame	Wind Turbine Housing
	Bedplate
	Yaw System
Tower & Foundation	
Machine Controls	Overspeed
	Lightning Protection
Electrical Systems	Cables
	Switchgear
	Transformers
	Electronic Power Converters
	Batteries / storage system

Table 3.2: Major systems & components of a Horizontal Axis Wind Turbine (Authors own table)

The conceptual design aimed to select the most suitable topology for the SWT from the endless combinations of design choices. The most important design choices relating to SWT topology are as follows:

1. Rotor axis orientation: HAWT or VAWT.
2. Rotor position: Upwind or downwind of tower.
3. Rotor blades: Number of blades.
4. Hub type: Rigid, teetering or hinged blades.
5. Power control: Stall, variable pitch, controllable aerodynamic

surfaces or yaw control.

6. Tower structure: Tilt-up, fixed or free standing.

3.4.2 Rotor Axis Orientation

Only 2 options were considered for the rotor axis orientation – HAWT with a horizontal drive shaft and reliant on aerodynamic lift to generate torque, and VAWT with a vertical drive shaft and reliant on either aerodynamic lift, drag or a combination of both to generate torque. Burton et al. (2001) argued that VAWTs have not proven to be commercially competitive although they were investigated in considerable detail in the 1980's. Manwell, McGowan & Rogers (2003) argued that no VAWT have met with the same success as the horizontal axis, lift driven rotor. The closest runner was the darrieus VAWT, but this design could not compete with the HAWT for cost of energy. Tangler (1990) stated that the cost effectiveness of the VAWT did not equal that of the HAWT for reasons not fully documented. Hau (2006) discussed the highest potential C_P rotor power coefficients for different rotor axis orientations the most common method used to compare the most efficient wind turbines. The C_P summary in table 3.3 suggests that three bladed HAWTs are about 23% more efficient than the most efficient VAWT. The maximum achievable value of the power coefficient was shown to be 0.593, a value known as the Betz Limit.

Rotor type	C_P power coefficient
Three bladed HAWT	0.49
Two bladed HAWT	0.47
One bladed HAWT	0.42
Darrieus VAWT	0.40

Table 3.3: Power coefficients (Hau 2006)

A basic assessment of strengths and weaknesses was used to assess the suitability of both VAWT and HAWT configurations and the BOD rating system assessment was applied to determine the most suitable design for this application.

VAWT configuration:

Advantages:

- Generator, gearbox etc. may be placed on the ground so a tower may be avoided.
- Easier to maintain since the drive train components are near the ground.
- Easier installation if a tower is not used.
- Yaw mechanism is not required, reducing the need for a yaw bearing.
- Efficiency loss from the yaw device tracking the wind is negated.
- Usually have a lower tip speed ratio so less likely to break in high winds.
- Ability to utilise wind from any direction without efficiency losses from yaw and pitch changes.
- Doesn’t have to shut down in high winds, reducing power losses.

Disadvantages:

- The VAWTs lack of a tower eliminates most of the additional energy available higher up due to wind shear.
- Aerodynamically, VAWTs utilise less efficient symmetric aerofoils than those used on HAWTs which have higher lift-to-drag ratios.
- The constant chord VAWT blades adversely affect blade efficiency and self start capability; normally needs a ‘push’ to start.
- Rotor wake induced losses of VAWTs are greater than those of HAWTs since VAWTs only operate at optimum lift-to-drag ratio over a small azimuth of the rotation. This leads to excessive wind energy going into rotor thrust loads rather than useful power output.
- Overall efficiency is low.
- High thrust loads on bottom bearing due to rotor weight.
- The highly cyclic power and thrust generated by VAWT rotors result in higher fatigue loads.
- Bearing replacement requires full strip down of machine.
- A VAWT tends to be a lower RPM machine that derives more power from torque than RPM which results in greater machine weight and cost than a HAWT.

HAWT configuration:

Advantages:

- Blades are to the side of the wind turbine centre of gravity, helping stability.
- Ability to wing warp, giving blades the best angle of attack and improved usage of wind energy.
- Ability to pitch the blades in a storm to minimise damage.
- Tall towers improve access to stronger winds.
- Can be set up in forests above the tree-line.
- Usually self-starting.

Disadvantages:

- HAWTs have difficulty operating near the ground where the wind flow is more turbulent.
- Transportation of tall towers can be difficult.
- Environmental impacts associated with tall towers.
- Down-wind HAWTs suffer from fatigue and structural failure due to turbulence.

Conclusion:

BOD rating scores (refer to Appendix C for full calculations and explanatory notes) were as follows:

HAWT configuration: 58

VAWT configuration: 53

The HAWT configuration was found to be considerably more suitable as per the BOD rating system and was the chosen configuration, owing mainly to cost and efficiency advantages. This is consistent with the general sentiment of the industry and texts which are generally based on industry experience. VAWT appear to have found a niche in urban environments where the wind resource is more turbulent, and roof-top mounting is available offering considerable height gains without the use of a tower. The rural market is a different story and appears to be firmly in favour of the HAWT.

3.4.3 Rotor Position

The rotor position is relevant to only the HAWT configuration and has major consequences on virtually all drive train component design requirements.

Upwind Configuration:

Upwind machines have the rotor facing the wind. This configuration is by far the most common position for HAWTs.

Advantages:

- Tower shadow effect is much less, reducing dynamic rotor blade loading, noise and power reduction.
- Lower blade fatigue.

Disadvantages:

- Accurate predictions of blade deflections in turbulent wind are required to prevent the rotor blades from striking the tower.
- Tilting rotor blades back to prevent tower strike reduces power output slightly.
- Stiffer rotor blades may be required which may have higher stresses during high winds.
- Requires load inducing mechanical yaw mechanism to keep the rotor facing the wind.
- May require an extended nacelle to position the rotor far enough away from the tower to prevent tower strike.

Downwind Configuration:

Downwind machines have the rotor on the lee side of the tower.

Advantages:

- Allows the use of very flexible blades without the risk or tower striking.
- Flexible blades may reduce weight.
- Flexible blades can be less expensive to make.

- Flexible blades may take some loading off the tower in high winds due to the blade bending absorbing some of the wind energy.
- May be built without a yaw mechanism, if the nacelle is designed to follow the wind passively.
- The tower can be allowed to bend in the wind, economically permitting higher towers for higher wind speeds.
- Easy to take advantage of centrifugal forces to reduce blade root flap bending moments.

Disadvantages:

- Blades are subject to large negative impulse loads each time they pass the tower, contributing to fatigue damage and a 'thump' noise effect.
- Design implications of cable twist with constant passive yawing SWTs.
- Fatigue and structural failure due to turbulence.

Conclusion:

BOD rating scores (refer to Appendix C for full calculations and explanatory notes) were as follows:

Upwind configuration: 52

Downwind configuration: 51

The downwind comparison featured slightly better reliability and maintainability because of the absence of the yawing mechanism; however the environmental drawbacks due to increased noise made the upwind configuration marginally more attractive.

3.4.4 Rotor Blades

This section relates to the dilemma of 'how many blades'. The upwind three bladed rotor was found to be the industry accepted standard. The power coefficient increases as the number of blades increase, albeit with diminishing returns as can be seen in figure 3.2. More than three blades generally shows little return in performance for the additional cost of extra blades, and was not considered for this design.

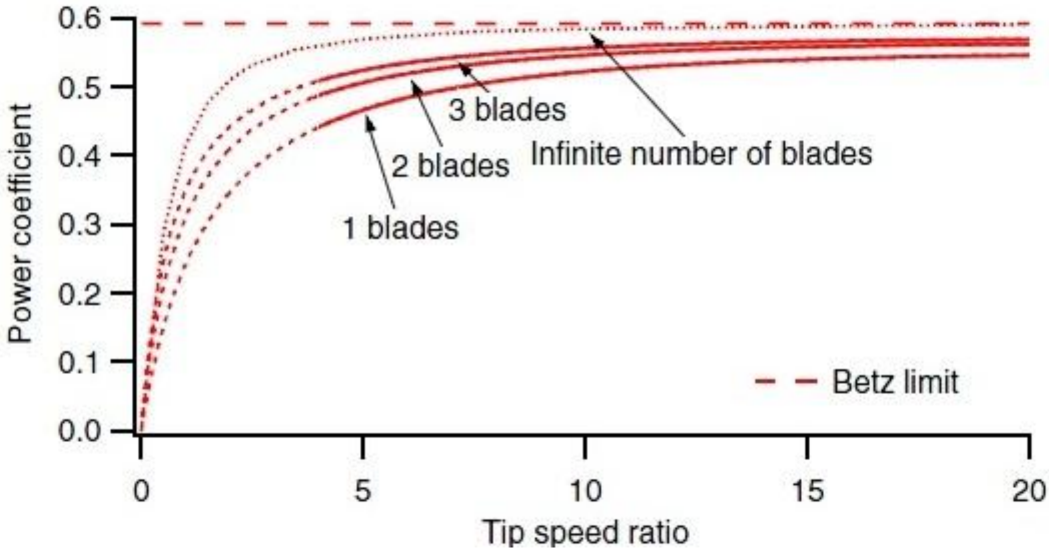


Figure 3.2: Maximum achievable power coefficients as a function of number of blades (Manwell, McGowan & Rogers 2003)

Three blades

Three bladed rotors were found to be the accepted industry standard and tend to be the standard against which all other concepts are evaluated; the vast majority of commercial SWT were found to have three blade rotors in the market survey in appendix B.

Advantages:

- Lower impulsive noise from tower shadow than two or one blades.
- Three per revolution noise is less annoying than one or two per revolution.
- More aesthetically pleasing than one or two blades.
- More dynamically balanced rotor due to 120 degree spacing of blades.
- Three percent more aerodynamically efficient than two blades.

Disadvantages:

- Cost associated with extra blades.

Two blades

Two bladed rotors are slightly less efficient than three bladed rotors and generally need to be mounted on a teeter hinge to combat the aerodynamic imbalances to the turbine when a rotor blade passes the tower. Teetering hubs are considerably more complex than the fixed hubs generally found on three bladed rotors.

Advantages:

- Cost & weight saving over three blades.
- Six percent more aerodynamically efficient than one blade.
- Improved blade, drive train, tower, nacelle & yaw bearing load relief due to teetering mechanism.

Disadvantages:

- Increased rotor noise due to higher tip speed.
- Requires up to fifty percent increased rotor radius to achieve roughly the same power output as a three bladed rotor.
- Visual ‘flicker’ effect of fewer blades.
- Sensitive to once per rotation rotor mass imbalance vibration.
- Require higher rotational speeds to yield the same energy output as three blades.
- Requires more complex hub design – hinged (teetering) hub is required.

One Blade

One-bladed rotors do exist but are not widespread; they generally experience all the same problems experienced with a two bladed rotor but to a larger extent.

Advantages:

- Cost & weight saving over two and three blades.

Disadvantages:

- Increased rotor noise due to higher tip speed.
- Flicker effect of fewer blades.
- Sensitive to once per rotation rotor mass imbalance vibration.

- Require higher rotational speeds to yield the same energy output as two blades.
- Requires more complex hub design – hinged (teetering) hub is required.
- Requires a counterweight to balance the rotor.

Conclusion:

BOD rating scores (refer to Appendix C for full calculations and explanatory notes) were as follows:

Three blades: 60

One blade: 57

Two blades: 57

The three bladed rotor design was chosen on the grounds of its superior environmental performance and the potential for a simpler design, negating the need for a complex teetering hub. The cost saving potential for one and two-blade configurations were not expected to be realised due to the requirement for larger blades, teetering hubs and counterweight.

3.4.5 Hub Type

Three mainstream options were found to be available:

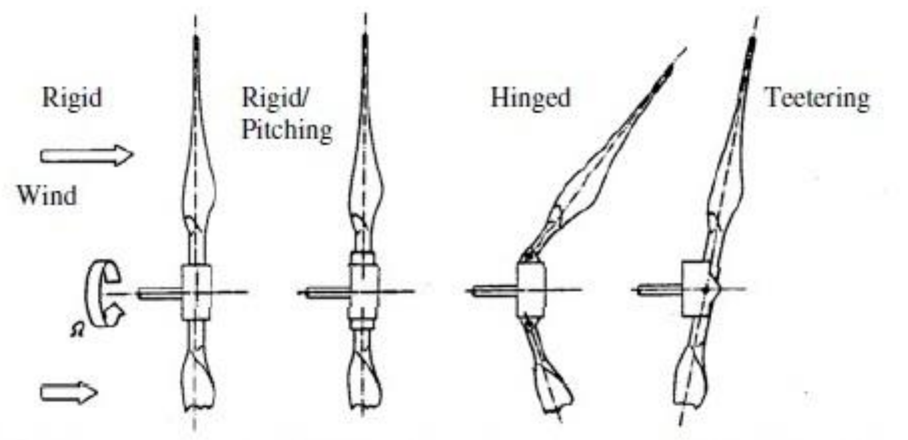


Figure 3.3: Hub options (Manwell, McGowan & Rogers 2003)

Rigid

Most SWTs were found to use rigid hubs. This means the blades are fixed, however they may incorporate variable pitch blades. The main body of the hub is a casting or weldment to which the blades are attached, with the hub attached to the drive shaft. A hub on a variable pitch machine must incorporate bearings at the blade roots which secure the blades against all motion except for pitching, and a pitching mechanism must also be incorporated.

Advantages:

- Simple mechanism with no moving parts on fixed pitch rigid hubs.

Disadvantages:

- Not suitable for one or two blade rotors.
- Variable pitch hubs required complicated bearing mechanisms.

Teetering

One and two bladed rotors are usually teetering, meaning the hub is mounted on bearings so the blades can move back and forward much like a child's see-saw.

Advantages:

- Particularly suitable to one or two bladed turbines.
- Bending moments on rotor blades are very low during operation.
- Can reduce aerodynamic imbalances or loads due to dynamic effects from rotation of blades or yawing of turbines.

Disadvantages:

- Complexity is far greater than rigid hubs (requires trunnion pins, bearings & dampers).
- Requires two types of bearings – cylindrical radially loaded, and thrust.
- Complex design required to incorporate variable pitching.

Hinged hubs

Hinged hubs are generally used on two bladed rotors. They are a cross between the rigid design and the teetering design. They are arranged so the rotor blades are mounted on independent hinges onto a rigid type hub and can move in and out of the plane of rotation independently of each other.

Advantages:

- Suitable for one or two blade rotors.

Disadvantages:

- Requires and extra balancing mechanism.
- Complex mechanisms required including springs and dampers.

Conclusion:

BOD rating scores (refer to Appendix C for full calculations and explanatory notes) were as follows:

Rigid hub:	64
Teetering hub:	56
Hinged hub:	56

The rigid hub was the chosen configuration due its simplicity. Both teetering and hinged hubs require complex bearing arrangements which negatively impact several design goals including maintenance, reliability & costs. The incorporation of variable pitching into the rigid hub is subject to evaluation in the control method section, however a pitching mechanism was considered to be considerably less complex than teetering or hinge mechanisms.

3.4.6 Power Control

Various control methods were found to be available to either optimise or limit power output, required so that the SWT achieves maximum advantage from the wind and reaches its maximum or rated power at the desired wind speed. Speed control is required to put a ceiling on the rotational speed and output power as the wind speed increases, to serve as a protection mechanism preventing the rotor blades from rotating too fast and possibly breaking. Active control systems depend on transducers to sense conditions and motors to drive the control actuation, adding complexity and cost to the SWT design. For this SWT design the control philosophy was that control must be simple and passive (use natural forces for actuation) to minimise complexity and cost. The mainstream control options are summarised here:

Pitch control

The purpose of pitch control is to optimise the blade angle to achieve certain rotor speeds or power output. This can be to achieve maximum advantage from the wind, and also for overspeed protection in high wind. The rotor blades have the ability to rotate about their axis which changes the pitch angle, the angle of attack and the torque produced by the blades as shown in figure 3.4.

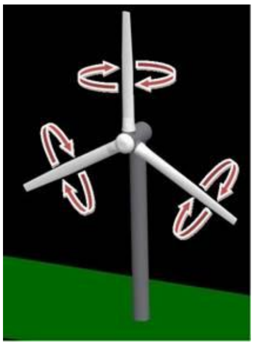


Figure 3.4: Pitch adjustment (National Instruments 2010)

Pitch adjustment can be used to stall or furl the rotor blades as follows:

- By stalling a rotor blade the angle of attack is increased which causes the flat side of the blade to face further into the oncoming wind.
- By furling a rotor blade the angle of attack is decreased which causes the edge of the blade to face further into the oncoming wind.

This process is known as blade feathering and requires a complicated hub arrangement incorporating pitch bearings and pitch actuation. On SWTs pitch actuation is generally passive to reduce complexity and cost, and uses centrifugal force either by flyweights or geometric design without hydraulic or electronic controls.

Advantages:

- Control can be achieved passively.
- Increased energy capture.
- Provides aerodynamic braking.
- Reduced extreme loads on the turbine when shut down.
- Very effective way to limit output power by changing aerodynamic force on the blade at high wind speeds.
- Can still generate power in extreme wind speeds.

Disadvantages:

- Large power swings likely to occur due to reaction times.
- Complicated hub arrangement including pitch actuation devices.
- Sometimes powered by hydraulic or electric motors.

Blade aerodynamic surfaces

Aerodynamic surfaces such as ailerons may be incorporated into the blades to alter the aerodynamic characteristics of the blades, usually for the purpose of braking.

Advantages:

- Control can be achieved passively.
- Complicated hub mechanisms can be avoided.
- Can still generate power in extreme wind speeds.

Disadvantages:

- Complex blades required.
- Blades not likely to be commercially available requiring independent design.

Yaw control

Yaw refers to the rotation of the entire wind turbine to face the oncoming wind as shown in figure 3.5. The yaw control ensures that the turbine rotor is constantly facing into the wind to achieve maximum effective rotor area resulting in maximum power output. Overspeed control is possible to ensure the rotor is turned away from the wind to reduce power, utilising the same mechanism that yaws the rotor into the wind for maximum power.

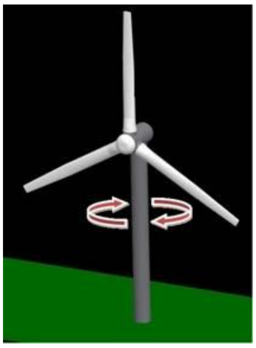


Figure 3.5: Yaw adjustment (National Instruments 2010)

Advantages:

- Control can be achieved passively.
- Fairly simple arrangements are possible.
- Rigid hub can be used with no variable pitch mechanism.

Disadvantages:

- Requires a robust yaw system.
- Large moments of inertia about nacelle and yaw axis.
- Slower reaction than other control methods.
- Only really practical for variable speed machines.

Furl control

Furl control refers to a simple means of passive overspeed protection. The aerodynamic forces on the rotor cause a thrust force pushing back on the rotor, which increases with increased wind speeds. The thrust force acts through the centreline of the rotor, which is offset from the centreline of the yaw axis so that the thrust force on the rotor is always trying to push the rotor over to the side away from the wind. Through careful engineering design the geometry of the wind turbine is balanced so that in low wind speeds the tail vane keeps straight and the rotor is aligned to the wind, but in high wind gusts the rotor force acting on the yaw offset is large enough to overcome the preset force holding the tail straight, and the entire rotor turns sideways to the wind (furls), thus limiting its speed.

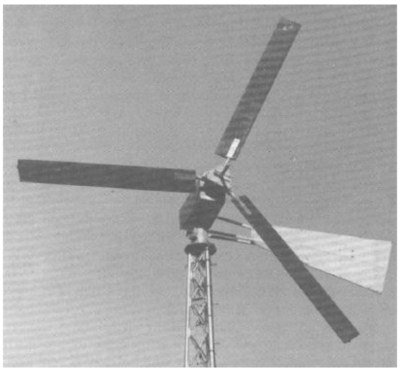


Figure 3.6: Furl control showing furled rotor (Source unknown)

Advantages:

- Control can be achieved passively.
- Fairly simple arrangements are possible with no wear points.
- Rigid hub can be used with no variable pitch mechanism.

Disadvantages:

- Requires a robust yaw system.
- Large moments of inertia about nacelle and yaw axis.
- Slower reaction than other control methods.
- Not suitable for turbulent wind areas.
- In high wind speeds the power production is shutdown, meaning no power is generated.

Stall control

This method incorporates blades which are bolted to a rigid hub at a fixed angle and relies on increasing the angle of attack (the angle at which the relative wind strikes the blades), which in turn reduces the induced drag. This is usually achieved through sophisticated aerodynamic blade design, incorporating some twist into the blade so that when the wind speed becomes too high, it gradually creates turbulence on the side of the rotor blade which is not facing into the wind, thus preventing the lift force from acting on the rotor (stalling).

Advantages:

- Control can be achieved passively.
- Rigid hub can be used with no variable pitch mechanism.
- No moving parts necessary.
- Can be made to happen passively (occurs automatically as the blades speed up).
- Can still generate power in extreme wind speeds.

Disadvantages:

- Complex aerodynamic blade design required.
- Stall induced vibrations may affect tower design.
- Can produce too much power in high winds causing generator damage.
- Degree of blade pitch may increase audible noise levels.

Electronic control

This method relies on the electronic systems of the SWT and is generally achieved by using electronic converters that are coupled to the generator. The generator is disconnected from the grid to control the synchronous speed of the generator independently of the grid voltage or frequency.

Advantages:

- Effective way of optimising maximum power output at low wind speeds.

Disadvantages:

- Control cannot be achieved passively.
- Requires complex electrical engineering.
- Unlikely to be available in modular form, requiring independent design.
- Reliability unpredictable due to random nature of failure of electronic components.
- Maintenance and repairs likely to require specialists.
- May require grid connection.
- Susceptible to lightning.
- Can still generate power in extreme wind speeds.

Conclusion:

BOD rating scores (refer to Appendix C for full calculations and explanatory notes) were as follows:

Pitch control:	57
Yaw control:	57
Furl control:	56
Stall control:	53
Electronic Control:	48
Blade aerodynamics:	45

Pitch control and yaw control were assessed as being equally suitable for this application. They both offer minimal negative noise related environmental impact which was a major deciding factor. Both were deemed to be relatively inexpensive to design and manufacture as bearing arrangements and mechanisms were expected to be uncomplicated for this small sized wind turbine. All other concepts had significant disadvantages relating cost and/or environmental considerations. Furl control was not chosen because of the major disadvantage that it shuts down completely during high wind speeds and is unable to produce power, where the pitch control is still able to produce power.

The pitch control concept was chosen for this design to limit power output by putting a ceiling on the rotor speed and thus output power as the wind speed increases. The yaw control concept was also chosen to optimise power by rotating the entire wind turbine to face the oncoming wind, which was considered to be unachievable through the pitch control method.

3.4.7 Tower Structure

The function of the tower is to elevate the SWT above the low wind speeds experienced at the base of the vertical wind profile, and above obstructions such as buildings, trees & hills. The tower must support the weight of the SWT and also handle the thrust loads put on it by the wind. Three basic tower types were found to be used in SWT installations and are summarised below:

Tilt-up tower

Usually tilt-up towers are tubular steel construction with sections of pipe coupled together, and 4 sets of guy wires attached at each joint. They consist of the tower pole and a 'gin pole' that is attached to it at 90 degrees. When the tower is down the gin pole sticks up in the air at 90 degrees and is used as a lever to lift or lower the tower, pivoting on a sturdy base.

Advantages:

- Inexpensive.
- No crane required for installation.
- Easy maintenance with no climbing.
- Heights of up to 40 m are achievable for SWT.

Disadvantages:

- Large footprint required (a 10 m high tower requires a diamond area 15 m x 10 m).
- The footprint area needs to be clear and reasonably level.
- Minor repairs are potentially more difficult due to the requirement to lower the entire tower rather than simply climbing the tower.

Fixed, guyed tower

These towers are lifted up once, do not tilt down and are held up by guy wires. Installation is possible without a crane by using temporary gin poles however using a conventional crane is the usual method.

Advantages:

- Inexpensive.
- The footprint area does not need to be as clear and level as tilt-up towers.

Disadvantages:

- Maintenance on the turbine or tower is difficult and requires climbing the tower.
- Medium sized footprint is required (a 10 m high tower requires a 10 m diameter footprint).
- Requires a crane to install.

Free-standing tower

These towers have no guy wires but rely on the concrete foundation and the steel (or other material) tower to hold them up.

Advantages:

- Small footprint required.
- Requires very little cleared space.
- Most aesthetically pleasing option.
- Enhanced reliability due to elimination of damage to guy wires.
- More adaptable to composite structural material construction.

Disadvantages:

- Maintenance on the turbine or tower is difficult and requires climbing the tower.
- Requires crane to install and other equipment to construct concrete foundation.
- Foundation may require independent civil engineering design.
- Expensive – at least a third to half higher cost than tilt-up or guyed towers.

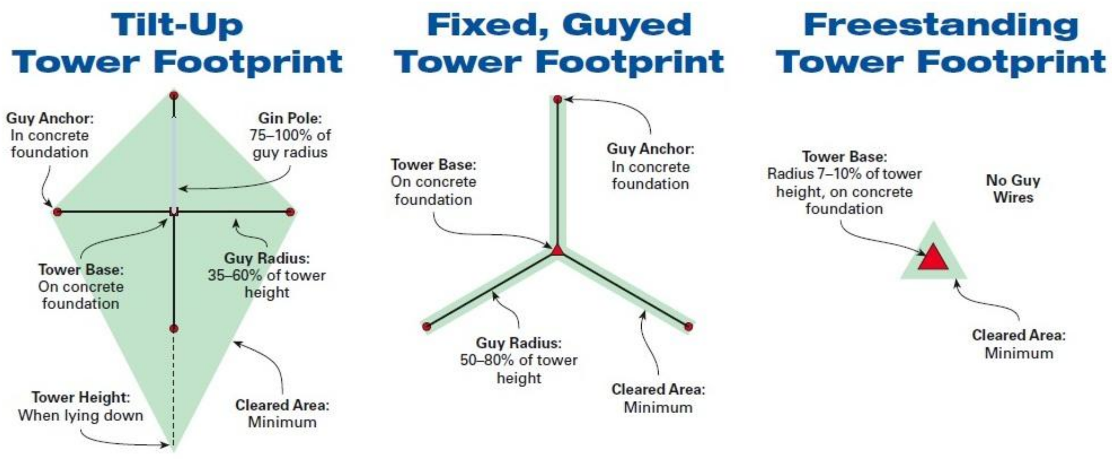


Figure 3.7: Tower footprints (Woofenden 2005)

Conclusion:

BOD rating scores (refer to Appendix C for full calculations and explanatory notes) were as follows:

Tilt-up tower: 50

Fixed, guyed tower: 45

Free-standing tower 42

The tilt-up configuration was considerably more suitable as per the BOD rating system and was the chosen configuration. This is consistent with the general sentiment of the industry and texts. The issue of footprint area and the necessity to have clear flat ground was not covered in the weighted BOD assessment, however this was not perceived to be an issue in the farming communities in Victoria where topography is generally clear and flat and land area is normally not a limiting factor.

3.5 Preliminary Load Estimates

3.5.1 Australian Standard Design Requirements

The foremost source of design standards throughout this SWT design was the Interim Australian Standard AS 61400-2 (Int.) (2006) *Wind Turbines - Part 2: Design requirements for small wind turbines*, which is virtually identical to IEC 61400-2, Ed.2

(2006) *Wind Turbines - Part 2: Design requirements for small wind turbines.* AS 61400-2 deals specifically with safety philosophy, quality assurance and engineering integrity for SWT design. Throughout this design project AS 61400-2 was used as a reference wherever possible; however when the AS 61400-2 scope was insufficient then alternative reference sources were used.

3.5.2 The Wind Resource

The single most important consideration when selecting a site for a wind turbine is the wind speed. When the wind speed doubles, the power in the wind increases by a factor of eight. AS 61400-2 (Standards Australia 2006) stated the formula used to calculate available wind power as follows:

$$P_r = C_p \ \tfrac{1}{2} \ \rho \, V_{hub}^{\ 3} A \qquad (3.1)$$

where
P_r is the rotor power [W]
C_p is the coefficient of power
ρ is the air density, here assumed to be 1.225 [kg/m^3]
A is the area of rotor swept area [m^2]
V_{hub} is the air velocity at the hub [m/s]

Thus a design value for wind velocity is required to calculate the power output of the SWT. The prescribed method of determining wind velocity described in AS 61400-2 (Standards Australia 2006) is to carry out site wind speed testing using an anemometer. For this project appropriate wind atlas data was utilised to represent the target market of rural Victoria. The Victorian Government Department of Planning and Community Development (2009) stated that the average wind speed across Victoria is 6.5 m/s, and approximately two thirds of Victoria's land area has an average wind speed of 5.8 to 7.2 m/s. Figure 3.8 illustrates the wind atlas produced by Sustainability Victoria (2010) which models average annual wind speeds in Victoria using the Windscape resource mapping tool that was developed by the Wind Energy Research Unit of the CSIRO Land and Water.

By comparing the average annual wind speed illustration in figure 3.8 with the land use illustration in figure 3.9, it was observed that the areas of lower average wind speed approximated the areas of forestry and natural conservation. These areas are generally the mountainous and heavily forested areas associated with the great dividing ranges in eastern Victoria. The average wind speed for agricultural areas appears to lie between 6.5 and 7.0 m/s in figure 3.8, suggesting that the claim of 6.5 m/s average Victorian wind speed by The Victorian Government Department of Planning and Community Development (2009) was slightly conservative for agricultural land use. 6.5 m/s at 65m height was thus chosen as the design wind speed for this project, however it required some adjustment to match the typical height for an SWT since it is unlikely that the rotor will be positioned at a height of 65m .

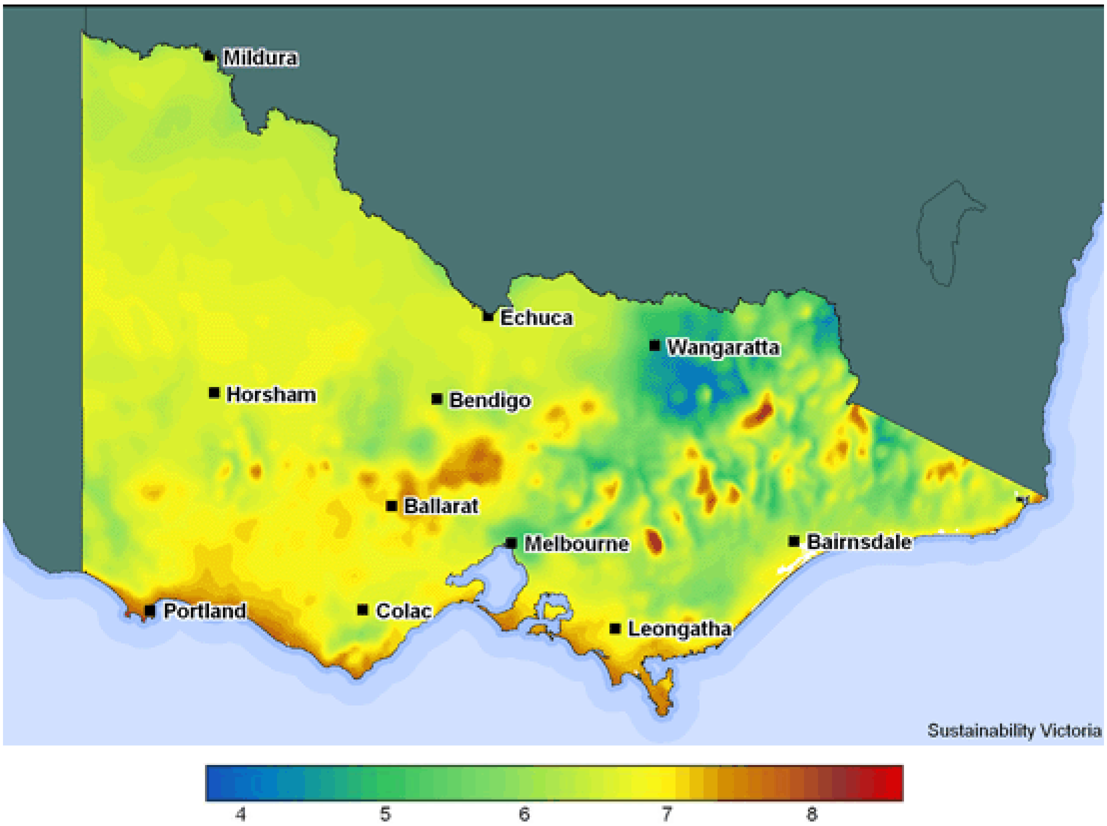


Figure 3.8: Average annual wind speed in m/s at 65m above ground (Sustainability Victoria 2010)

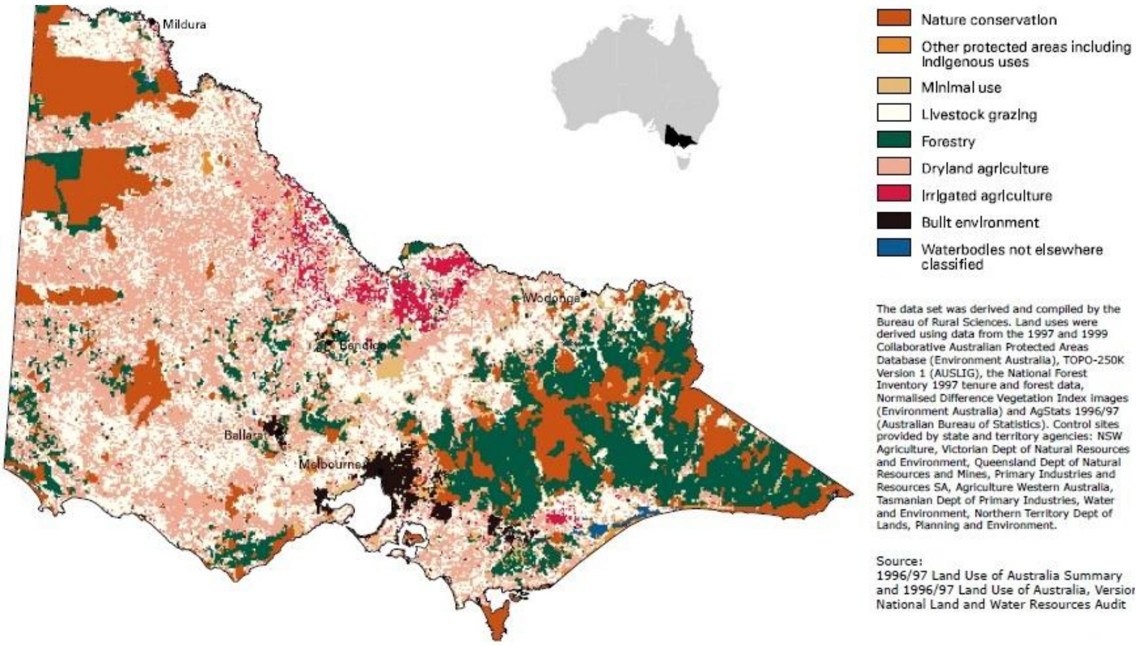


Figure 3.9: Land use in Victoria (Australian Government 2009)

3.5.3 Logarithmic Wind Profile

An important characteristic of the wind resource is the variation of the wind speed with relation to the vertical distance from the ground. This is called the vertical profile, or vertical wind shear, which is important to determine the productivity of the wind turbine at a certain height. The vertical wind profile was shown to be calculated using equation 3.2 by Manwell, McGowan & Rogers (2003), which is known as the logarithmic wind profile or log law:

$$U\,(z) \;=\; \frac{U^*}{k}\;\ln\;\frac{z}{z_0} \tag{3.2}$$

where	$U\,(z)$	is the wind speed [m/s]
	U^*	is the friction velocity [m/s]
	k	is von Karman's constant = 0.4
	z	is the height [m]
	z_0	is the surface roughness length [m]

Values of surface roughness were given as follows by Burton et al (2001):

Terrain description	z_0 (m)
Cities, forests	0.7
Suburbs, wooded countryside	0.3
Village, countryside with trees & hedges	0.1
Open farmland, few trees & buildings	0.03
Flat grassy plains	0.01
Flat desert, rough sea	0.001

Table 3.4: Typical surface roughness lengths (Burton et al, 2001)

For typical farmland in Victoria corresponding to the target market for this SWT project, a z_0 value of 0.03 m was chosen. The typical Victorian open farmland topography assumed the available land is large enough to locate the SWT away from most buildings. Using equation 3.2 to calculate the vertical wind profile with 6.5 m/s wind speed at 65 m hub height and a terrain consisting of open farmland with few trees or buildings, the profile was plotted as a straight line on a logarithmic scale and is shown in figure 3.10:

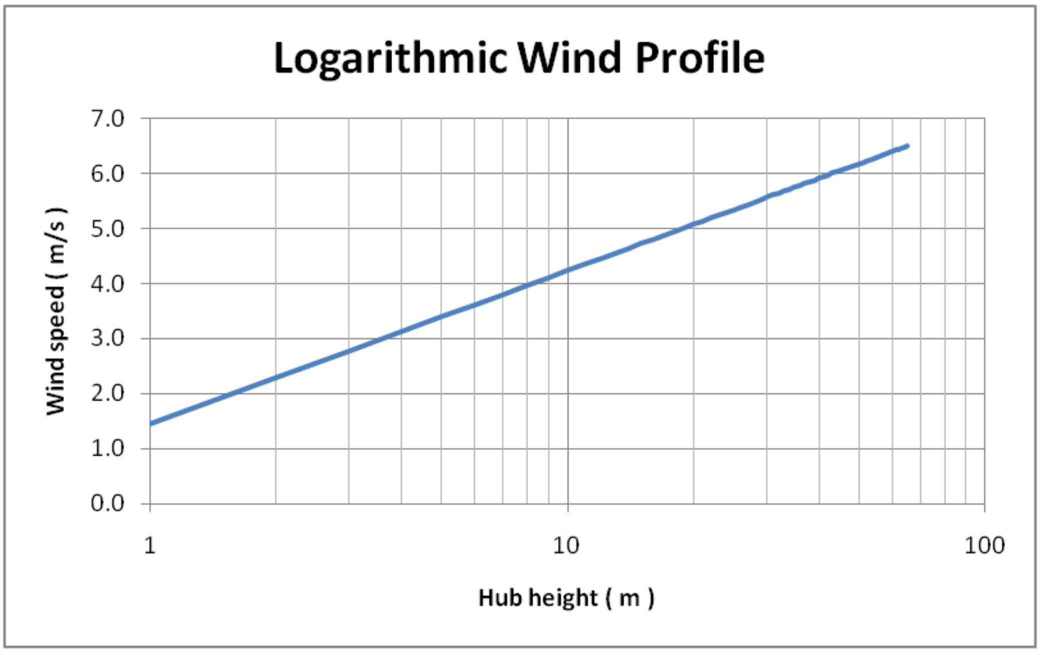


Figure 3.10: Vertical profile for z_0 = 0.03 & $U(z)$ = 6.5 m/s at z = 65 m (Authors own image)

Hub heights below 10 m should be avoided due to the sharp logarithmic decrease in wind speed due to the effects of the boundary layer. Hub heights above 20 m make good use of the logarithmic nature of the boundary layer effect of the vertical wind profile and provide good wind speeds for electricity production.

3.5.4 Normal Wind Profile

AS 61400-2 (Standards Australia 2006) stated that the Normal Wind Profile (NWP) model is assumed to be given by the power law given in equation 3.1. The NWP is used to define the average wind velocity across the rotor swept area.

$$V(z) = V_{hub} \, (z / z_{hub})^{\alpha} \qquad (3.3)$$

where
- $V(z)$ is the average wind speed as a function of height z [m/s]
- V_{hub} is the wind speed at hub height averaged over 10 minutes [m/s]
- z is the height [m]
- z_{hub} is the hub height of the wind turbine [m]
- α is the power law exponent, assumed to be 0.2

Thus for an average wind speed of 6.5 m/s at 65 m height, a corresponding hub height of 18 m yielded a hub velocity of 5.03 m/s.

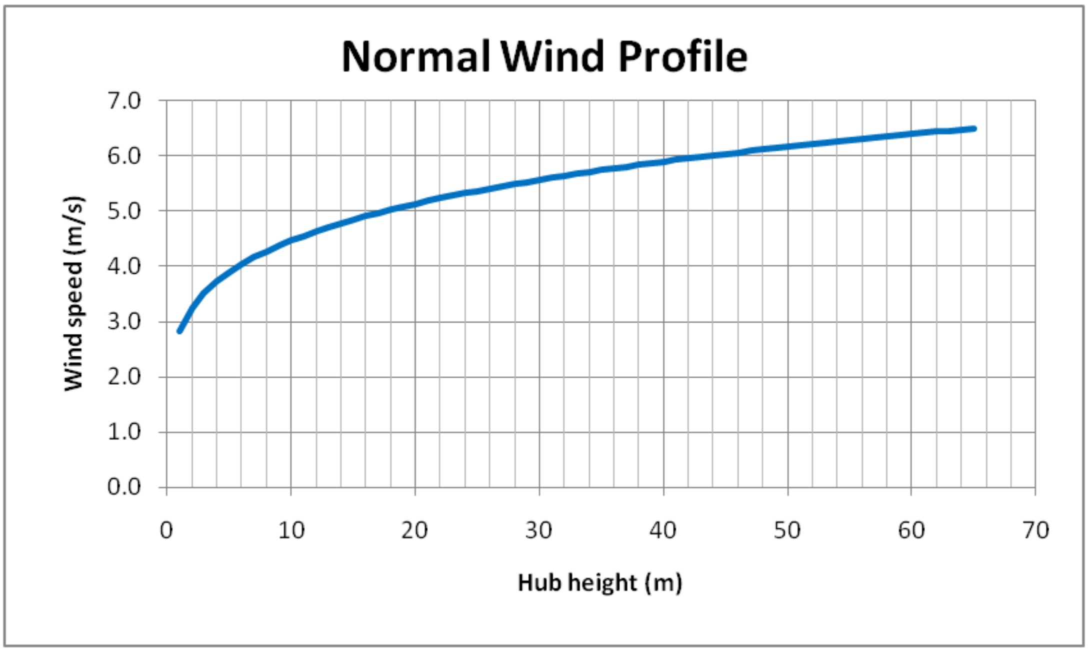


Figure 3.11: Normal Wind Profile for $V(z) = 6.5$ m/s at $z = 65$ m (Authors own image)

Figure 3.12 compares the logarithmic wind profile to the normal wind profile. It demonstrates that for hub heights of 20 m and above, the NWP closely resembles the logarithmic wind profile with a surface roughness length of 0.3 m, corresponding to suburbs and wooded countryside. Between hub heights of 5 m and 20 m the NWP resembles a surface roughness length between 0.1 m an 0.3 m, corresponding to suburbs and villages. It appears that the two different profiles closely resemble each other in residential or built up areas, however in farmland they differ substantially. It was decided to use the NWP model because it is more conservative and allows for a greater range of surface roughness lengths than the logarithmic wind profile. This permits the farmers to install the SWT amongst groups of buildings or trees, and most importantly it keeps the design in compliance with AS 61400-2.

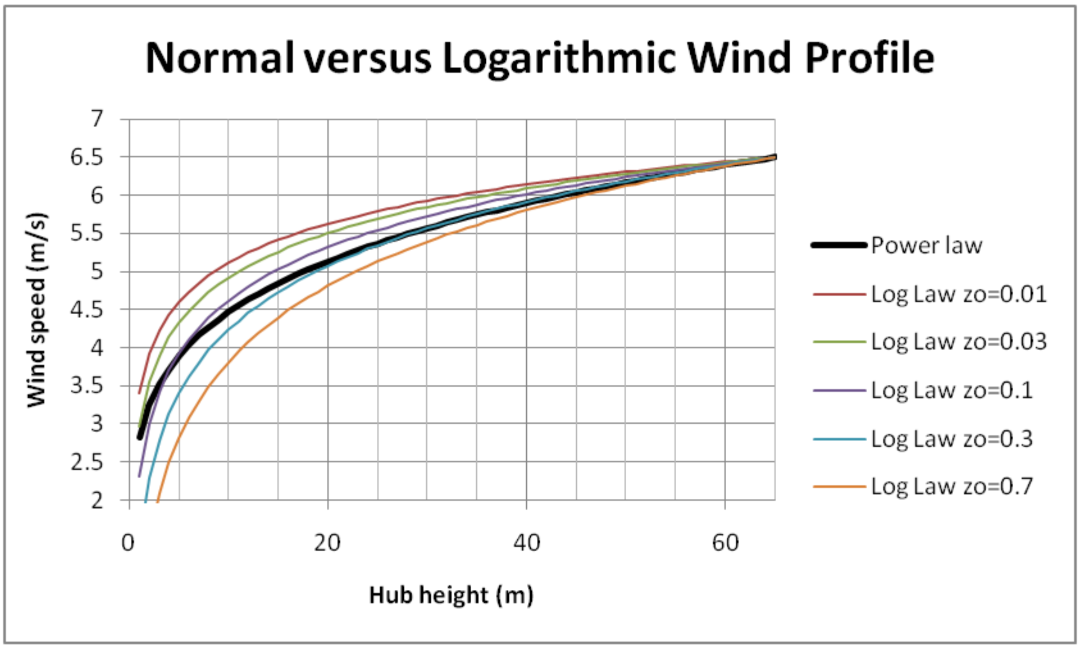


Figure 3.12: Normal Wind Profile versus Logarithmic Wind Profile (Authors own image)

3.5.5 SWT Class Selection

AS 61400-2 specified that the SWT must be defined in terms of classes I, II, III, IV or S which covers most applications and is summarised in table 3.5. Based on NWP calculations this particular design was identified as an SWT class IV with an average wind velocity of 6 m/s. This was the design value used in all subsequent calculations. From equation 3.3 it was calculated that a NWP wind speed of 6.0 m/s occurs at a hub height of 43.5 m, thus for hub heights between 43.5 m and 65 m the SWT is classified as Class III.

SWT Class		I	II	III	IV	S
V_{ref}	(m/s)	50	42,5	37,5	30	Values to be specified by the designer
V_{ave}	(m/s)	10	8,5	7,5	6	
I_{15}	(-)	0,18	0,18	0,18	0,18	
a	(-)	2	2	2	2	

where

- the values apply at hub height, and
- I_{15} is the dimensionless characteristic value of the turbulence intensity at 15 m/s,
- a is the dimensionless slope parameter to be used in equation (7).

Table 3.5: Basic parameters for SWT classes (Standards Australia 2006)

3.5.6 Design Parameters

For SWT Class IV the following parameters were provided in AS 61400-2 (Standards Australia 2006):

V_{ref} = 30 m/s

V_{ave} = 6 m/s

I_{15} = 0.18

a = 2

where V_{ref} is the reference wind speed averaged over 10 minutes [m/s]

V_{ave} is the annual average wind speed at hub height [m/s]

I_{15} is the characteristic value of hub height turbulence intensity at a 10 minute average wind speed of 15 m/s

a is the dimensionless slope parameter to be used in Normal Turbulence Model (NTM) calculations

AS 61400-2 (Standards Australia 2006) stated that the Extreme Wind Model (EWM) for one year and fifty year extremes is based on the reference wind speed as per equation 3.1. The following calculations were based on a preliminary hub height of 18 m:

$$V_{e50}(z) = 1.4\, V_{ref}\ (z / z_{hub})^{0.11} \tag{3.4}$$
$$= 1.4 \times 30 \times (18/18)^{0.11}$$
$$= 42 \text{ m/s}$$

and

$$V_{e1}(z) = 0.75\ V_{e50} \tag{3.5}$$
$$= 0.75 \times 42$$
$$= 31.5 \text{ m/s}$$

where $V_{e50}(z)$ is the 50 year extreme wind speed [m/s]
$V_{e1}(z)$ is the 1 year extreme wind speed [m/s]

AS 61400-2 (Standards Australia 2006) stated that the design wind speed is defined as follows:

$$V_{design} = 1.4\ V_{ave} \tag{3.6}$$
$$= 1.4 \times 6$$
$$= 8.4 \text{ m/s}$$

where V_{design} is the design wind speed [m/s]

The design power was selected as per the project specification in Appendix A:

$$P_{design} = 1{,}000 \text{ W}$$

where P_{design} is the design power [W]

The design tip speed was based on the guidelines given in Manwell, McGowan & Rogers (2002), adapted to the relatively fast rotor speed anticipated in this design:

> "For a water pumping windmill, for which greater torque is needed, use $1 < \lambda < 3$. For electric power generation use $4 < \lambda < 10$. The higher speed machines use less material in the blades.... but require more sophisticated blades."

$$\lambda_{design} = 8$$

where λ_{design} is the design tip speed ratio

AS 61400-2 (Standards Australia 2006) defined the relationship between tip speed ratio, rotor radius and design rotational speed as follows:

$$\lambda_{design} = R\ \pi\ n_{design}\ /\ (30\ V_{design}) \qquad (3.7)$$

therefore

$$n_{design} = 30\ V_{design}\ \lambda_{design}\ /\ (\pi\ R) \qquad (3.8)$$

where R is the rotor radius [m]

n_{design} is the design rotational speed [RPM]

and

$$\omega_{design} = \pi\ n_{design}\ /\ 30 \qquad (3.9)$$

where ω_{design} is the rotational speed [rad/s]

AS 61400-2 (Standards Australia 2006) defined the design torque as follows:

$$Q_{design} = 30\ P_{design}\ /\ \eta\ \pi\ n_{design} \qquad (3.10)$$

where Q_{design} is the design shaft torque [Nm]

η is the drive train efficiency, here assumed to be 0.6

3.6 Summary

The overall topology of the SWT design was selected to best suit the application and BOD guidelines as follows, which was similar to the industry standard:

- Rotor axis orientation is HAWT.
- Rotor position is upwind.
- Rotor is three bladed.
- Power control is passive pitching and passive yaw.

- Hub type is pitching rigid.
- Tower structure is tilt up.

Appropriate wind speed data was identified for use in rural Victoria giving an average velocity of 6.5 m/s at 65 m hub height. The Normal Wind Profile method was selected to calculate the corresponding wind speed at a lower hub height to take into account the vertical wind shear. The SWT was allocated to SWT class IV as per IEC 61400-2 (Standards Australia 2006) and design parameters calculated as per the guidelines given. This information was sufficient to begin detailed component design and selection in the following chapter.

CHAPTER 4 – DETAIL DESIGN & VALIDATION

4.1 Introduction

This chapter aims to build on the conceptual design identified in chapter three and develop individual component designs. Where possible components are sought as modular components available commercially rather than manufactured 'in-house'. As per the conceptual design, the BOD is used to determine suitability of components to satisfy the project aims and objectives.

4.2 Design Methodology Overview

The list of systems and components outlined in table 4.1 was used to methodically work through the detail component design and selection, beginning with the rotor.

System	Component
Rotor	Blades
	Supporting Hub
Drive Train	Generator
	Coupling
	Mechanical Brake
Nacelle & Main Frame	Bedplate
	Nacelle Cover
	Yaw System
Tower	
Machine Controls	
Electrical Systems	Cables
	Switchgear
	Transformers
	Electronic Power Converters

Table 4.1: Major systems & components of a Horizontal Axis Wind Turbine (Authors own table)

The wind turbine design checklist shown in table 4.2 (Eggleston & Stoddard 1987) was also used as a reference to ensure that vital elements of the detailed design were not overlooked. Some elements of the table 4.2 would typically be covered in the 'refine design' part of the overall design, thus they are beyond the scope of this project.

Rotor	Tip-speed ratio, solidity, number of blades
	Aerodynamic optimisation
	Static and dynamic operating loads
	Parked rotor loads
	Material selection
	Manufacturing process
	Structural dynamics
	Fatigue
	Starting torque vs. Friction torque
	Primary overspeed control
	Secondary overspeed control
	Blade tower clearance
	Braking system
	Yaw control
	Hub fairing (or not?)
Tower:	Height (local ordinances)
	Type: pole or truss, tilt up?
	Structural loads
	Strength
	Structural dynamics
	Tower shadow or dam effect
	Erosion protection
Generator:	Type: ac (synchronous, 3 phase, single phase), or dc (alternator, generator)?
	Size
	Weight
	Efficiency curves
	Speed-torque characteristics
	Power conditioning

	Excitation
Gearbox:	Ratio: max. Speed
	Torque capacity
	Strength and load deflections
	Noise
	Structural dynamics
	Lubrication
Control system:	
	Mechanical and/or electrical system
	Control algorithm
	Power supply; consequences of failure
	Start-up and shutdown transients
	Wind speed and direction sensors
	Reliability
	Failure analysis
	Lightning protection
General:	Can it be simplified?
	System dynamics
	Shipping and erection
	Installation method
	Maintenance
	Aesthetics
	Sensitivity to vandalism and UFOs
	Safety
	Corrosion protection
	Specifications and quality control
Cost:	Design life
	Development cost
	Cost per kWh of power produced
	Cost per kW installed
	Tax benefits
	Rate of return; payback period

Table 4.2: Design tasks required for a typical wind turbine (Eggleston & Stoddard 1987)

4.3 Rotor Design

4.3.1 Functional Description

The rotor consists of the rotor blades and hub. The purpose of the rotor is to convert kinetic energy into torque. In the case of the HAWT the rotor blades utilise the aerodynamic property of lift resulting from the cross-sectional profile of the rotor blade, which resembles that of an aircraft wing. The rotor blade must satisfy a wide range of objectives as follows:

- Maximise energy yield for the wind resource.
- Resist extreme and fatigue loads.
- Avoid resonances.
- Minimise weight and cost.
- Limit maximum power output in stall regulated machines.
- Resist deflection to avoid tower strike in upwind machines.

The purpose of the hub is to connect the rotor blades to the drive shaft of the SWT assembly thereby transmitting the loads generated from by rotor blades to the drive shaft. The hub may also house a pitching mechanism to alter the pitching on the individual rotor blades. A nose cone is attached to the upwind side of the hub to streamline the aerodynamics of the hub face thus reducing turbulence near the blade roots, and to protect the hub itself from damage due to the weather.

4.3.2 Rotor Blades

From equation 3.1 a theoretical rotor radius was calculated for the power output requirement. An example calculation of rotor power using V_{design} and P_{design} values from section 3.5.6 Design Parameters is shown here:

$$\begin{aligned} P_r &= C_p \ \tfrac{1}{2} \ \rho \ V_{hub}^{\,3} A \\ &= C_p \ \tfrac{1}{2} \ \rho \ V_{hub}^{\,3} \pi \ R^2 \qquad (4.1) \end{aligned}$$

therefore $R = (P_r / (C_p \; ½ \; \rho \; \pi \; V_{hub}^{\;3}))^{0.5}$ (4.2)

$= (1000 / (0.49 \text{ x } 0.5 \text{ x } 1.225 \text{ x } \pi \text{ x } 8.5^{\;3}))^{0.5}$

$= 1.31$ m

where

- P_r is the rotor power, here assumed to be 1,000 [W]
- C_p is the coefficient of power, here assumed to be 0.49 as per figure 2.18
- ρ is the air density, here assumed to be 1.225 [kg/m^3]
- V_{hub} is the wind speed at the hub height [m/s]
- A is the area of rotor swept area [m^2]
- R is the radius of the rotor [m]

Rotor blade design is a complex area of study requiring comprehensive aerodynamic and structural design. Fortunately there are many 'off the shelf' components commercially available. To satisfy the project specification requirement to use 'commercially available parts', and due to the complexity of rotor blade design, commercially available rotor blades were chosen.

Some common material options for rotor blades include steel, aluminium, and composite materials such as wood, fibreglass, carbon fibre and resin. The blades need to be as light as possible to reduce gyroscopic and inertial loads which contribute to blade fatigue. Fatigue performance is conventionally measured by mean fatigue strength at 10^7 cycles, as a percentage of ultimate compressive strength. The most common materials used for rotor blades are listed here:

Steel

Steel blades are heavier than composites and thus suffer from reduced fatigue life.

Aluminium

Aluminium blades are also heavier than composites and thus suffer from reduced fatigue life.

Wood

Wood is easy to make and easily destroyed; it is sometimes used in laminated composite structures but generally suffers from low fatigue strength making it unsuitable for fast spinning blades.

PVC

PVC is popular in very small wind turbines and is very light weight.

Thermoplastics

High performance thermoplastic matrices are being used in the aerospace industry and have recently undergone testing in the wind turbine blade application. It is not yet in commercial production as it requires more research and development.

Glass Fibre Reinforced Composites (GFRC)

GFRC is a low cost composite material with reasonably good tensile strength. It is the most popular material for SWT blade construction at present. Three types of binders are normally used – polyester, epoxy or vinyl ester.

Carbon Fibre Reinforced Composites (CFRC)

CFRC are more expensive than GFRC by a factor of 15 (Burton et al. 2001), but they are stronger and stiffer. CFRC have the best all round properties by far but are not popular due to the high cost. It is possible to compromise by using a mixture of carbon and glass fibres to reduce cost. As with GFRC three types of binders are normally used – polyester, epoxy or vinyl ester.

Material	Specific Gravity	Fatigue Strength (MPa)	Young's Modulus (MPa)	Compressive strength to weight ratio
Glass / polyester ply	1.85	140	38	390
Glass / epoxy ply	1.85	140	38	390
Glass / polyester laminate	1.85	120	33.5	310
Carbon fibre / epoxy ply	1.58	350	142	700
Wood / epoxy laminate	0.67	16.5	69	109
High yield steel	7.85	50	210	65
Weldable aluminium	2.71	17	69	109

Table 4.3: Structural properties of materials used for wind turbine blades (Burton et al. 2001)

As can be seen in table 4.3 CFRC had superior fatigue strength and would have been the clear choice except for its high cost. GFRC blades satisfied the requirements for this application due to their combination of high strength and low cost. Windmax Green Energy was identified as a world leading manufacturer of small wind turbine blades and was selected as the supplier of GFRC blades for this project due to their comprehensive range of different sizes availability and low cost. Windmax Green Energy blades have the following features (Windmax Green Energy 2010):

- Durable reinforced fibreglass material with UV protection coating.
- Power Coefficient C_p = 0.49.
- Can be supplied with hub.

Table 4.3 summarised available Windmax Green Energy rotor sizes and costs:

Rotor Diameter (m)	Cost without hub AUD	Cost including hub AUD	Total cost including shipping AUD
2.07	70	93	442
2.59	88	111	594
2.83	116	140	666
3.23	131	154	749
3.99	232	279	944
4.51	781	n/a	3,349
6.40	1,166	1,399	3,968

Table 4.4: Windmax rotor sizes available (Windmax Green Energy 2010)

A 2.83 m diameter rotor was initially selected (Windmax 0093WH) as it was slightly larger than the requirement of 2.63 m calculated in equation 4.1. The specifications of this particular rotor blade were listed as follows:

- Blade material: reinforced fibreglass composite.
- Blade diameter: 2.835 m (radius = 1.417 m).
- Rated wind speed: 8 m/s (overspeed control must be implemented to limit the rotation speed at or above rated wind speed).
- Start-up wind speed: 2.4 m/s.
- Weight: 2.63 kg per blade.

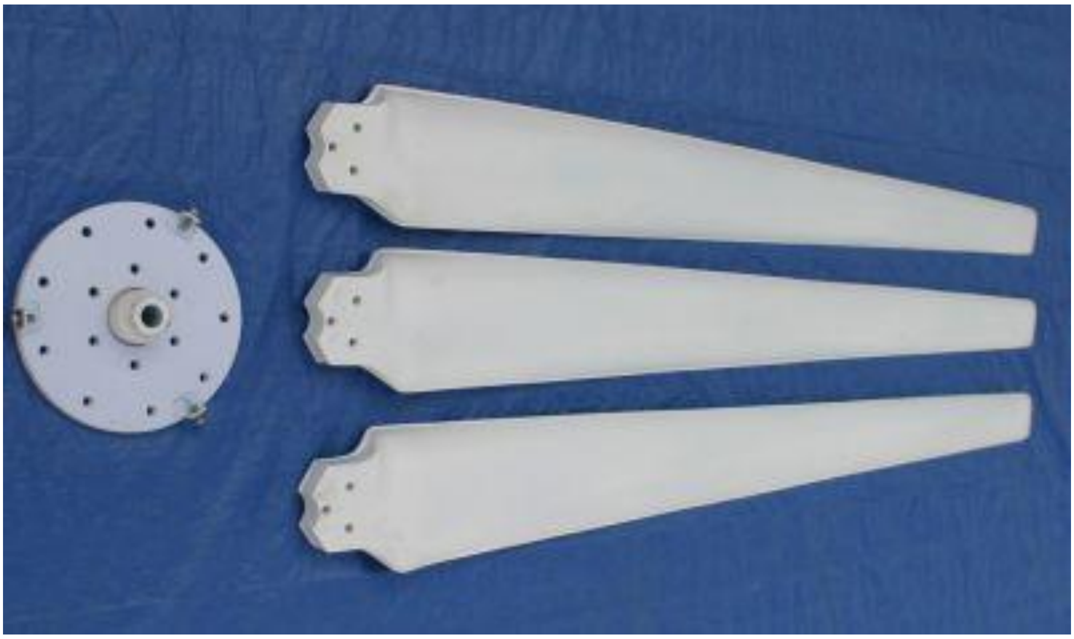


Figure 4.1: Windmax 0093WH rotor blades with hub (Windmax Green Energy 2010)

The Windmax 0093WH appeared to be suitable based on the theoretical rotor radius however further checks were required. Because the rotor radius depends on the power output it must generate and also the wind regime in which it must operate, the design wind speed is a very important parameter. A mistake in the design parameters especially the wind speed can make or break the success of a SWT design in its intended market. This particular rotor design was based on an average wind speed of 6 m/s as per AS 61400-2 (Standards Australia 2006) however it was calculated in chapter 3.5.4 that the average NWP for Victoria was somewhat lower than this. This means the power output for a typical SWT installation in an area of average wind speed may be less than the calculated output for design wind speed. The two main ways to increase power output are:

- Increase the rotor diameter.
- Increase the wind speed by increasing the tower and thus the rotor hub height.

Thus it was prudent to check if the rotor chosen will match a suitable tower height for an average wind speed in Victoria. By inputting the 1.42 m rotor radius of the Windmax 0093WH into equation 4.1, the wind speed required to generate 1,000 Watts was estimated for the rotor radius and thus the tower height requirement.

$$P_r = C_p \tfrac{1}{2} \rho V_{hub}^3 \pi R^2 \qquad (4.1)$$

therefore

$$V_{hub} = (P_r / C_p \tfrac{1}{2} \rho R^2 \pi) \wedge 0.333 \qquad (4.3)$$

$$= (1000 / 0.49 \times 0.5 \times 1.225 \times 1.42^2 \times \pi) \wedge 0.333$$

$$= 8.07 \text{ m/s}$$

It was be interpolated from figure 4.2 that a 36 m high tower is required in the NWP model to generate 1,000 Watts in 8.07 m/s wind using a 1.42 m radius rotor. A tower of this height was considered to be unsuitable as it would be too expensive and difficult to erect, thus the next size rotor was tested for hub height requirements.

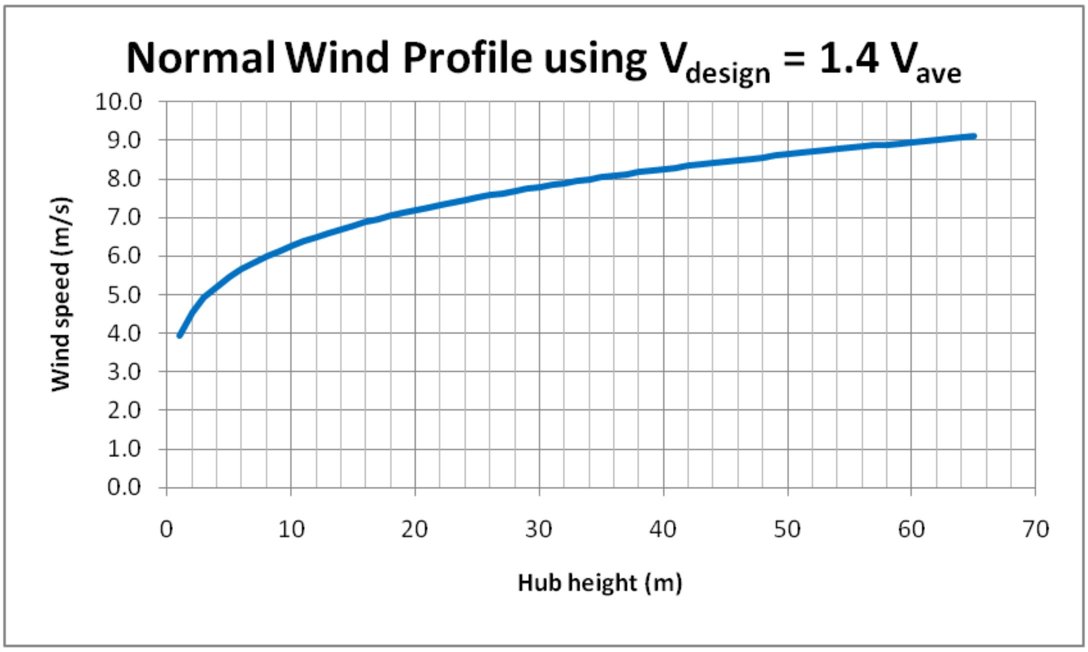


Figure 4.2: Normal Wind Profile using design wind speed (Authors own image)

A 3.23 m diameter rotor was selected (Windmax 106WH), the specifications of this particular rotor blade were listed as follows:

- Blade material: reinforced fibreglass composite.
- Blade diameter: 3.23 m (radius = 1.62 m).
- Rated wind speed: 8 m/s (overspeed control must be implemented to limit the rotation speed at or above rated wind speed).
- Start-up wind speed: 2.4 m/s.

- Weight: 2.63 kg per blade.

By inputting the 1.62 m rotor radius into equation 4.1, the required wind speed was estimated to generate 1,000 Watts for the 1.62 m rotor radius and thus the tower height requirement:

$$P_r = C_p \ ½ \ \rho \ V_{hub}^{\ 3} \ \pi \ R^2 \qquad (4.1)$$

therefore

$$V_{hub} = (P_r \ / \ C_p \ ½ \ \rho \ R^2 \ \pi \ ) \wedge 0.333 \qquad (4.4)$$
$$= (1000 \ / \ 0.49 \ x \ 0.5 \ x \ 1.225 \ x \ 1.62^2 \ x \ \pi \ ) \wedge 0.333$$
$$= 7.39 \text{ m/s}$$

It was be interpolated from figure 4.2 that a 23 m high tower was required in the NWP model to generate 1,000 Watts in 7.39 m/s wind using a 1.62 m radius rotor. A tower of this height is more acceptable with regards to cost and installation requirements and thus the Windmax 106WH rotor was chosen rotor this design. This was a larger than average rotor, specifically chosen to suit the moderate to low average wind velocities expected in typical Victorian farmland. It was possible to make further calculations regarding the rotor based on the information available. Inputting the selected rotor radius into equation 4.1:

$$P_r = C_p \ ½ \ \rho \ V_{hub}^{\ 3} \ \pi \ R^2 \qquad (4.1)$$
$$= 0.49 \ x \ 0.5 \ x \ 1.225 \ x \ 8.5^3 \ x \ \pi \ x \ 1.615^2$$
$$= 1{,}511 \text{ W}$$

where $V_{hub} = V_{design}$

$P_r = P_{design}$

The design power rating was calculated to be 1,511 Watts for the design wind speed of 8.5 m/s, which was above the project specification of 1,000 Watts. The reason for this difference was that the actual average wind speeds were expected to be substantially lower than the design wind speeds, thus the extra power generating capacity was warranted. Design rotational speed was calculated using equation 3.8, given in AS 61400-2 (Standards Australia 2006):

$$n_{design} = 30 \; V_{design} \; \lambda_{design} \; / \; (\pi \; R) \qquad (3.8)$$

$$= 30 \times 8.4 \times 8 \; / \; (\pi \times 1.615)$$

$$= 397.2 \text{ RPM}$$

$$= 41.60 \text{ rad/s}$$

Design torque was calculated using equation 3.10, given in AS 61400-2 (Standards Australia 2006):

$$Q_{design} = 30 \; P_{design} \; / \; \eta \; \pi \; n_{design} \qquad (3.10)$$

$$= 30 \times 1{,}511 \; / \; (0.600 \times \pi \times 397.2)$$

$$= 60.54 \text{ Nm}$$

4.3.3 Rotor Hub

The conceptual rotor hub design was a rigid design incorporating a variable pitch mechanism. Rigid hubs are generally made of steel - welded, machined or cast depending on the size and design. It was considered feasible to construct a hub using another type of metal such as aluminium; however the high strength and low cost of steel make it the superior material for this application. This design requires a relatively small hub so machined mild steel was chosen as the most suitable material.

The hub must be attached to the shaft in such a way that it does not slip or spin on the shaft. A simple design suited to the SWT is to incorporate a key into the shaft and the hub design, to thread the end of the shaft and to lock the hub onto the shaft using a conventional nut. The selected Windmax 106WH rotor blades are supplied in a complete set with a rigid mild steel rotor hub included, complete with a protective coating, designed to fit 23.4 mm / 28.2 mm diameter tapered shaft.

4.3.4 Hub Nose Cone

A popular material used for the manufacture of nose cones on SWTs was found to be GFRC, otherwise known as fibreglass. This material is versatile, inexpensive, lightweight, strong, weatherproof, and can be manufactured with an attractive finish.

GFRC is the chosen material for the hub nose cone. Manufacturing could be hand-made single units for a reasonable price, or upsized to mass production as required. Usual manufacturing techniques were identified as follows:

- Fibreglass hand lay-up – sheets of fibreglass laid on a mould then resin and catalyst are applied by hand.
- Fibreglass spray lay-up – fibre and resins are sprayed onto a mould.
- Poltrusion – fibres are pulled off a spool through a device that coats them in resin, shapes and cuts to length.

4.4 Drive Train Design

4.4.1 Functional Description

The drive train includes the shaft, gearbox, coupling, mechanical brake and generator. For this SWT design a gearbox is not necessary due to the low power requirements of the design and to minimise overall complexity. The generator converts the mechanical energy into electrical energy. The generator works with a power source (the wind) which supplies fluctuating mechanical power in the form of torque. The generator must be able to deliver the power developed by the variable speed SWT over a wide range of wind speeds. The generator of choice for SWTs was the Permanent Magnet Generator (PMG), which works by permanent magnets providing the magnetic field in a simple, rugged construction. The PMG used in most SWTs are classed as asynchronous, meaning they are generally not connected to the AC (Alternating Current) grid. The power generated from the PMG is initially variable voltage and frequency AC and is often rectified immediately to DC (Direct Current) which is then either directed to DC loads or battery storage, or else inverted to AC with fixed frequency and voltage.

4.4.2 Generator

A fully assembled generator is required to satisfy the project aim of using commercially available parts for the SWT. The industry standard for SWT design is the PMG, which featured in 100 percent of the SWTs surveyed in Appendix B. The PMG was the chosen type for this application due to its availability in the commercial market, its simplicity, reliability and low cost. A suitable PMG was sourced from a world leading wind turbine parts supplier - Ginlong Technologies Inc. from China. Ginlong Technologies Inc. markets an extensive range of PMGs from 500 W through to 30 kW. Three of Ginlong Technologies Inc. PMGs were selected for evaluation in this design as shown in table 4.5. Some of the design features common to all three were:

- Specifically designed for SWT applications.
- Three phase star connected AC output.
- Aluminium casing treated to resist corrosion and oxidation.
- Designed for a 20 year operating life.

	GL-PMG-1000	GL-PMG-1500	GL-PMG-1800
Rated power output (W)	1000	1500	1800
Rated rotation speed (RPM)	450	550	480
Rectified DC current at rated output (A)	6	30	6
Rectified torque at rated power (Nm)	31.5	35	44.5
Phase resistance (Ohm)	5	5	5
Output wire square section (mm^2)	4	4	4
Output wire length (mm)	600	600	600
Weight (kg)	15.7	15.7	18.3
Starting torque (Nm)	0.5	0.7	0.9

Table 4.5: Generator data comparison (Ginlong Technologies Inc. 2006)

Each option was evaluated for the SWT design speed of 397 RPM and design torque of 60.5 Nm, which were coincident with the design wind speed of 8.4 m/s. The values in table 4.6 were interpolated from the performance graphs supplied by Ginlong Technologies Inc. (2006).

	GL-PMG-1000	GL-PMG-1500	GL-PMG-1800
Power output at design speed (W)	900	820	1350
Rotation speed required for 1000 W (rpm)	430	440	350
Voltage at design speed (V)	250	51	330
Torque at design speed (Nm)	29	27	40

Table 4.6: Generator data correlations (Ginlong Technologies Inc. 2006)

Although the GL-PMG-1000 requires the lowest torque to generate its design power output, it requires wind speeds well above the design wind speed to generate the SWT design power output of 1,000 Watts. The GL-PMG-1500 requires even lower torque but is still unable to generate the SWT design power output at the design wind speed. The GL-PMG-1800 is able to generate the SWT design power output at sub-design wind speeds and the torque required is only about two thirds of the design torque which is ample. The GL-PMG-1800 was the chosen PMG for this application as it offers the best option to match the SWT design data. The power curve can be seen in figure 4.4 and the torque curve in figure 4.5. The cost of this unit was listed as $1,043.

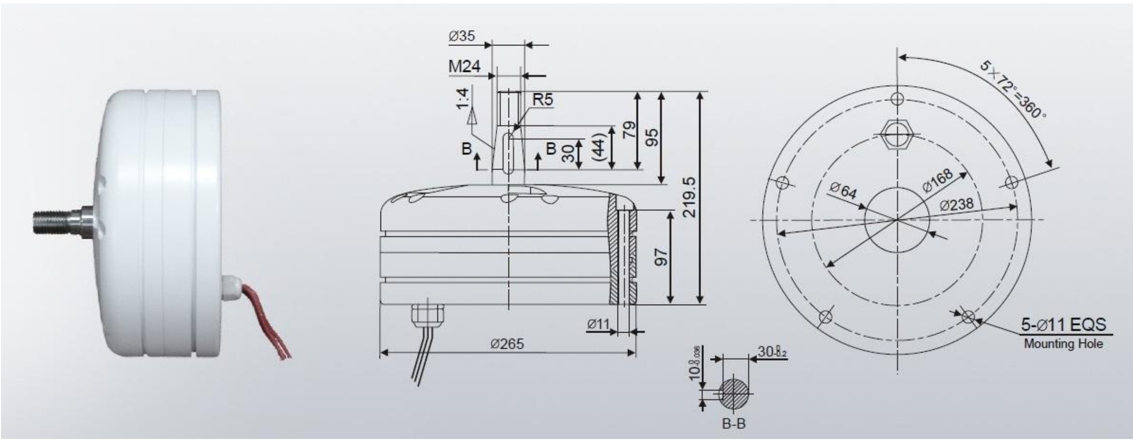


Figure 4.3: GL-PMG-1800 general arrangement (Ginlong Technologies Inc. 2006)

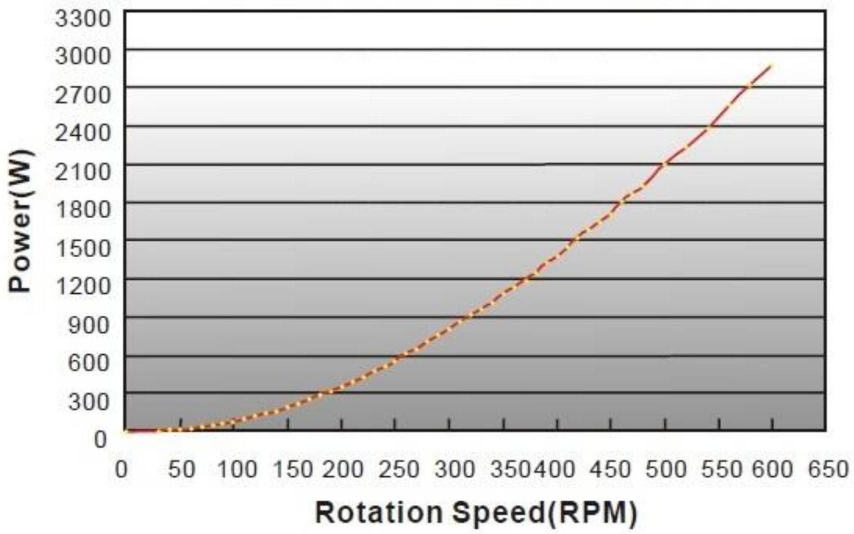


Figure 4.4: GL-PMG-1800 power curve (Ginlong Technologies Inc. 2006)

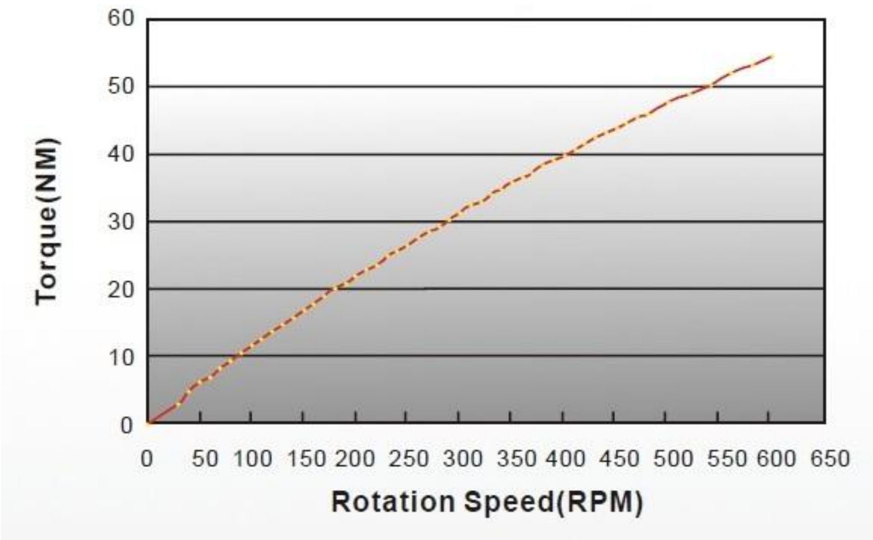


Figure 4.5: GL-PMG-1800 torque input curve (Ginlong Technologies Inc. 2006)

4.4.3 Coupling

The coupling connects the drive component (rotor) to the driven component (generator). One of the most common reliability issues with rotating machinery is misalignment between the drive shaft & driven shaft. A flexible coupling was chosen because it can accommodate misalignments and dampen vibrations. Several types of flexible coupling are available including tyre, pin, flexible jaw, flexible spider, flexible gear, grid, cone ring, gear, and universal shaft. The tyre coupling configuration was chosen because it tolerates large amounts of misalignment in all planes and is simple to install and inspect.

It is also lubrication free and has excellent shock absorbing properties. The Fenaflex tyre coupling was chosen because it is inexpensive, locally available, comes in 15 different sizes and can be supplied with taperlock bushings for easy installation and maintenance.

Figure 4.6: Fenaflex tyre coupling (Blackwoods 2010)

4.4.4 Mechanical Brake

AS 61400-2 (Standards Australia 2006) chapter eight deals with the protection and shutdown system requirements for SWTs. Key points in chapter eight are as follows:

- Active and/or passive overspeed protection system is required to limit the turbine rotation speed to n_{max} (maximum rotor speed).
- For turbines with a swept area of greater than 40 m^2 there shall be a manual shutdown button / switch and shutdown procedures.
- For turbines with a swept area of less than 40 m^2 a manual stop button / switch is not required but is recommended.
- A safe method for shutting down for maintenance must be specified which includes bringing the rotor and yaw mechanism to a standstill.
- The lowering of an SWT on a tilt tower is an acceptable method of bringing the turbine to a standstill.

The 3.23 m diameter rotor selected (Windmax 106WH) has a swept area of 8.2 m^2, therefore a stop switch is not required and is not included as part of this design. Section 9.2.4 of AS 61400-2 (Standards Australia 2006) stated that n_{max} must be determined by live testing by measuring the rotor speed during the turbine condition most likely to give the highest rotor speed (example wind gust or loss of load) at wind speeds between 10 m/s and 15 m/s. An arbitory n_{max} value was estimated as a starting point during the pre-load design for the blade pitching mechanism. The lowering of the SWT on the tilt tower provides sufficient shutdown braking capacity provided a procedure is provided in the SWT manual. Therefore no mechanical braking mechanism was incorporated into this design to help reduce overall complexity and cost.

4.5 Nacelle & Main Frame Design

4.5.1 Functional Description

The function of the nacelle bedplate is to transfer the load from the rotor to the yaw bearing and to provide a solid mounting for the yaw mechanism and generator components. The function of the nacelle cover is to protect the generator components, drive shaft and coupling from the weather, wildlife (birds) and to a lesser extent as a safety guard providing protection from rotating equipment. The yaw system consists of the yaw bearing which permits and supports the wind turbine to rotate to face the oncoming wind atop the fixed tower, and the tail fin which aligns the rotor to face the incoming wind using aerodynamic forces.

4.5.2 Nacelle Bedplate

The bedplate requires good strength characteristics to transmit loads from the rotor to the yaw bearing. Some obvious material choices are as follows:

- Die cast aluminium.
- Weldable aluminium.
- Steel casting or forging.
- Plain carbon steel.

Due to the small batch quantities required for manufacturing, die cast aluminium and steel castings or forgings are likely to be prohibitively expensive due to set up costs. Plain carbon steel was chosen over aluminium because it is approximately three times the strength and is likely to be the least expensive option. A simple flat plate with a fitted, machined yaw bearing housing welded in place was considered to be suitable as the manufacturing technique. The addition of mounting holes and brackets may also be required to mount the various components. Surface protection was specified using two-part epoxy coating which provides a tough, UV resistant protective coating with excellent hardness.

4.5.3 Nacelle Cover

The most popular material used for the manufacture of nacelle covers on SWTs was found to be GFRC, otherwise known as fibreglass. This material is versatile, inexpensive, lightweight, strong, weatherproof, and can be manufactured with a very attractive finish. GFRC is the chosen material for the nacelle cover. Manufacturing can be hand-made single units for a reasonable price or can be upsized to mass production as required. Usual manufacturing techniques are as follows:

- Fibreglass hand lay-up – sheets of fibreglass laid on a mould then resin and catalyst are applied by hand.
- Fibreglass spray lay-up – fibre and resins are sprayed onto a mould.
- Poltrusion – fibres are pulled off a spool through a device that coats them in resin, shapes and cuts to length.

4.5.4 Yaw Mechanism

The tail fin must be lightweight so as not to induce unnecessary fatigue loads and stress on the bedplate; it must also be stiff and strong enough to resist the yawing loads on the wind turbine during strong wind gusts. The obvious choices for the tail fin are aluminium plate or GFRC as they both have suitable density and strength properties. Aluminium plate was chosen because it is likely to be simpler to fabricate and less expensive. The suggested manufacturing technique is to profile cut the thin aluminium plate which is then bolted to a thin aluminium rod, which is in turn bolted to the bedplate via a simple aluminium mounting bracket. Surface protection is recommended as the same two-part epoxy coating as the bed-plate.

The yaw loads on the yaw bearing consist of three terms: centrifugal force, gyroscopic and eccentricity of axial load (Standards Australia 2006). Due to the combination of thrust and axial loading the three most suitable types of bearings to suit this application are angular contact ball bearing, tapered roller bearing and spherical roller bearing. Angular contact ball bearings are the least expensive and the bearing of choice for this application. The preference of the author is to use SKF bearings as they are world renowned for their excellent reliability. A grease nipple should be fitted to the bearing and an annual lubrication routine specified in the manual, because the 20 year design life was considered to be too long for a sealed bearing to survive without lubricant replenishment.

4.6 Tower Design

4.6.1 Functional Description

The tower assembly consists of the tower and the foundation. Its two primary functions are to:

- Carry the loads from the SWT.
- Elevate the SWT to a height to access sufficient wind velocities.

The tower must also provide a suitable means of accessing the SWT for both planned maintenance and repairs, which in the case of tilt-up towers, is lowering and raising the tower. The tilt-up tower was the selected configuration for this design as per the conceptual design chapter. This tower configuration offers cost-effectiveness and ease of installation. It also reduces the life cycle cost of the SWT by making it easier for the owner to lower and raise the tower for inspections and maintenance without the extra costs of specialist machinery or expert personnel.

4.6.2 Tower Selection

To satisfy the project aim of using commercially available parts it was decided to source a tower in kit-form. Research revealed many suitable tilt-up tower kits which were commercially available, and that galvanised steel tube was the material of choice due to its superior strength and low cost. A comparison of potential kit form towers available on the Australian market revealed the following options:

Distributor	Tower Height (m)	Construction	Pipe Section	Cost (AUD)
Soma	13	Steel Tube	DN65	$1,859
Southwest Windpower	13.6	Steel Tube	DN40	$466
Soma	19.5	Steel Tube	DN65	$3,913
Southwest Windpower	20	Steel Tube	DN65	$1,819
Southwest Windpower	21	Steel Tube	DN100	$2,599
Southwest Windpower	25	Steel Tube	DN65	$2,199

Table 4.7: Comparison of kit SWT towers (Authors own table)

Chapter 4.3.2 calculated that a 23 m tower is necessary for the Windmax 106WH to generate 1,000 Watts using the average NWP for Victoria. The 25 m tower manufactured by Southwest Windpower appears to be the most suitable kit, which uses DN65 galvanised steel tube with the option of using different wall thicknesses to suit loading requirements. It was proposed to supply the 25 m Southwest Windpower tilt-up tower kit for installations with average Victorian wind speeds, with the option of supplying the 19 m Southwest Windpower tilt-up tower kit for locations with above average wind speeds to reduce overall costs. Energy Matters (2009) provided the following information about the 25 m tilt-up tower kit:

> "With the help of a winch, beast of burden or vehicle, two people can easily erect the tower in a few hours. All that is required is the necessary tubing and the proper anchors for your soil. At least two people should be present to safely raise the tower.

The 25m tower uses a gin pole to assist in raising the tower. The basic principle of the gin pole is described [in figure 4.7]. The tower kit uses galvanised steel tube with separate pivots for both the tower and gin pole. The tower base has a footprint of [406 mm] square. In many cases a concrete pad for the tower base is not necessary."

The sequence of raising the tower using a tractor was illustrated in figure 4.7.

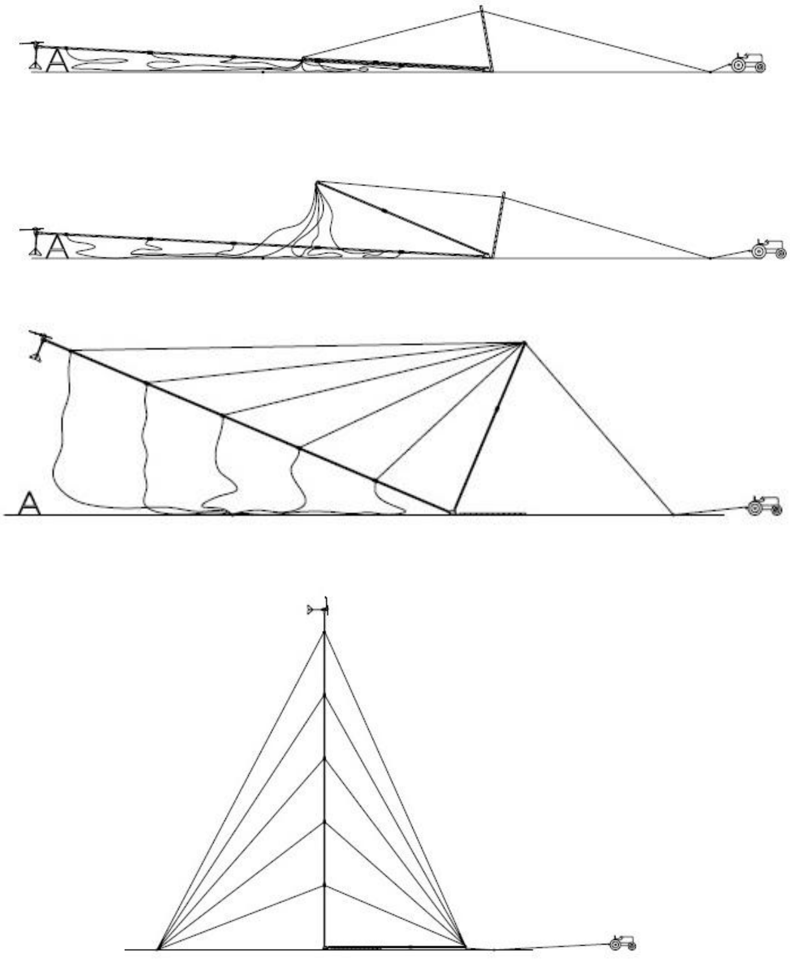


Figure 4.7: Raising the tilt-up tower using a tractor (Energy Matters 2009)

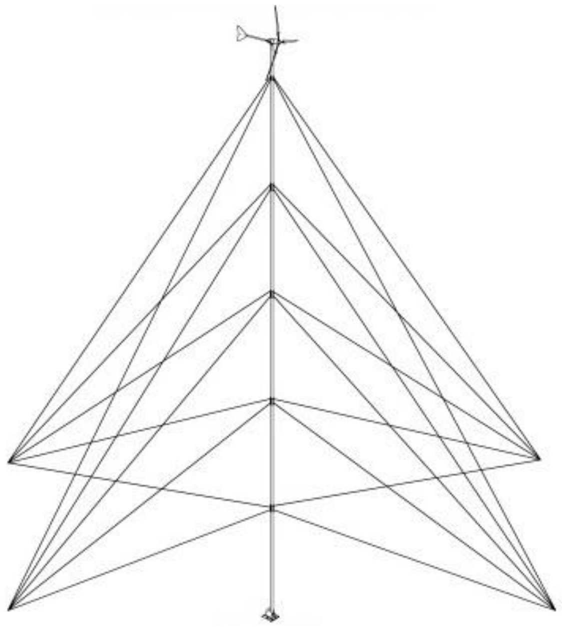


Figure 4.8: Southwest Windpower 25m tower erected (Energy Matters 2009)

The tower pipe wall thickness requirements were stated as follows (Energy Matters 2009):

- Maximum wind speed = 136 km/h (38 m/s), use 3.0 mm wall thickness
- Maximum wind speed = 160 km/h (44 m/s), use 3.6 mm wall thickness

Since the 50 year design wind speed V_{e50} for this design was specified as 42 m/s, 3.6 mm wall thickness is required. This pipe section was further verified using the load calculations in the following section. The following pipe sections require purchasing separate to the 25 m tilt-up tower kit:

- 4 x 4.57 m lengths of DN65 schedule 40 galvanised pipe for tower.
- 1 x 6.1 m length of DN65 schedule 40 galvanised pipe for tower.
- 1 x 5.8 m length of DN65 schedule 40 galvanised pipe for gin pole.
- 1 x 4.0 m length of DN65 schedule 40 galvanised pipe for gin pole.

Quoted price for DN65 schedule 40 galvanised pipe was $45.75 per metre, thus for 7 x 6.5 m lengths the cost was calculated to be $2,081. Refer to appendix D for an excerpt of the Southwest Windpower 25 m tilt-up tower installation manual, which contains further details of components and installation techniques.

4.6.3 Load Calculations

The main load consideration for a tower design is the bending moment caused by the force of the wind on the SWT rotor and components. AS 61400-2 (Standards Australia 2006) stated that the maximum bending moment shall be calculated using a combination of:

a) The thrust load as per equation 4.5.
b) The load on each component i.e. tower & nacelle as per equation 4.6.

For guyed towers the maximum bending moment occurs at the upper guy wire attachment. The thrust force needs to be calculated for the worst case design scenario, in this case the 50 year extreme wind speed. A third load case also needs to be considered for transportation, assembly, maintenance and repair. This includes gravity loads on the tower when it is not upright, when it is being hoisted into position, tooling loads and erection loads.

4.6.3.1 Thrust Load

The thrust load was calculated at the 50 year extreme wind speed, where it was assumed that the rotor was parked by overspeed protection devices. The parked rotor thrust load was specified in Standards Australia (2006) as follows:

$$F_{\text{x-shaft}} = B\ C_d\ \tfrac{1}{2}\ \rho\ V_{e50}^{2}\ A_{\text{proj,B}} \qquad (4.5)$$

where
$F_{\text{x-shaft}}$ is the axial shaft load [N]
B is the number of blades
C_d is the drag coefficient which shall be taken as 1.5
$A_{\text{proj,B}}$ is the planform area of the blade [m^2]
ρ is air density, here assumed to be 1.225 [kg/m^3]
V_{e50} is the wind speed for 50 year wind extreme [m/s]

Exact blade component dimensions were not available for the blades used in this design however 0.220 m^2 per blade was estimated from a scaled photograph provided by the blade manufacturer. Using known values in equation 4.5 the thrust load was calculated as follows:

$$F_{x\text{-shaft}} = 3 \times 1.5 \times 0.5 \times 1.225 \times 42^2 \times 0.220$$
$$= 1{,}070 \text{ N}$$

4.6.3.2 Component Forces

AS 61400-2 (Standards Australia 2006) stated to use the following formula to calculate component forces:

$$F = C_f \ ½ \ \rho \ V_{e50}^{\ 2} \ A_{proj} \qquad (4.6)$$

where F is the load on each component [N]

C_f is the force coefficient as per table 4.8

A_{proj} is the component area in its most unfavorable position [m^2]

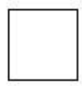
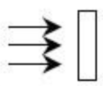
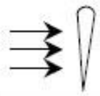
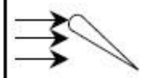
						
Characteristic length < 0,1 m	1,3	1,3	1,5	1,5	1,5	2,0
Characteristic length > 0,1 m	0,7	1,2	1,5	1,5	1,5	2,0

Table 4.8: Force coefficients, C_f (Standards Australia 2006)

Since the final design was not fully developed, estimates for the area and force coefficient were required. The assumption was a 1.0 m^2 solid rectangular object with a force coefficient of 1.5, which should be a conservative estimate for both size and shape.

$$F = C_f \ ½ \ \rho \ V_{ref}^{\ 2} \ A_{proj}$$

$$= 1.5 \times 0.5 \times 1.225 \times 30^2 \times 1.0$$
$$= 826.9 \text{ N}$$

The total axial load calculated combines the parked rotor thrust load and the component load:

$$F_{total} = F + F_{x\text{-shaft}} \quad (4.7)$$
$$= 1{,}070 + 826.9$$
$$= 1{,}897 \text{ N}$$

4.6.3.3 Transportation, Assembly, Maintenance and Repair Loads

AS 61400-2 (Standards Australia 2006) specified that equation 4.8 shall be used to calculate these loads, which includes a dynamic amplification factor of 2. Some assumptions regarding weight were necessary to estimate the bending moment.

$$M_{tower} = 2 \left(m_{towertop} + m_{overhang} / 2 \right) g \, L_{lt} \quad (4.8)$$
$$= 2 \left(100 + 7/2 \right) \times 9.81 \times 1.60$$
$$= 3{,}249 \text{ Nm}$$

where M_{tower} is the bending moment of the tower at the lifting point attachment [Nm]

$m_{towertop}$ is the mass of the rotor and nacelle combined, here assumed to be 100 [kg]

$m_{overhang}$ is the mass of the tower between the lifting point and the tower top, here assumed to be 7 [kg]

g is gravity, which shall be taken as 9.81 [m/s^2]

L_{lt} is the distance between the lifting point and the top of the tower, here assumed to be 1.6 [m]

4.6.3.4 Tower Stress Calculations

The bending moment due to the total axial load was calculated from the upper guy wire attachment (Standards Australia 2006), which in this case was 1.6 m:

thus $M = F_{total} \; L$ (4.9)

$= 1,897 \times 1.6$

$= 3,034$ Nm

where M is the bending moment [Nm]

F_{total} is the total axial force [N]

L is the length [m]

The maximum stress in the tower section was calculated using the following formula from AS 61400-2 (Standards Australia 2006):

$$\sigma = M \; y \; / \; I \qquad (4.10)$$

where σ is the maximum stress [Pa]

y is the distance from the neutral axis [m]

I is the moment of inertia of the section [m^4]

The cross section selected was hollow tube with outside diameter of 73.02 mm and inside diameter of 62.71 mm. Moment of inertia was calculated using equation 4.11:

$$I = \pi \; (D_o^{\,4} - D_i^{\,4}) / 64 \qquad (4.11)$$

$$= \pi \; (0.07302^{\,4} - 0.06271^{\,4}) / 64$$

$$= 6.364 \times 10^{-7} \; m^4$$

where D_o is the outside diameter [m]

D_i is the inside diameter [m]

For the axial load:

$$\rho = M \; y \; / \; I$$

$$= 3,034 \; \times \; 0.06271 \; \times \; 0.5 \; / \; 6.364 \times 10^{-7}$$

$$= 149 \; \text{MPa}$$

For the maintenance load:

$$\rho = M \; y \; / \; I$$

$$= 3{,}249 \times 0.06271 \times 6.634 \times 10^{-7}$$

$$= 186 \text{ MPa}$$

The yield strength of steel is 205 MPa. AS 61400-2 (Standards Australia 2006) prescribed a safety factor of 1.1 to be applied to ultimate strength calculations, thus 205 MPa was modified by this safety factor to become 186 MPa. Maximum stress in the tower section should not exceed the modified yield strength of 186 MPa. Both the axial load and the maintenance loads were within the yield strength limit of the DN65 standard section. The weight of the complete design requires validation and this load re-calculated; if the weight of the rotor and nacelle assembly was over 100 kg then the pipe wall thickness may require increasing to reduce the maximum stress.

4.7 Machine Control Design

4.7.1 Functional Description

The control system performs the following functions:

- Enable automatic operation of the wind turbine.
- Keep the wind turbine aligned to the wind.
- To protect the wind turbine from damage by overspeed in strong winds.
- Engage and disengage the generator.
- On a fixed speed wind turbine, to govern the rotor speed.
- To detect malfunctions and raise alarms for maintenance or repairs.

In a SWT design not all of these functions are included due to cost restrictions; however the first three functions must be present in virtually all wind turbines.

4.7.2 Yaw Mechanism

On large wind turbines the yaw mechanism is often a complex design requiring transducers to sense the wind direction, drive motors and gears to change the direction of the rotor to face the oncoming wind. In SWT design the yaw mechanism most commonly consists of a simple tail fin mounted to the nacelle bed-plate. This design incorporates a simple rigidly mounted tail fin due to the simplicity and reliability of this design. There is simply no requirement for any more complexity.

4.7.3 Variable Pitching Mechanism Options

The conceptual design identified passive pitch control as the preferred overspeed control method. The main features of this design are as follows:

- The hub must provide bearings at the blade roots as a means of securing the blades against all motion except for pitching.
- A pitching mechanism is incorporated into the design.
- The pitching mechanism actuation is of a passive nature, with no requirement for hydraulic of electric motors to drive the pitch actuation.

In order to develop a suitable conceptual design for the pitch control mechanism some of the concepts in use on existing passive pitch control wind turbines were examined next.

4.7.3.1 Linkages

A pitch rod passes through the main shaft together with linkages connected from the hub to the roots of the blades. The pitch rod may be driven by a motor mounted either on the main non-rotating part of the turbine, or directly onto the hub with power provided via slip-rings. Alternatively the pitch rod may be driven by centrifugal force acting on the rotor blades.

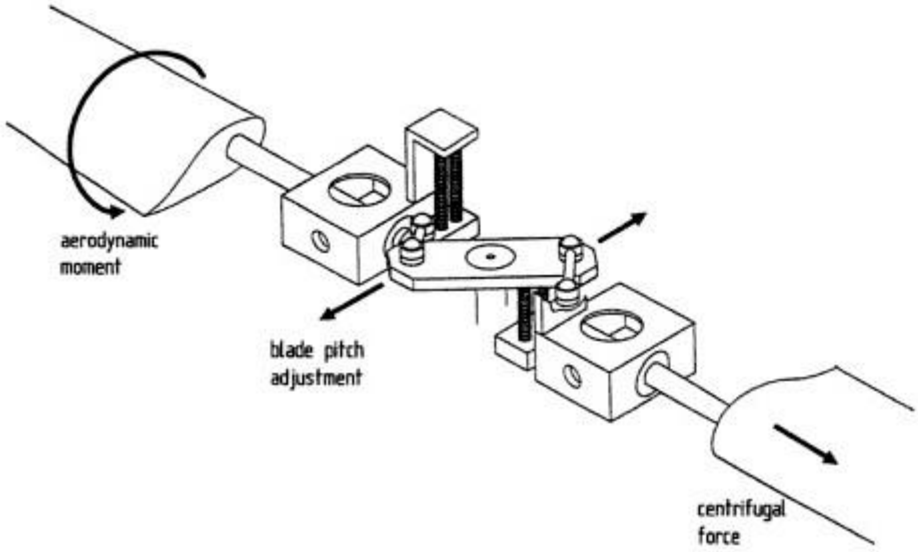


Figure 4.9: Passive pitch blade adjustment (Hau 2006)

4.7.3.2 Centrifugal Stalling

This is a passive control method where flyweights are attached to the blades so that the blades have a high angle of attack for starting, but as the rotational speed of the rotor increases the flyweights produce a moment that moves the angle of attack towards a run position. For overspeed protection the flyweights continue to rotate the blade angle of attack until the blades stall and the increased drag reduces the rotor rotational speed. In this design it is critical that the flyweights are adjusted accurately so the generator does not incur overspeed damage.

4.7.3.3 Centrifugal Preloading

This concept uses a screw cylinder and a preloaded spring to passively control the pitch of each blade. It is normally applied to blade tips however it can theoretically be applied to entire blades at the blade roots. When the centrifugal load of the blade exceeds the preload the blade is driven outward against the spring and the blade pitch angle changes as per figure 4.10.

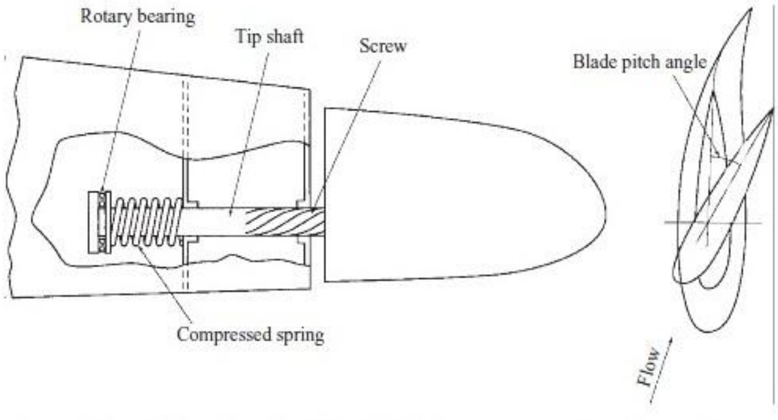


Figure 4.10: Passive control of tip blade (Burton et al. 2001)

4.7.3.4 Tentortube

A ‘Tentortube’ is a patented invention otherwise known as ‘load attenuating passively adaptive wind turbine blade’, in which carbon fibre reinforced tubes are used with all the fibres set at an angle to the axis such that the centrifugal loading induces twist in the rotor blade. It is generally intended to be placed inside hollow steel tipped shafts which carry the aerodynamic loading of the blade. The actual Tentortube is still in the testing phase and is undergoing investigations into carbon/epoxy composites, innovative geometric designs and flexible resin systems.

4.7.4 Load Cases

Due to space restrictions in the SWT hub the most suitable option is one which utilised simple, compact mechanisms. Two simple load cases were considered – centrifugal and thrust loading. Simplified load cases are illustrated in figure 4.11, which shows that the thrust force is parallel to the oncoming wind direction and the centrifugal force is normal to the oncoming wind direction.

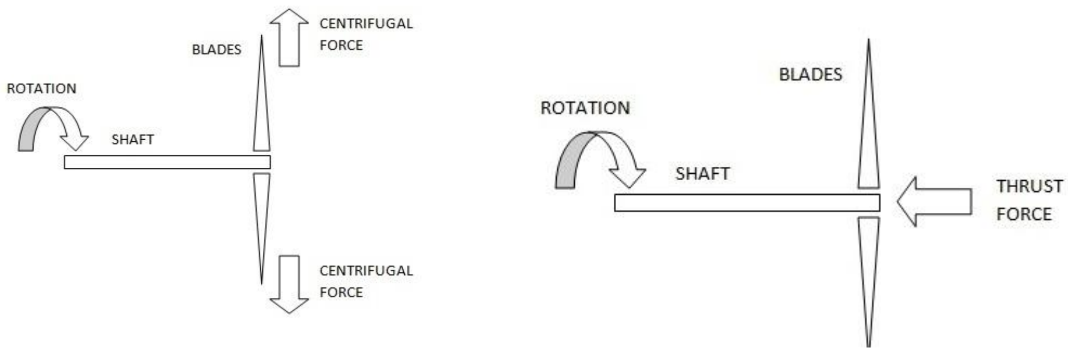


Figure 4.11: Centrifugal and thrust forces (Authors own image)

4.7.4.1 Centrifugal Loading Case

Centrifugal loading occurs on each blade due to the effects of inertia that arise in connection with rotation and results in an outward force away from the centre of rotation. When the rotor reaches a rotational velocity equal to the maximum power output the value of the centrifugal force acting on each blade can be estimated; AS 61400-2 (Standards Australia 2006) stated that centrifugal load in the blade root F_{zB} is calculated as follows:

$$F_{zB} = m_B \, \omega_{n,design}^2 \, R_{cog} \tag{4.12}$$

where F_{zB} is the centrifugal load in the blade root [N]
m_B is the blade mass [kg]
$\omega_{n,design}$ is the design rotor speed [rad/s]
R_{cog} is the radius to the rotor centre of gravity [m]

For the Windmax 106WH, relevant specifications are as follows:

- Blade mass = 2.63 kg per blade.
- Blade radius = 1.615 m. Radius to centre of gravity is assumed to be one third of the length = 0.538m.
- Maximum rotor speed at n_{design} = 41.60 rad/s.

therefore F_{zB} = 2.63 x 41.60 ^{2} x 0.538
= 2.449 kN

By positioning a screw along the rotor blade axis and incorporating a compression spring, bearings and a damper the centrifugal force could be used to drive passive pitching to the rotor blade. General layouts of the system are depicted in figure 4.12:

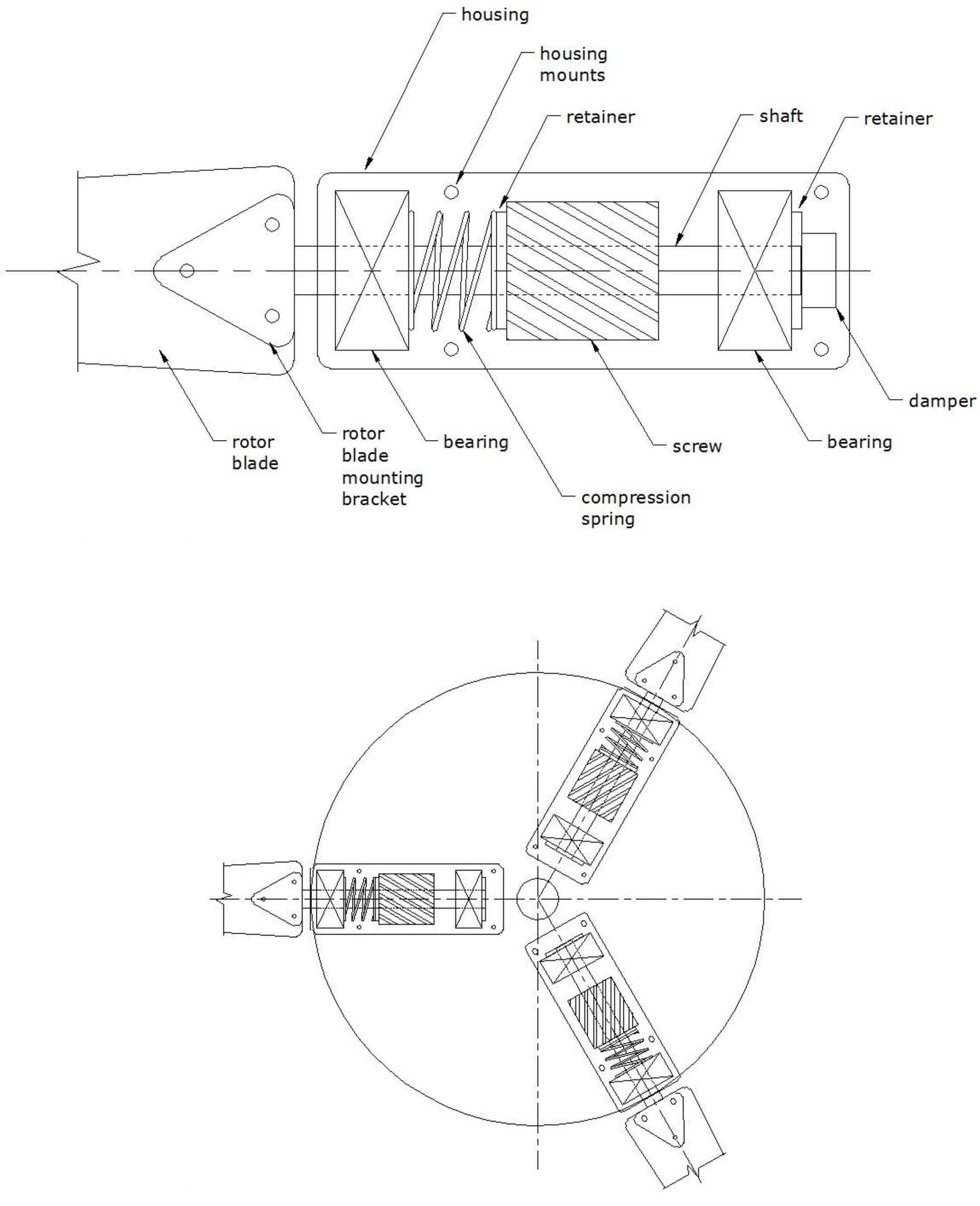


Figure 4.12: Centrifugal pitch control general layout (Authors own images)

4.7.4.2 Thrust Loading Case

The thrust load component acts parallel to the rotor shaft. AS 61400-2 stated that the maximum thrust load is given by the following formula:

$$F_{x\text{-shaft}} = C_T \; 3.125 \; \rho \; V^2_{ave} \; \pi \; R^2 \qquad (4.13)$$

where $F_{x\text{-shaft}}$ is the thrust load on the rotor [N]

C_T is the thrust coefficient, equal to 0.5

ρ is the air density, here assumed to be 1.225 [kg/m^3]

V_{ave} is the average wind velocity [m/s]

R is the rotor radius [m]

therefore $F_{x\text{-shaft}} = 0.5 \text{ x } 3.125 \text{ x } 1.225 \text{ x } 8.4^2 \text{ x } \pi \; x \; 1.615^2$

$= 1.107 \text{ kN}$

A prototype variable pitch model aircraft propeller is illustrated in figure 4.14, which illustrates a linkage mechanism which could possibly be re-arranged to suit the requirements of this design. The control shaft through the centre of the rotor drive shaft could be replaced by a spring mechanism driven by the thrust force acting on the rotor to control the passive pitching as illustrated in figure 4.13.

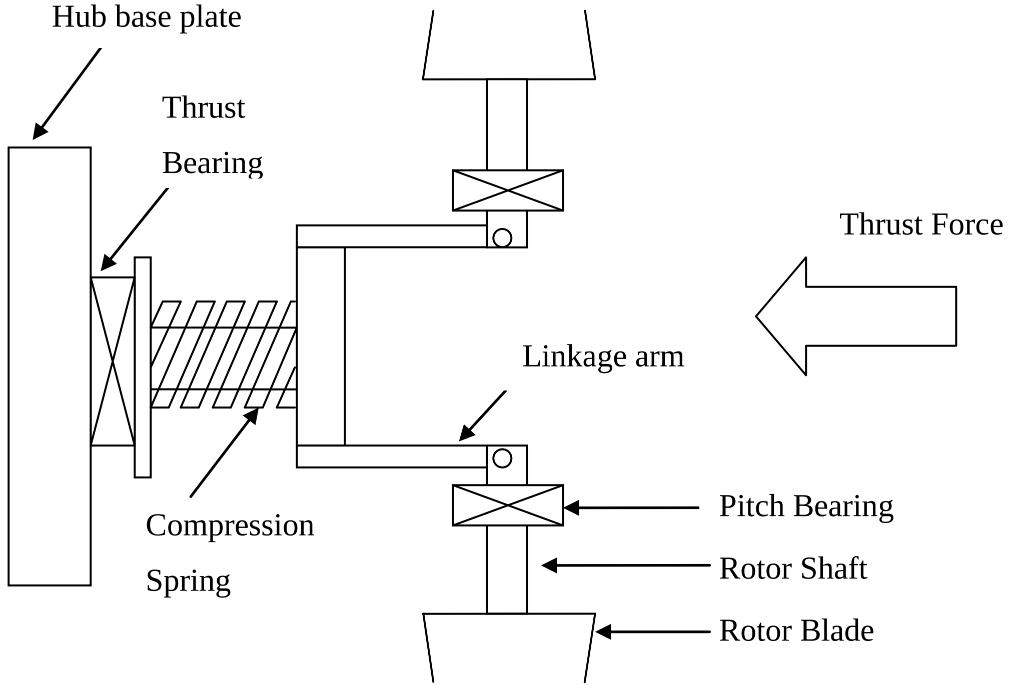


Figure 4.13: Thrust pitch control schematic (Authors own image)

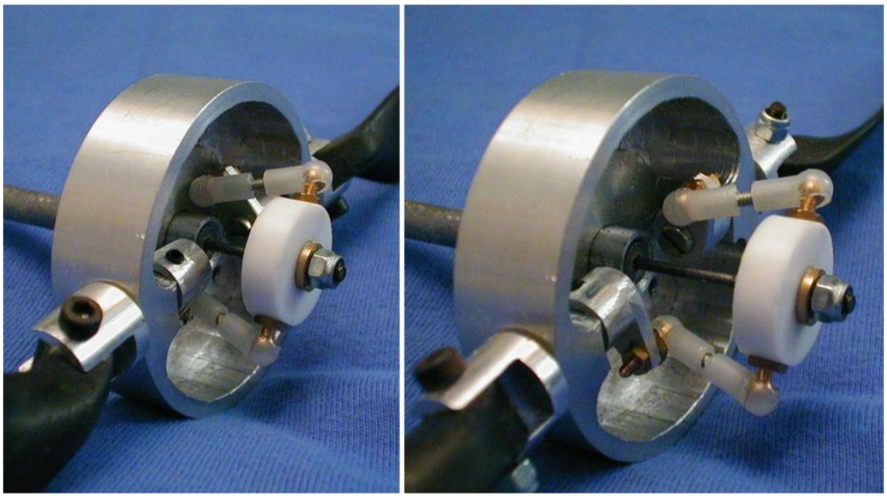


Figure 4.14: Variable pitch aircraft propeller (Bassett 2010)

4.7.5 Conclusion

Both the centrifugal and the thrust force pitch control activation methods offer feasible pitch actuation design options. They can both utilise spring compression pre-load force to actuate the pitch control mechanism and both can be calibrated by altering the spring pre-load. The centrifugal load design was chosen as the preferred design for this SWT design as it offers the following advantages over the thrust load design:

- Centrifugal force is more than double the thrust force at the design speed, giving more available power to actuate the mechanism.
- More compact design can be achieved.
- Can be mounted onto a simple ‘flat plate’ rigid hub via mounting bolts.
- Less visible moving parts means a sleeker design is achievable.
- Spare parts can be simplified to a single modular component, offering better maintainability.
- Can be reliably lubricated using fully sealed, packed grease units.
- Complexity of multi-axis linkage arms is not required.
- Ball joints are not required, which are considered to be a high wear point and a potential reliability issue.
- Overall better reliability is expected.

4.8 Electrical System Design

4.8.1 Functional Description

The electrical system must transmit the electricity produced by the generator through wiring down the tower to its end use. The size of this particular SWT (1 kW) indicates that the system will most likely be off-grid, which would suggest a battery based system. Users would generally choose this system if grid connection is prohibitively expensive, or for independence in remote locations. A secondary electrical system is the lightning protection system which attempts to protect the SWT, electrical systems and people in the event of a lighting strike.

4.8.2 Lightning Protection

AS 61400-2 (Standards Australia 2006) mandated that the design of a SWT system includes a local earthing electrode system to meet the requirements of IEC 60364-5-54 and local electrical code authorities. The earthing system is generally a combination of earth electrodes, conductors, bars and main terminals, and is individually designed to match the application. Generally the SWT support structure (including guy wires) must be appropriately earthed to reduce damage from lighting. Guidance for the design of the lightning protection system is found in IEC 61400-24 *Wind Turbines Part 24 – Lightning Protection*, which forms the minimum requirements as per AS 61400-2. It is not necessary for protective measures to extend to the blades.

IEC 61400-24 (International Electrotechnical Commission 2010) stated that the main purpose of lightning protection for small wind turbines is to provide transient protection to grid connection and communications and control system connections (if any), in order to ensure that the systems can still operate after a lighting strike. Appendix M (guidelines for SWT) of IEC 61400-24 stated that:

> "Although lighting strikes are relatively rare the systems need to remain relatively safe, both in terms of maintaining physical integrity and not causing damage to people or property if structure breaks off and also in terms of avoiding the fire hazard or damage to the electrical system to which the turbine is connected."

Appendix M of IEC 61400-24 also stated that:

> "The ultimate lightning protection solution may incorporate a lightning rod reaching above the rotor and equipotential electrical bonding and some form of surge protection device (SPD)."

Whilst detail electrical design was not part of the scope of this project, it was identified that the lighting protection system should consist of the following three major components:

1. Lighting rod – a conductive rod which extends above the rotor.
2. Electrode – a copper rod buried into the ground and connected to the tower via an earth strap.
3. Surge protection device – Power protection for the sophisticated electronic equipment provided by a simple surge diverter installed between the slip rings and the charge controller.

4.8.3 Electrical Components

For this application it is recommended that the following components make up the electrical system:

Slip rings are used so that discontinuous cable may be used in the wind turbine. With one set of cables connected to the generator, slip rings and brushes are used to transfer power to a second cable running down the tower. The slip rings are normally mounted to the bottom of the mainframe of the wind turbine, so that as the wind turbine yaws the brushes are continuously in contact with the slip rings.

Power cables transfer the power from the generator down the tower to the electrical switch gear at the base of the wind turbine. A substantial amount of slack cable is normally left so that as the wind turbine yaws the slack is taken up and then the slack is released as the wind turbine yaws in the opposite direction.

Batteries are used to store the electricity generated by the wind turbine. For off-grid systems normally a bank of deep cycle batteries are sized to store enough electricity to keep the household or consumer running for one to three calm days.

Charge controller (also called controller or regulator) is used to protect the battery bank from overcharging. It does this by monitoring the battery bank charge, and when it is fully charged the controller sends electricity from the battery bank to a dump or diversion load.

Dump load (also called diversion load or shunt load) is used so that the circuit can be turned off open-circuited with no damage. The generator should generally not be operated unloaded as this can cause catastrophic damage to the generator so the diversion controller allows this protection to the generator.

System meter (also called battery meter, amp-hour meter or watt-hour meter) is a meter used to measure how full the battery bank is, how much electricity is being generated by the SWT and how much electricity is in use.

Main DC disconnect (also called battery / inverter disconnect) is a DC rated breaker used to disconnect the battery from the inverter. This is used for servicing and for protection for the inverter-battery wiring from electrical fires.

Inverters are devices used to convert DC to AC. They are commonly used to transform the electricity produced by the SWT and stored in the battery banks into AC power commonly used in homes to power lights and appliances.

AC panel breakers (also called mains boxes) is the point where the household or installation electrical wiring meets the source of the electricity i.e. the battery bank or inverter output. The AC panel breaker normally contains a number of labelled circuit breakers and allows electricity to be disconnected for servicing, and protects the installations wiring from electrical fires.

4.8.4 System Description

Due to time constraints and limited electrical expertise, electrical component selection and system design were not completed as part of this project scope. It is envisaged that the complete SWT assembly may be marketed along with a recommended system of electrical components which is carefully designed and balanced. Each electrical component can generally be sourced in component form and the complete system may be 12, 24 or 48 volt configuration depending on customer requirements. It is possible that the customer may already have part or all of the electrical system in place so the system may be customised to customer requirements to reduce costs where possible. The simplified electrical system for this system is illustrated in figure 4.15:

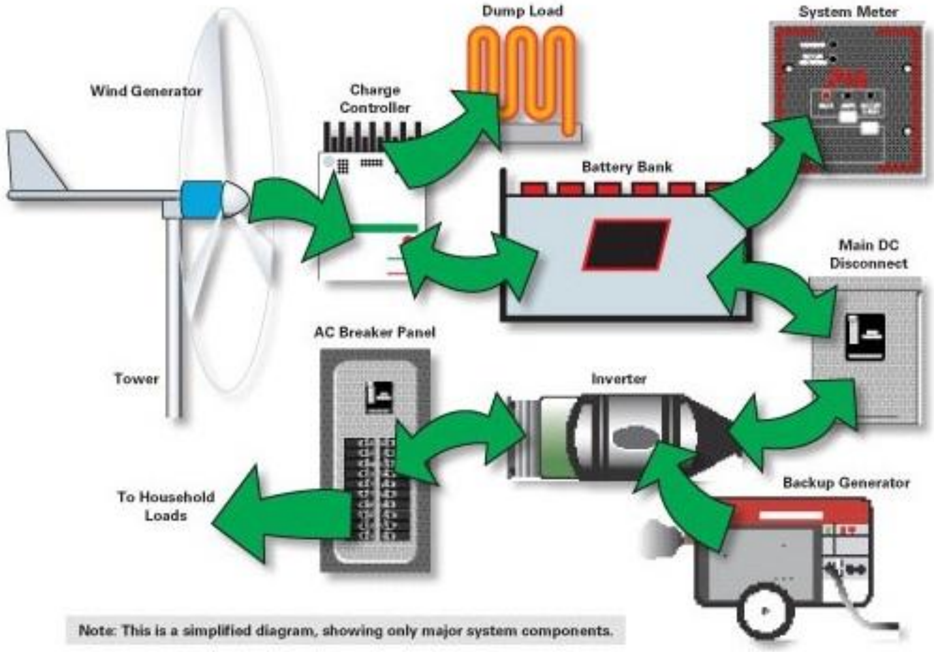


Figure 4.15: Electrical system (Home Power Inc 2010)

4.9 Summary

Detailed engineering design and analysis of the mechanical components was performed with an emphasis of development of innovative alternatives, particularly with the passive pitch control mechanism. Alternative material selections were evaluated, and the composite material GFRC identified as a suitable alternative in various components. The complete design included various commercially available parts which greatly reduced the manufacturing requirements.

The rotor assembly consisted of American manufactured GFRC rotor blades complete with machined steel hub, and a GFRC nose cone which requires manufacturing in-house. The rotor hub supplied with the rotor blades requires modifications to house the passive pitching mechanism, and the complete rotor assembly is a combination of commercially available components, custom made parts, innovative solutions and composite structural materials.

The drive train consists of a Chinese manufactured PMG coupled to the rotor hub via a flexible tyre coupling. All components appear to be excellent quality and capable of offering world class reliability. The design is simple and robust as well as inexpensive.

The nacelle and mainframe system consist of the nacelle bed-plate, the nacelle cover and the yaw mechanism. The steel nacelle bed-plate offers some potential for further innovation with the mounting of the yaw mechanism and components, whilst the cover could potentially utilise alternative composite structural materials than GFRC. The yaw mechanism adds to the diversity in material design by incorporating aluminium construction. Surface protection was evaluated and two-part epoxy paint selected for the tail fin and bed-plate.

The tilt-up tower was nominated as a commercially available kit mainly for its simplicity. This required no further design however stress and moment calculations were carried out to ensure that the tower chosen is sufficient to withstand estimated axial and maintenance loads.

The machine control incorporates significant innovation into the project by offering a conceptual design for a centrifugal activated passive pitch mechanism as a means of overspeed control. In developing this design various existing concepts were evaluated and the two significant loading cases of centrifugal and axial were compared. The proposed design shows strong potential to be simple, robust and reliable; however it requires a large design effort to develop the design to the manufacturing drawing stage.

The electrical system was identified as a combination of various components; however detail electrical design was not specifically covered as part of this scope. Included was an overview of a simple lightning protection system which was mandated by both Australian and International Standards.

Although the detail design was not finalised, good progress was made by identifying the major components. Finite Element Analysis, further detail design, computations, component selection and manufacturing drawings are still required to further develop this detail design.

CHAPTER 5 – RESULTS & DISCUSSION

5.1 Introduction

The aim of this chapter is to discuss the results of the conceptual and detail design chapters, and to carry out a brief Cost Benefit Analysis. The SWT specifications and power performance curve are summarised and discussed, which summarise the results of the design and of the complete package as it would be presented to a potential purchaser.

The Cost Benefit Analysis is used to see whether the project design is likely to be economically feasible. The manufacturing costs are estimated to evaluate the cost side of the equation, and the benefits evaluated by calculating how much electricity can potentially be generated and assigning a cost. A pay-back period is evaluated to see whether the design may be competitive in the market place. A brief discussion of manufacturing requirements assesses equipment and workshop facilities required for the SWT assembly.

5.2 SWT Specifications

AS61400-2 (Standards Australia 2006) did not specify requirements for a table of specifications for a SWT design, however the following specifications are relevant to this design:

Specification	Details
Design life	20 years
Type	Three blade upwind horizontal axis
Rotor diameter	3.23 m GFRC
Start-up wind speed	2.4 m/s
Rated wind speed	7.4 m/s
Cut-out wind speed	8.8 m/s
Maximum design wind speed	42 m/s
Rated power	1,000 W
Maximum power	1,200 W
Overspeed mechanism	Automatic pitch control
Yaw system	Passive tail-fin yaw control
Gearbox	None, direct drive
Generator	Permanent Magnet Generator
Output form	12, 24 or 48 VDC
Tower	25 m tubular steel tilt-up
Functional features	Heavy duty slip rings, GFRC housing, GFRC nose cone

Table 5.1: SWT specifications (Authors own table)

5.3 Power Performance Curve

The power performance curve predicts the power output against the wind speed. The basic formula for calculating the power comes from equation 4.1:

$$P_r = C_p \tfrac{1}{2} \rho V_{hub}^{3} \pi R^2 \qquad (4.1)$$

A plot of this data, neglecting the effect of the overspeed protection (pitching) system, is shown in figure 5.1. This plot forms the transient response part of the generator output.

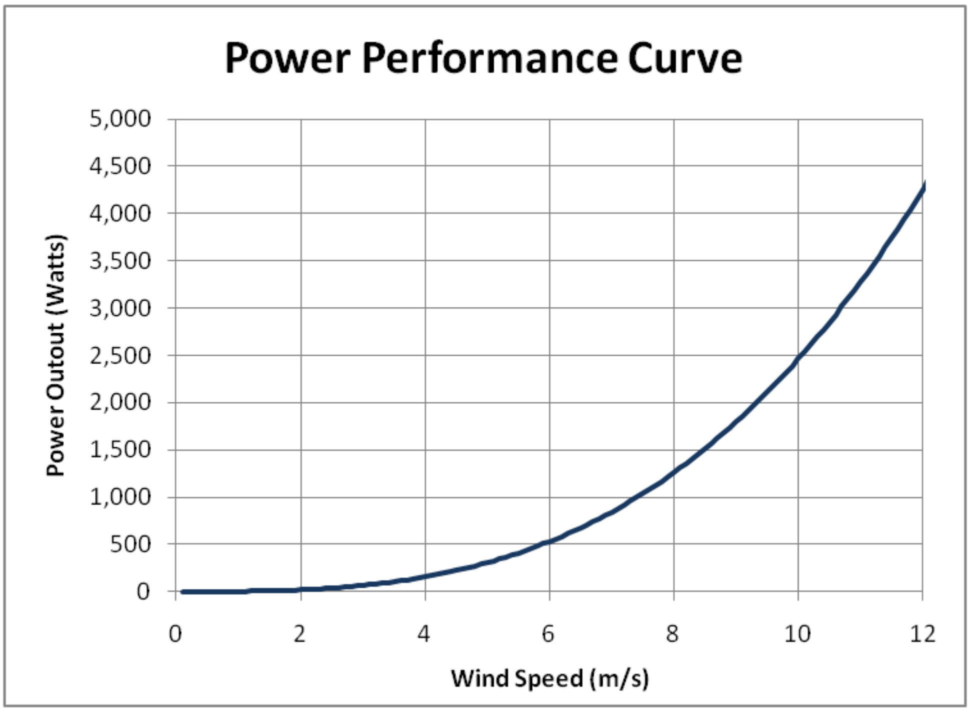


Figure 5.1: Power performance curve with no pitching (Authors own image)

As per the rotor calculations in chapter 4 the design power output of 1,000 Watts can be achieved at a wind speed of 7.4 m/s, however figure 5.1 shows that the power output continues to increase with no ceiling limit. The maximum power output rating of 1,350 Watts as specified by the generator manufacturer can be achieved at a wind speed of 8.2 m/s using formula 4.1 so this is the illustrated as the cut-out speed in figure 5.2 which shows the power curve modified to a maximum (steady state) power output of 1,300 Watts at wind speeds above 8.2 m/s. This would be achieved by pitching the blades of the rotor so that the centrifugal force experienced at 8.2 m/s pitches the blades sufficiently to sustain a constant rotational speed.

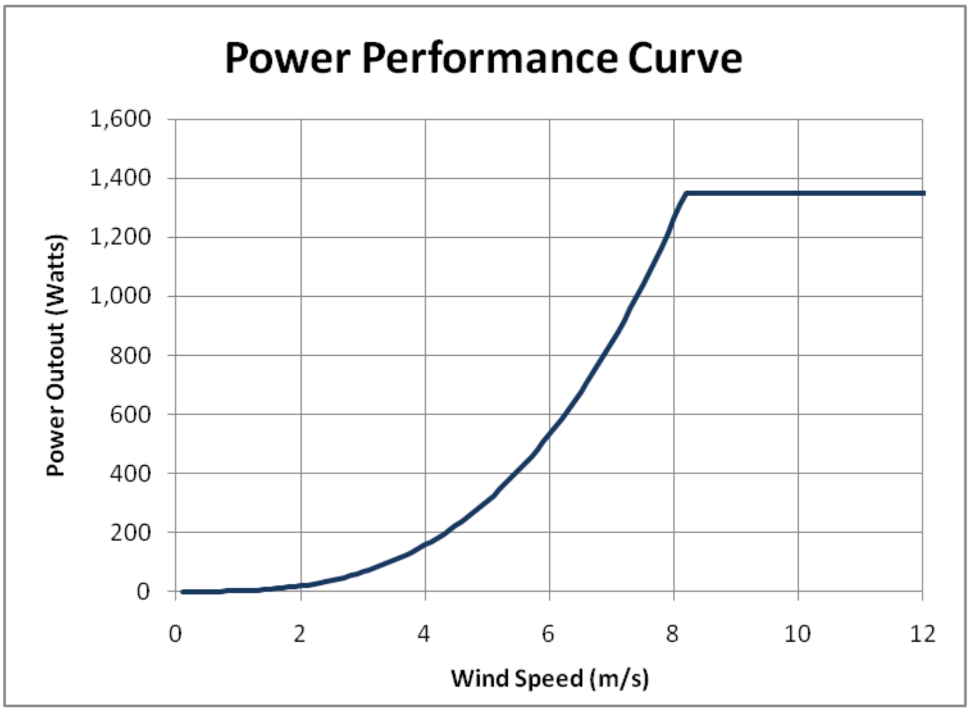


Figure 5.2: Power performance curve with instantaneous pitching (Authors own image)

A gradual transition from the transient response to the steady state is expected due to the compression spring gradually altering the pitch of the rotor blades. The compression force in the spring should be such that the pitching does not begin until the centrifugal force experienced at 7.4 m/s is exceeded. This centrifugal force was calculated from equations 3.8 and 4.12, which should roughly coincide with the compression spring preload:

$$n = 30 \text{ x } V \text{ x } \lambda \; / \; (\pi \text{ x } R) \qquad (3.8)$$

$$= 30 \text{ x } 7.4 \text{ x } 8 \; / \; (\pi \text{ x } 1.61)$$

$$= 350.5 \text{ RPM}$$

$$= 36.7 \text{ rad/s}$$

and

$$F_{zB} = m_B \; \omega^2 \; n_{,design} \; R_{cog} \qquad (4.12)$$

$$= 2.63 \text{ x } 36.7^2 \text{ x } 0.538$$

$$= 1.906 \text{ kN}$$

The compression spring should be balanced with the pitching mechanism by rigorous field testing to yield a final power curve similar to that shown in figure 5.3. Note that the maximum power was reduced to 1,200 Watts to provide some safety margin to the generator which has a maximum power output of 1,350 Watts.

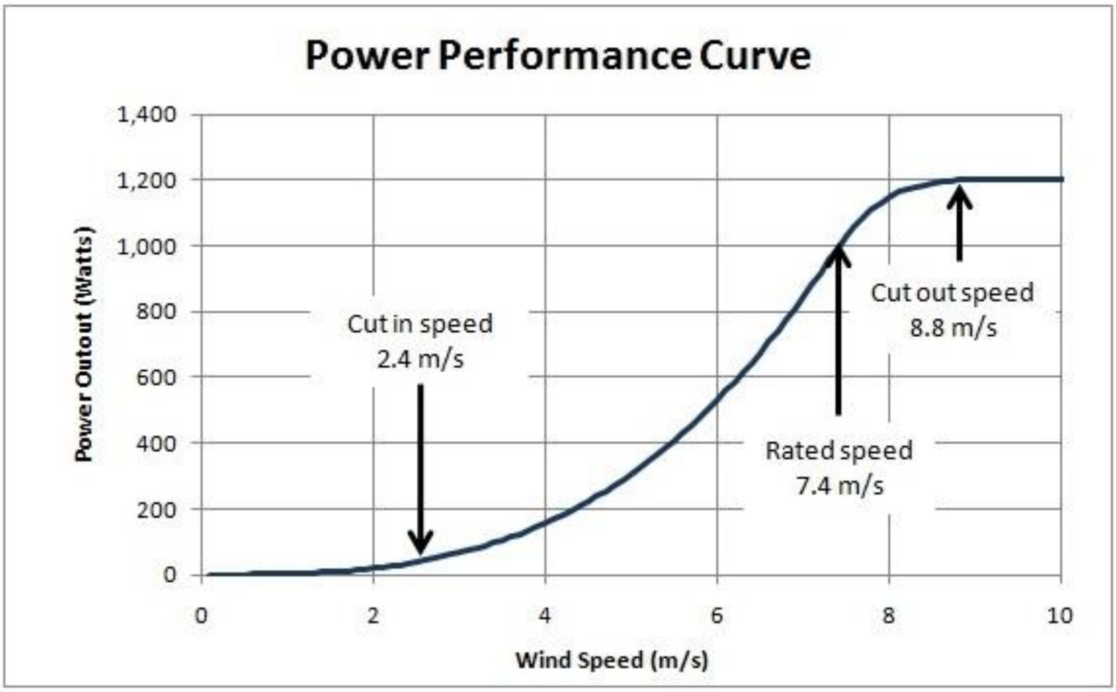


Figure 5.3: Power performance curve with transitional pitching (Authors own image)

5.3.1 Damping

Although the theoretical power performance curve in figure 5.3 shows a gradual transition between the transient response at 1,000 Watts and the steady state response at 1,200 Watts, a high degree of stability of the pitching mechanism is required to achieve this smooth transition and to minimise oscillations in the power curve during the steady state phase at 1,200 Watts. An underdamped response would most likely result from the compression spring if no damping device is used, as illustrated in figure 5.4, where the power output would correspond to the vertical axis and time to the horizontal axis. The oscillations represent the power output as a result of the rotational speed of the rotor changing with the pitch of the rotor blades. Oscillations in the power output may decrease and eventually disappear, they may remain constant or they may increase and become unstable. Thus a damping device was seen as a necessity in the pitch control mechanism.

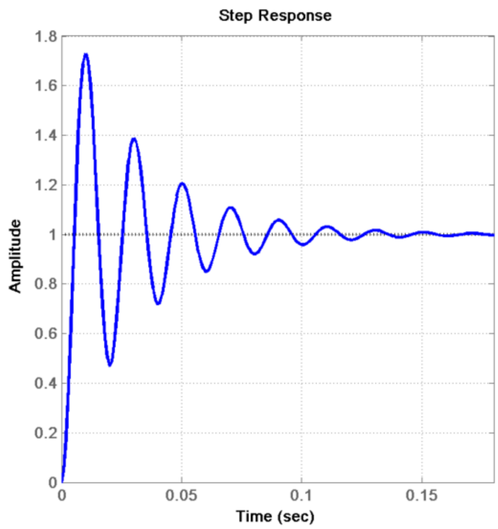


Figure 5.4: Typical underdamped response (Source unknown)

The function of the damper in the pitching mechanism is to dissipate kinetic energy. It is essentially a shock absorber, not indifferent to the type used in automobiles to provide a smooth ride. It may be in the form of a compression spring, a hydraulic cylinder or a combination of both, and the aim is to produce an overdamped response similar to the typical response shown in figure 5.5.

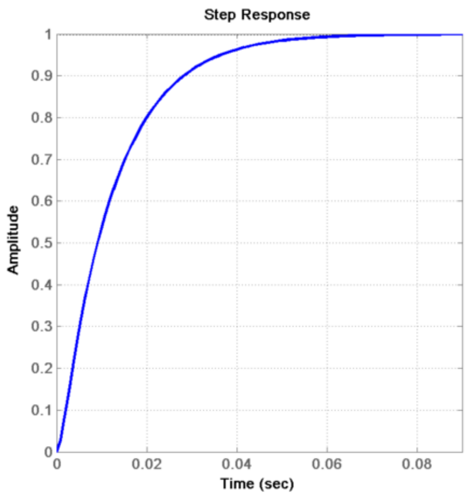


Figure 5.5: Typical overdamped response (Source unknown)

The perfect overdamped response is considered to be unachievable in this system due to the inertial effects of the rotating rotor which would prevent an instantaneous response of the shaft speed when the blades are pitched. The aerodynamic force of drag acting on the rotor blades initiates the rotational speed reduction of the shaft, thus a fairly slow response is predicted. This would induce a time lag between the pitching of the blades and the power output, resulting in the propagation of oscillations in the system response. Fine tuning the damping device should help to minimise and stabilise the oscillations as much as possible. This necessitates rigorous prototype testing and analysing of results as it is difficult to theoretically estimate all factors influencing the system response.

5.4 Manufacturing Costs

5.4.1 Single Unit Manufacturing Costs

The manufacturing and assembly costs were roughly estimated from information presented in the detail design. Table 5.2 shows itemised costs and includes a column to indicate whether the cost is derived from a quote, or if a ‘best guess’ estimate was used. Since wind power is still an emerging technology, sourcing of parts and price lists was a challenging task and financial information somewhat elusive. Time constraints and lack of actual buying power meant that real prices were largely unobtainable for many components, thus estimates were used for the purpose of building a cost model for the Cost Benefit Analysis.

System	Component	Cost $	Quote/Est
Rotor	Blades	$749	Quote
	Nose cone	$100	Estimate
	Pitching Hub	$1,000	Estimate
Drive Train	Generator	$1,043	Quote
Nacelle	Housing	$200	Estimate
	Yaw System	$200	Estimate
Tower	Tower kit	$2,199	Quote
	Steel tube	$2,081	Quote
Controls	Lighting protection	$200	Estimate
Electrical	Slip rings	$80	Estimate
	Power cables	$250	Estimate
	Batteries	$600	Estimate
	Charge Controller	$291	Quote
	Dump load	$50	Estimate
	System meter	$200	Estimate
	Main DC disconnect	$80	Quote
	Inverters	$1,089	Quote
	AC Panel breakers	$150	Estimate
Miscellaneous	Packaging	$200	Estimate
	Hardware & fasteners	$400	Estimate
	Manuals	$70	Estimate
	Assembly labour	$1,000	Estimate
	Delivery	$200	Estimate
Sub Total		$12,432	
10% markup		$1,243	
Total		**$13,675**	

Table 5.2: Single unit manufacturing cost summary of SWT (Authors own table)

The tower was by far the most expensive system estimated at $4,280, followed by the electrical system at $2,790, so these were the obvious systems to target for cost cutting. A 10% mark-up was also added as profit margin as per usual commercial practice, albeit this is considerably lower than most manufacturers would use.

5.4.2 Production Line Manufacturing Costs

The quotes and estimates made no attempt to ‘shop around’ for the best deals and there was no attempt to refine or improve manufacturing techniques in the single unit manufacturing cost summary. Some potential cost saving strategies were identified as follows:

- In all pre-purchased components, shop around for better deal (estimated potential savings of 10% or $1,243).
- Shop around for better value component alternatives which may offer the same or better quality (estimated potential savings of 10% or $1,243).
- Form supplier agreements where possible, where the supplier may offer further discounted rates and improved payment terms (estimated potential savings of 10% or $1,243).
- Issue tender documents for the manufacture of selected items. Manufacturing companies may have more suitable equipment to manufacture some items and the ability to manufacture at a reduced cost. Suitable components are nose cone, pitching hub, housing, tail fin, tower & electrical systems (estimated potential savings of 10% of component costs or $370).
- Manufacture the tower kit rather than buy it in kit form (estimated potential savings of 40% of component costs or $880).
- Re-design the tower to utilise full lengths of galvanised steel tubing to reduce wastage (estimated potential savings of $595).
- Weld galvanised steel tube off-cuts together to reduce wastage.
- Purchase fasteners and hardware in bulk amounts (estimated potential savings of $100).
- Manufacture in production runs of perhaps 10 units rather than by single units (estimated potential savings of 10% or $1,243).

These cost saving strategies were incorporated into the ‘Single Unit Manufacturing Cost Summary’ on a component by component basis to evaluate likely cost savings. These were listed in table 5.3 ‘Production Line Manufacturing Cost Summary’, which presents a realistic cost of manufacturing the units in batches of five or more.

System	Component	Cost $	Adjustment
Rotor	Blades	$599	20%
	Nose cone	$80	20%
	Pitching Hub	$800	20%
Drive Train	Generator	$834	20%
Nacelle	Housing	$160	20%
	Yaw System	$160	20%
Tower	Tower kit	$1,319	40%
	Steel tube	$1,189	43%
Controls	Lighting protection	$160	20%
Electrical	Slip rings	$64	20%
	Power cables	$200	20%
	Batteries	$480	20%
	Charge Controller	$233	20%
	Dump load	$40	20%
	System meter	$160	20%
	Main DC disconnect	$64	20%
	Inverters	$871	20%
	AC Panel breakers	$120	20%
Miscellaneous	Packaging	$160	20%
	Hardware & fasteners	$300	25%
	Manuals	$70	0%
	Assembly labour	$1,000	0%
	Delivery	$200	0%
Sub Total		$9,264	
10% markup		$926	
Total		**$10,191**	

Table 5.3: Production line manufacturing cost summary of SWT (Authors own table)

The total manufacturing cost was reduced by some 25% due to the savings strategies outlined above, bringing the total cost to $10,191. Note that shipping and insurance costs were not included, which may have amounted to a further $500 for a rural Victorian community. This gave a total outlay to the purchaser of $10,691. This was still fairly conservative and great potential still exists for large cost savings. The author believes that a total cost of around $8,000 may be possible should the project go ahead, particularly with some re-engineering to further reduce costs.

5.5 Cost Benefit Analysis

5.5.1 Life Cycle Costs

Manwell, McGowan & Rogers (2003) suggested that the total generating costs for a wind turbine installation are determined using the following factors:

- Wind regime.
- Energy capture efficiency of the wind.
- Availability of the system.
- Lifetime of the system.
- Capital costs.
- Financing costs.
- Operation and maintenance costs.

Wind regime:

As per chapter 3 the average wind speed was assumed to be 6.5 m/s at 65 m height across Victoria. As per the NPV model this gave an average wind speed of 5.37 m/s at the design tower height of 25 m.

Energy capture efficiency of the wind:

This was accounted for in the coefficient of power (0.49) used for the calculation of design power in chapter 4. A wind speed of 5.37 m/s at the tower height of 25 m resulted in a theoretical average power output of 381 Watts by applying equation 4.1:

$$P_r = C_p \ ½ \ \rho \ V_{hub}^{\ 3} \ \pi \ R^{\ 2} \qquad (4.1)$$

$$= 0.49 \ x \ 0.5 \ x \ 1.225 \ x \ \pi \ x \ 5.37^{\ 3} \ x \ 1.62^{\ 2}$$

$$= 381 \text{ Watts}$$

To calculate the energy produced the power output was multiplied by the number of hours:

$$\text{Energy produced} = 381 \times 24 = 9.14 \text{ kWh per day} \quad (5.1)$$

Availability of the system:

Manwell, McGowan & Rogers (2003) suggested that availability is in the order of 98%, which is the availability target for this installation.

Lifetime of the system:

20 years was used here as the design lifetime as per recommendations by Manwell, McGowan & Rogers (2003).

Capital costs:

As per the previous section $10,691 was the capital cost used for subsequent calculations, which included delivery costs.

Installation costs:

Because the SWT was designed to be installed by 2 farmers using a tractor or light truck and using their own hand-tools, the installation costs were generally minimised. The labour and machinery costs for this part of the installation were considered to be zero as they were assumed to be provided by the owner free of charge. Technical expertise was not considered necessary due to the simplicity of the design, further minimising installation costs. There may be some civil works required to bury cable using specialised machinery such as a ditch-witch or back-hoe, and some electrical works to wire up the equipment which should be carried out by a licensed electrician. Installation costs were thus summarised as follows:

Civil works – machinery to bury cable:	$300
Electrician for 8 hours to connect wiring:	$640
Total installation cost:	$940

Operation and Maintenance Costs:

Manwell, McGowan & Rogers (2003) stated that the annual operation and maintenance (O&M) costs for wind turbines generally range between 1.5 to 3.0% of the original turbine costs. These costs are mostly for regular servicing. Since this SWT design is low maintenance the lower end of the range was deemed the most relevant.

O&M costs = 1.5% x $10,691 = $160 per annum

Financing Costs:

It may be assumed that a loan is taken out to finance the installation, thus the standard fixed loan rate was considered relevant for cost calculations. At the time of writing the fixed loan rate for personal loans was 14.90 % per annum, with an establishment fee of $150 and monthly service fees of $10 (Commonwealth Bank 2010).

5.5.2 Cash flows

The revenue of this SWT installation was considered to be the money saved by not having to either purchase electricity from the grid supply or to purchase gasoline/ diesel to run a portable generating set. Two cost models were therefore required to cover both of these scenarios.

5.5.2.1 Grid Power Model

Energy produced was calculated by multiplying 98% availability by 9.14 kWh = 8.96 kWh per day, or 3,273 kWh per annum. At the time of writing the tariffs for the supply of electricity from the grid in Victoria were $0.20 per kWh + $0.86 per day supply charge (Australian Gas Light Company 2010).

A quick calculation of the value of energy produced per day was calculated as follows:

$$\text{Value} = (\text{energy produced} \times \text{tariff rate}) + \text{supply cost} \quad (5.2)$$
$$= (8.96 \times 0.20) + 0.86$$
$$= \$2.65$$

That is to say the average amount of energy generated daily from the SWT would cost $2.65 if it were purchase from a grid supplier in Victoria.

5.5.2.2 Generating Set Power Model

Honda recommended the EU65i generating set to run 10 x 40 Watt lights, 1 x 200 Watt refrigerator and 1 x 400 Watt air cooler, with a combined total load of 2,200 Watts accounting for the increased starting loads. The EU65i is a 5,500 kVA inverter generator which consumes 30 litres of petrol over an 8 hour period on full load, and 10.9 litres of petrol over an 8 hour period at 25% load. At the time of writing the average price in Victoria was $1.169 per litre of unleaded petrol. The cost of running the EU65i for an 8 hour period was therefore calculated to $12.74 at 25% load and $35.07 for full load. For these calculations the assumption was the 25% load case of $12.74 per day for fuel. The recommended retail price for the EU65i was calculated as $6,399. At a rate of 3% the maintenance costs were therefore $192 per annum.

Summary:

Capital cost:	$6,399
Maintenance cost:	$192 per annum
Fuel cost:	$12.74 per 8 hour day

That is to say that it would cost $12.74 per 8 hour day to run a generating set to power a similar number of appliances as the SWT could power.

5.5.3 Simple Payback Period Analysis

The Simple Payback Period Analysis was used for a preliminary estimate of the SWT feasibility. It is easy to understand and does not include detailed economic parameters. It compares the revenue with costs and determines the length of time required to recoup the capital investment. The formula used was as follows (Manwell, McGowan & Rogers 2003):

$$SP = C_c \;/\; AAR \qquad (5.3)$$

where

SP	is the simple payback period [years]
C_c	is the installed capital cost [$]
AAR	is the average annual return [$]

The Renewable Energy Certificates for this SWT installation were calculated in section 2.2.2 as $2,115. This is in effect a refund paid by the Federal Government to offset the capital cost of the wind turbine installation, and is traded on an open market at a fluctuating price. A refundable value of $2,000 was included for the installation which accounts for brokerage fees. The cost to the purchaser was therefore reduced to $8,691 after the Government rebate.

$$C_c = \text{capital cost} + \text{installation costs} - REC \qquad (5.4)$$

where

REC is the value of the Renewable Energy Certificates paid by the Federal Government [$]

$$C_c = 10{,}691 + 940 - 2000$$
$$= 9{,}631$$

For the grid power model:

$$AAR = \text{daily cost} \times \text{days in year}$$
$$= \$2.65 \times 365$$
$$= \$967$$

$$SP = 9{,}631 \;/\; 967$$
$$= 9.96 \text{ years}$$

For the diesel generator model

$$AAR = \$12.74 \times 365$$
$$= \$4,650$$

$$SP = 9,631 \; / \; 4,650$$
$$= 2.07 \text{ years}$$

The preliminary feasibility estimate calculated a payback period of 10 years compared to purchasing grid supplied electricity, and a payback period of 2 years when compared to operating a portable generating set. For the grid power model, considering the design life of the wind turbine is 20 years, the remaining 10 years constitutes pure profit, or free energy period. This was a satisfactory outcome and one which indicated both a feasible and marketable design.

For more detailed economic evaluation the Life Cycle Costing method is preferred. The LCC method summarised expenditures and revenues over time into a single number to consider the time value of money, and to allow an economic decision to be made. On this occasion the LCC method was not used as the SP method has yielded a satisfactory feasibility result, considering that the ongoing costs were deemed to be low for the SWT installation.

5.6 Manufacturing Requirements

Although the SWT design chosen was mainly an assembly of pre-manufactured components, some custom manufacturing was still required. Whether the manufacturing is carried out in-house in a workshop, or whether the custom components are sub-contracted to outside workshops is a matter to be decided by detailed cost-benefit analysis and outside the scope of this project. The main custom made parts which require individual manufacturing are as follows:

Tower

Although the chosen tower is supplied in kit form, it was identified as a major cost saving strategy to manufacture the tower instead. The following manufacturing processes constitute an in-house tower fabrication and assembly:

- Steel tube to be cut to length.
- Steel tube off-cuts to be butt-welded to eliminate wastage.
- Couplings mounts and footing plate to be profile cut from flat steel plate (oxy/acetylene or plasma cut).
- Coupling mounts to be fillet welded to purchased couplings.
- Coupling mounts to be hot dip galvanised or painted.
- Anchor pins to be cut & welded.
- Anchor pins to be hot dip galvanised or painted.

A basic welding/fabrication workshop would be sufficient to carry out all tower manufacturing processes. Profile cutting can be adequately handled using a variety of equipment, with plasma cutting and oxy-acetylene being the most common options available. A large fabrication workshop may have automated and high precision equipment to carry out this task, or the components may be individually fabricated. Individual tower components may even be outsourced to a large fabrication workshop for a better finish and cheaper price.

Rotor Hub

The rotor hub requires further detail design however the following manufacturing processes were identified:

- Rotor hub plate machining on a lathe.
- Rotor hub plate keyway machining on a milling machine.
- Rotor hub plate mounting holes drilled on a drill press.
- Pitching mechanism housing to be cast and/or machined steel.
- Pitching mechanism shaft to be machined on a lathe.
- Rotor hub plate to be two-part epoxy painted.

A basic engineering workshop with machining equipment would be required to perform the pitching mechanism manufacturing. Some basic fitting and assembly of bearings, springs and shafts can also be carried out in a basic engineering workshop. It is likely that the manufacture of the pitching mechanism mounting block would be out-sourced as casting, forging or complex machining may be required which is beyond the capabilities of a basic engineering workshop.

Rotor Nose Cone and Nacelle Cover

The usual method of producing GFRC components is using labour intensive hand-laying methods; this may be sped up if the resin and catalyst are applied using pressurised spray equipment. The glass fibres can be laid by hand over moulds which can then be cleaned and re-used. An alternative may be to outsource GFRC moulding to larger manufacturers who have access to expensive automated equipment such as spray pumps, compaction rollers, high shear mixers, reciprocators for automatic spray-up, chopped strand feeders, liquid metering systems and mixer bucket lifters.

Nacelle Bedplate

Manufacturing techniques and equipment requirements are essentially the same as the rotor hub plate.

Yaw Mechanism

The yaw mechanism is a flat aluminium plate with a mounting bracket welded to a length of aluminium round-bar. The following manufacturing processes are required to assemble this mechanism:

- Tail fin & mounting bracket to be profile cut.
- Tail fin and mounting bracket to be MIG/TIG welded to round bar.
- Finished yaw mechanism to be two-part epoxy painted.

The profile cutting is likely to be performed by the aluminium supplier as this would require specialised equipment if it is to be finished to a high quality. A basic fabrication workshop with cutting and welding equipment would be required to perform the assembly of the three components. Painting is likely to be outsourced to a paint shop.

5.7 Summary

The SWT specifications presented compare favourably to other SWTs for sale in the current market. The passive pitching mechanism is quite a unique feature not found in the current SWT market, and offers a practical, simple and innovative method of control. The combination of low wind speeds, large diameter rotor and 1,200 Watts maximum power make the SWT a good practical solution for the customer who requires power production in average wind speed areas.

The power performance curve highlighted the requirement for the inclusion of a damping mechanism into the pitching mechanism. It also provided an excellent graphical representation on how the predicted power production increases with the wind speed. This curve was especially useful to illustrate the distinct advantage this SWT design has over other designs by generating electricity above the cut-off speed, when other wind turbines stop producing electricity. The result is above average electricity production.

The manufacturing cost calculations of the SWT were not exact due to the premature design stage of the project, and limited access to component cost data. The estimate did however give a good basis for feasibility estimates. These costs were further refined to include potential savings and optimisation strategies which may be possible if a small production line is established. It was noted that the SWT market is still in its infancy making the components difficult to source. This situation is expected to change dramatically over the remainder of this decade as the SWT industry becomes more established and SWT components become commonplace.

The Simple Payback Period Analysis gave a brief insight into the feasibility of the SWT rather than a detailed economical Life Cycle Cost model. It offered some very positive financial results, especially for the scenario where the SWT replaces a petrol/diesel powered portable generating set. Initial calculations indicated that the pay-back period is between two and ten years which was an encouraging result.

Manufacturing can be mostly accomplished by a basic engineering workshop with cutting, welding, milling and turning equipment. Assembly and packaging can also be carried out in the same workshop. Some processes could be possibly outsourced due the high capital cost of equipment, such as painting, profile cutting, and casting/forging.

CHAPTER 6 – CONCLUSIONS

6.1 Fulfilment of Project Aims

Background information was researched from the first recorded wind turbines to modern day SWTs. The evolution of large wind turbine design was also researched but unfortunately had little value in identifying suitable designs for this project. The early SWT designs were more significant as they highlighted the superiority of the three bladed HAWT with respect to efficiency, reliability, maintainability, robustness and cost effectiveness. The basic configuration of the 1922 Jacobs Wincharger is still the industry standard to this day and the reasons are well justified – this three bladed upwind HAWT configuration is simple, cheap, efficient and reliable. Some VAWT and other options were briefly examined however their strengths were found to be incompatible to this particular application.

Component technologies were researched to a limited extent, however this proved to be a difficult area of research due to the intellectual and commercial restrictions imposed by most SWT manufacturers. With the exception of the mainstream three bladed HAWT configurations, most manufacturers were found to make a concerted effort to protect their product development and information regarding their innovations. The majority of literature researched related to large wind turbine component development, and it was very difficult to find technical literature relating to SWTs. The SWT industry is still in its infancy and it is envisaged that soon this information will become more easily obtainable as it becomes published as a mainstream body of knowledge.

Wind availability data for regional Victoria was found to be freely available in the form of an average annual wind speed database provided by Sustainability Victoria (2010). This is available online and can be drilled down to regions, towns or districts throughout the entire state. The limitation of this data is that it relates to a reference height of 65 metres, so that the Normal Wind Profile equation 3.3 must be applied to reduce this to more typical heights for SWT installations.

Some basic conceptual and detail design was carried out on various components however detail design was avoided where possible in favour of purchasing 'off the shelf' components. Some innovation was incorporated into the design process by introducing a centrifugal passive pitching mechanism into the machine control design. Although still in the conceptual stage, this innovation showed promise of a being a marketable, simple and robust alternative for SWT control. It was initially hoped that some innovation may be identified which may reduce moving parts and thus reduce wear and tear. This proved to be an elusive challenge because with rotating machinery such as a three bladed HAWT there are inevitably moving parts.

Alternative material selection was evaluated in the rotor blades, hub, nacelle bedplate, nacelle cover and yaw mechanism. No major innovations were identified in this area and all materials selected were similar to those used in other SWTs in the marketplace. The tower was not assessed for alternatives because the conceptual design identified the tilt-up kit-form tower as the most suitable alternative, which is best suited to steel tube.

The overall design was successfully identified as modular component form, with the rotor, generator, drive coupling and tower all identified as components which may be purchased as pre-manufactured components. This vastly simplified the manufacturing requirements of the complete assembly and reduced workshop equipment requirements.

Costs and benefits of the SWT assembly were assessed and found to be economically feasible with a pay-back period in the vicinity of two to ten years depending on the scenario. The complete SWT assembly could be manufactured for around $10,000 and the package appears to be marketable and suitable for the target market.

6.2 Limitations of Project

As per section 3.2 the project scope aimed to cover the following design guidelines:

- Develop tentative design.
- Predict performance.
- Evaluate design.

The tentative design is still very much in the conceptual stages and requires further detail design to develop it to the desired level of design. One major concern with the conceptual design is with the robustness of the overspeed protection system. This is also related to the philosophy of the early European windmills, which was to allow small components to fail first before the large components could be destroyed. This is a basic reliability philosophy which unfortunately has not been well represented in this SWT design. A major concern is with catastrophic failure of the overspeed automatic pitching mechanism, which could result in the elimination of overspeed protection on the SWT due to the absence of a backup system which could ultimately lead to catastrophic failure of other major components in the SWT. There may be a requirement for a secondary overspeed control mechanism, or the incorporation of a 'small component failure protection' philosophy to protect the SWT from catastrophic failure. A reliability study should be carried out on the SWT to identify further components which require further design for failure protection.

The performance predictions were restricted to very simple calculations to estimate the transient response; manual smoothing techniques were required to add the transitional stage to steady state response. Prototype field testing is the prescribed method in AS 61400-2 (Standards Australia 2006) for collating and documenting performance data, and is the only reliable way to properly estimate the power performance curve due to the vast amount of unknown factors.

To progress further, this SWT project needs to focus on the following design characteristics:

- Refine design.
- Build prototype.
- Test prototype.
- Design production machine.

6.3 Further Work

The hub pitching mechanism was the main innovation incorporated into this project but unfortunately has yet to undergo satisfactory development and analysis. An entire project could easily be devoted to the development of this mechanism which could include the following objectives:

- Develop a detailed model of all inputs and outputs.
- Simulate linear system control characteristics of the mechanism.
- Detailed selection of shaft size, bearings, springs and damper.
- Detailed design of housing including material selection and manufacturing.
- Finite Element Analysis of all components.
- Suggest further improvement to the conceptual design.
- Fitting arrangement of mechanisms to hub.
- Engineering drawings of mechanisms.

The nacelle bedplate is a primary structural component of the project and would be a good candidate for detailed component design and modelling. The following topics need to be further developed on this component:

- Evaluate using composite structural materials for this component.
- Detailed design of bedplate including manufacturing.
- Finite Element Analysis.

The electrical system could be treated as a separate project, to model, balance and optimise the complete system of electrical hardware and software, including:

- Identification of typical system requirements.
- Identification of suitable components.
- Costing of complete system.

The production of the SWT is a topic which requires further attention including workshop design, equipment layout and production techniques. The output of this study could be a workshop implementation and development plan including:

- Workshop layout requirements.
- Workshop equipment requirements.
- Costing study of workshop and equipment.
- Tooling requirements.
- Production techniques and optimisation.

Market research into SWTs is an area where little or no literature was discovered. Potential areas of future research include:

- SWT distribution in Australia.
- SWT sales history in Australia.
- Demographics of customers.
- Trends and future growth predictions.

In general it is felt that the area of machine control, including overspeed protection and yaw control, offers the most potential for innovative breakthroughs and future research. Machine control could be investigated in greater detail and more alternative concepts identified, modelled, designed and perhaps even tested. The lack of a prototype for testing was the main problem with this project due to the prohibitive expense, thus it is recommended to downsize future projects to component level, for example machine control, to make prototype testing a more viable prospect.

A positive contribution has been made to the development of renewable energy and SWT industries, with a potential new design being offered for further research and development. A typical rural market has been investigated and a suitable SWT layout identified to cater for the requirements of this particular market. This can be easily adapted to rural markets worldwide and the basic standards and necessary calculations have been identified to do so. Most importantly the SWT has been validated as a feasible alternative to address future energy requirements and to provide positive ethical, financial and environmental impacts to society.

APPENDIX A – Project Specification

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

<u>ENG4111/4112 Research Project</u>

PROJECT SPECIFICATION

FOR: **RAMON PERRY**

TOPIC: DESIGN OF A SMALL WIND TURBINE FOR A RURAL COMMUNITY IN AUSTRALIA

SUPERVISOR: Dr. Jayantha Epaarachchi

ENROLMENT: ENG4111 – S1, 2010
ENG4112 – S2, 2010

PROJECT AIM: To design a lightweight, durable and economical wind turbine (~1 kW) using commercially available parts and composite structural materials.

PROGRAMME: Issue B, 1st April 2010

1. Research background information of wind turbine design specifically relating to small wind turbines.
2. Critically evaluate past, current & emerging wind turbine component technologies to assess their usefulness in this application.
3. Obtain wind energy availability data for regional locations in Victoria and identify suitable data.
4. Carry out engineering design & analysis of mechanical components with an emphasis on development of innovative alternatives.
5. Evaluate alternative material selection including composite structural materials based on their commercial suitability for this application.
6. Design a wind turbine assembly including rotor, drive system, generator and tower using commercially available parts.

As time permits:

7. Evaluate the manufacturing requirements, cost and benefits associated with the selected design.
8. Produce a set of manufacturing drawings for the selected assemblies.

AGREED:

___________________ (Student) Approved_________ (Supervisor)

Date: 1 / 4 / 2010 Date: / / 2010

Examiner/Co-Examiner: ___________________________________

APPENDIX B – Survey of 0.8-1.2 kW Small Wind Turbine Market

Manufacturer: **Aeo Energy (China)**

Wind Turbine Model:	1,000 W Wind Turbine – 1 kW
Rotor:	HAWT three blade
	2.7 m diameter
	Fibreglass
	Upwind design
Drive Train:	Not specified
Generator:	Permanent magnet
Yaw system:	Wind Vane
Speed control:	Not specified
Tower:	Guyed steel tube or free standing

Manufacturer: **Aeolis (UK)**

Wind Turbine Model:	Aeolis H – 1 kW
Rotor:	HAWT Three blade
	3.2 m diameter
	Upwind design
Drive Train:	Not stated
Generator:	Permanent magnet
Yaw system:	Wind Vane
Speed control:	Not stated
Tower:	Guyed steel tube (lowest cost)
	Welded steel lattice (medium cost)
	Free standing steel tube (highest cost)

Manufacturer:	**Aeolis (UK)**
Wind Turbine Model:	Aeolis V – 1 kW
Rotor:	VAWT
Drive Train:	Not stated
Generator:	Permanent magnet
Yaw system:	Not required
Speed control:	Not stated
Tower:	Guyed steel tube (lowest cost)
	Welded steel lattice (medium cost)
	Free standing steel tube (highest cost)

Manufacturer:	**Aerocraft (Germany)**
Wind Turbine Model:	AC100 – 1 kW
Rotor:	HAWT Three blade
	2.4 m diameter
	Upwind design
Drive train:	Slip ring
Generator:	16 pole permanent magnet
Yaw system:	Wind vane
Speed control:	Eclipse control
Tower:	Modular mast system

Manufacturer:	**Aerotecture**
Wind Turbine Model:	510V Aeroturbine – 1 kW
Rotor:	Vertical helical rotor and airfoils house in a steel cage
	1.7m diameter
Drive train:	Slip ring
Generator:	Permanent magnet
Yaw system:	Not required
Speed control:	Self regulating – no overspeed protection required
Tower:	Building mounting system

Manufacturer:	**African Wind Power (South Africa)**
Wind Turbine Model:	AWP 3.6 – 1 kW
Rotor:	HAWT Three blade
	3.6 m diameter
	Foam core, resin transfer moulded, GRP composite design
	Upwind design
Drive train:	Slip ring
Generator:	30 pole ceramic magnet rotor, laminated axial stator
Yaw system:	Wind vane
Speed control:	Gravity yaw system
Tower:	Steel tube guyed tower

Manufacturer:	**Bergey (USA)**
Wind Turbine Model:	XL.1 – 1 kW
Rotor:	HAWT Three blade
	2.5m diameter
	Protruded fibreglass
	Upwind design
Drive train:	Slip ring
Generator:	Low speed permanent magnet
Yaw system:	Wind vane
Speed control:	BWC AutoFurl passive sideways furling system
Tower:	Tubular tilt up tower

Manufacturer:	**Exmork (China)**
Wind Turbine Model:	AR – 1,000 W – 1 kW
Rotor:	HAWT three blade
	2.8 m diameter
	Reinforced glass fibre
	Upwind design
Drive Train:	Not specified
Generator:	NdFeB permanent magnet alternator
Yaw system:	Wind Vane
Speed control:	Yaw and auto brake
Tower:	Guyed steel tube

Manufacturer:	**Kestrel (South Africa)**
Wind Turbine Model:	e300i - 1 kW
Rotor:	HAWT Three blade
	Glass fibre
	3.0 m diameter
	Upwind design
Drive train:	Pitch hub assembly
Generator:	Dual twin axial thrust permanent magnet brushless
Yaw system:	Tail vane
Speed control:	Passive blade pitch control incorporated into hub
Tower:	80-100 mm pipe

Manufacturer:	**Point.of.com. GmbH (Germany)**
Wind Turbine Model:	Cyclone - 1.2 kW
Rotor:	HAWT Three blade
	2.7 m diameter
	Upwind design
Drive train:	Not stated
Generator:	Not stated
Yaw system:	Wind Vane
Speed control:	Not stated
Tower:	Galvanised steel tube

Manufacturer:	**Southwest Wind Power Co. (USA)**
Wind Turbine Model:	Whisper 100 – 0.9 kW
Rotor:	HAWT Three blade
	2.1 m diameter
	Carbon reinforced fibre glass
	Upwind design
Yaw system:	Wind Vane
Speed control:	Side Furling Angle Governor
Tower:	Guyed steel tube tower

Manufacturer:	**Tangarie Alternative Power LLC (USA)**
Wind Turbine Model:	Gale 1 VAWT – 1 kW
Rotor:	VAWT
	13.5” diameter x 40.5” height
	Fibreglass
Drive Train:	Without gear
Generator:	Permanent magnet
Yaw system:	Not required
Speed control:	Electronic
Tower:	Metal / concrete

Manufacturer:	**True North Power NG (Canada)**
Wind Turbine Model:	Arrow - 1 kW
Rotor:	HAWT Three blade
	2.0 m diameter
	Carbon fibre
	Upwind design
Drive train:	Not stated
Generator:	Not stated
Yaw system:	Wind Vane, non mechanical
Speed control:	Microprocessor control with Active Flight Control
	Variable blade pitch setting
	Electronic automatic storm shutdown
Tower:	Galvanised steel tube guyed tower

Manufacturer:	**Urban Green Energy (USA)**
Wind Turbine Model:	UGE VAWT - 1 kW
Rotor:	VAWT
	1.8 m wide x 2.7m tall
	Carbon fibre & fibreglass
Drive Train:	Direct drive
Generator:	Permanent magnet
Yaw system:	Not required
Speed control:	Electronic overspeed protection
Tower:	Guyed steel tube (lowest cost)
	Welded steel lattice (medium cost)
	Free standing steel tube (highest cost)

Manufacturer: **Vaigunth Ener Tek (P) Ltd (India)**

Wind Turbine Model:	AR – 1,000 W – 1 kW
Rotor:	HAWT three blade
	4 m diameter
	Glass fibre
	Upwind design
Drive Train:	Planetary gear
Generator:	AC generator & brush
Yaw system:	Wind Vane
Speed control:	Not specified
Tower:	Guyed steel tube

Manufacturer: **Windmax (USA)**

Wind Turbine Model:	Windmax H12 - 1.05 kW
Rotor:	HAWT Five blade
	1.8 m diameter
	Mixed nylon & reinforced glass fibre
	Upwind design
Drive Train:	Not stated
Generator:	Brushless neodymium permanent magnet
Yaw system:	Wind Vane
Speed control:	Electromagnetic speed limitation
	Aerodynamic blade overspeed braking by blade deformation
Tower:	Guyed 2” steel tube (lowest cost)
	Free standing steel tube (medium cost)
	Free standing tapered steel tube (highest cost)

Manufacturer:	**Windspire (USA)**
Wind Turbine Model:	Standard unite - 1.2 kW
Rotor:	Vertical axis low speed Gyromill
	Recycled high grade steel with corrosion resistant coating
Drive Train:	Not stated
Generator:	Brushless permanent magnet
Yaw system:	Not required - instantaneous
Speed control:	Redundant electronic
Tower:	Not stated

Manufacturer:	**Zkernegy (China)**
Wind Turbine Model:	FD 2.7-1.0/12 – 1 kW
Rotor:	HAWT three blade
	2.7 m diameter
	Not specified
	Upwind design
Drive Train:	Direct drive
Generator:	NdFeB permanent magnet brushless alternator
Yaw system:	Wind Vane
Speed control:	Electro-magnetic braking
	Passive side furling
Tower:	Guyed steel tube

APPENDIX C – BOD Rating System Computations

Rotor axis orientation

BOD #	Description	BOD Weighting	VAWT	HAWT	VAWT weighted	HAWT weighted
1	Standards	10	6	10	6.0	10.0
2	Costs	10	4	8	4.0	8.0
3	Environmental	10	8	6	8.0	6.0
4	Transportability	8	8	6	6.4	4.8
5	Installation	8	8	6	6.4	4.8
6	Components	8	4	8	3.2	6.4
7	Innovation	7	8	6	5.6	4.2
8	Reliability	7	6	8	4.2	5.6
9	Maintenance	6	8	6	4.8	3.6
10	Materials	5	5	5	2.5	2.5
11	Manufacturing	4	5	5	2.0	2.0
	Total				**53.1**	**57.9**

Table B.1: BOD rating system for rotor axis orientation (Authors own table)

Key points pertaining to BOD rating system items in table B.1 are as follows:

1. The HAWT is more easily adapted to standards as the majority of literature and standards relate to HAWT design, whereas VAWT is not well covered.
2. Due to the inherent efficiency losses of the VAWT the construction costs escalate.
3. The VAWT offers superior noise qualities.
4. The VAWT is assumed to be mounted on a very low tower or close to the ground, negating the requirement for tower transport.
5. VAWT installation is assumed to be ground based; however the unit is likely to be much heavier than a HAWT offering a slight installation advantage.
6. Components are more readily available in the HAWT configuration due to their overwhelming popularity.
7. VAWT offers more opportunity for innovation particularly with rotor design.
8. Reliability issues on VAWT due to high thrust and fatigue loads.
9. Maintainability is a key advantage of VAWT due to its ground installation.

10. No materials advantages.
11. No manufacturing advantages.

Rotor position

BOD #	Description	BOD Weighting	Upwind	Down wind	Upwind weighted	Down wind weighted
1	Standards	10	5	5	5.0	5.0
2	Costs	10	5	5	5.0	5.0
3	Environmental	10	10	8	10.0	8.0
4	Transportability	8	5	5	4.0	4.0
5	Installation	8	5	5	4.0	4.0
6	Components	8	10	8	8.0	6.4
7	Innovation	7	5	5	3.5	3.5
8	Reliability	7	6	8	4.2	5.6
9	Maintenance	6	6	8	3.6	4.8
10	Materials	5	5	5	2.5	2.5
11	Manufacturing	4	5	5	2.0	2.0
	Total				**51.8**	**50.8**

Table B.2: BOD rating system for rotor position (Authors own table)

Key points pertaining to each BOD rating system item in table B.2 are as follows:

1. No advantages in standards compliance.
2. No advantages in costs.
3. The ‘thump noise’ of the downwind tower is a disadvantage.
4. No advantages in transportability.
5. No advantages in installation.
6. Rotor blades are more readily available in the rigid upwind style due to their overwhelming popularity, as are the hubs.
7. No advantages in innovation potential.
8. Downwind can expect slightly enhanced reliability due to the absence a mechanical yawing system.
9. Downwind can expect slightly enhanced maintenance due to the absence a mechanical yawing system.

10. No advantages in material design.
11. No manufacturing advantages.

Rotor blades

BOD #	Description	BOD Weighting	One blade	Two blades	Three blades	One blade weighted	Two blades weighted	Three blades weighted
1	Standards	10	5	5	5	5.0	5.0	5.0
2	Costs	10	8	7	6	8.0	7.0	6.0
3	Environmental	10	5	6	10	5.0	6.0	10.0
4	Transportability	8	5	5	5	4.0	4.0	4.0
5	Installation	8	8	7	6	6.4	5.6	4.8
6	Components	8	8	9	10	6.4	7.2	8.0
7	Innovation	7	10	8	5	7.0	5.6	3.5
8	Reliability	7	8	9	10	5.6	6.3	7.0
9	Maintenance	6	6	6	8	3.6	3.6	4.8
10	Materials	5	5	5	5	2.5	2.5	2.5
11	Manufacturing	4	8	10	10	3.2	4.0	4.0
	Total					**56.7**	**56.8**	**59.6**

Table B.3: BOD rating system for rotor blades (Authors own table)

Key points pertaining to each BOD item in table B.3 are as follows:

1. No advantages in standards compliance.
2. One blade requires larger chord radius, counterweight & teetering hub so costs savings in blade number is eroded.
3. Visual and noise disturbances much higher for less blades.
4. No advantages in transportability.
5. Slightly easier to install a lower number of blades.
6. Teetering hubs require custom building, as does counterweight.
7. Less blades designs lend themselves more to innovations.
8. Teetering hubs have more mechanical components to fail thus lower reliability.
9. Maintainability is slightly less due to the complexity of the teetering hub.
10. No materials advantages.
11. Manufacturing is more complex with counterweight & teetering hub designs.

Hub type

BOD #	Description	BOD Weighting	Fixed hub	Teeter hub	Hinged hub	Fixed hub weighted	Teeter hub weighted	Hinged hub weighted
1	Standards	10	5	5	5	5.0	5.0	5.0
2	Costs	10	10	8	8	10.0	8.0	8.0
3	Environmental	10	5	5	5	5.0	5.0	5.0
4	Transportability	8	5	5	5	4.0	4.0	4.0
5	Installation	8	10	8	8	8.0	6.4	6.4
6	Components	8	10	6	6	8.0	4.8	4.8
7	Innovation	7	6	10	10	4.2	7.0	7.0
8	Reliability	7	10	8	8	7.0	5.6	5.6
9	Maintenance	6	10	8	8	6.0	4.8	4.8
10	Materials	5	5	5	5	2.5	2.5	2.5
11	Manufacturing	4	10	8	8	4.0	3.2	3.2
	Total					**63.7**	**56.3**	**56.3**

Table B.5: BOD rating system for hub type (Authors own table)

Power control

BOD #	Description	BOD Weighting	Pitch control	Aerodyn control	Yaw control	Furl control	Stall control	Elec control	Pitch weighted	Aerodyn control weighted	Yaw control weighted	Furl control weighted	Stall control weighted	Elec control weighted
1	Standards	10	5	5	5	5	5	5	5.0	5.0	5.0	5.0	5.0	5.0
2	Costs	10	8	4	8	8	4	4	8.0	4.0	8.0	8.0	4.0	4.0
3	Environmental	10	8	6	8	8	4	10	8.0	6.0	8.0	8.0	4.0	10.0
4	Transportability	8	8	4	8	8	8	8	6.4	3.2	6.4	6.4	6.4	6.4
5	Installation	8	8	8	8	8	10	6	6.4	6.4	6.4	6.4	8.0	4.8
6	Components	8	6	4	6	4	4	4	4.8	3.2	4.8	3.2	3.2	3.2
7	Innovation	7	5	5	5	5	5	5	3.5	3.5	3.5	3.5	3.5	3.5
8	Reliability	7	6	6	6	8	10	6	4.2	4.2	4.2	5.6	7.0	4.2
9	Maintenance	6	8	8	8	9	10	4	4.8	4.8	4.8	5.4	6.0	2.4
10	Materials	5	6	6	6	6	8	6	3.0	3.0	3.0	3.0	4.0	3.0
11	Manufacturing	4	8	4	8	4	4	4	3.2	1.6	3.2	1.6	1.6	1.6
	Total								**57.3**	**44.9**	**57.3**	**56.1**	**52.7**	**48.1**

Table B.4: BOD rating system for power control (Authors own table)

Tower

BOD #	Description	BOD Weighting	Tilt-up	Fixed guyed	Free standing	Tilt up weighted	Fixed guyed weighted	Free standing weighted
1	Standards	10	5	5	5	5.0	5.0	5.0
2	Costs	10	8	8	4	8.0	8.0	4.0
3	Environmental	10	4	6	8	4.0	6.0	8.0
4	Transportability	8	5	5	5	4.0	4.0	4.0
5	Installation	8	8	4	2	6.4	3.2	1.6
6	Components	8	5	5	5	4.0	4.0	4.0
7	Innovation	7	5	5	5	3.5	3.5	3.5
8	Reliability	7	6	6	8	4.2	4.2	5.6
9	Maintenance	6	8	4	4	4.8	2.4	2.4
10	Materials	5	5	5	5	2.5	2.5	2.5
11	Manufacturing	4	8	6	4	3.2	2.4	1.6
	Total					**49.6**	**45.2**	**42.2**

Table B.6: BOD rating system for tower type (Authors own table)

Key points pertaining to each BOD item in table B.6 are as follows:

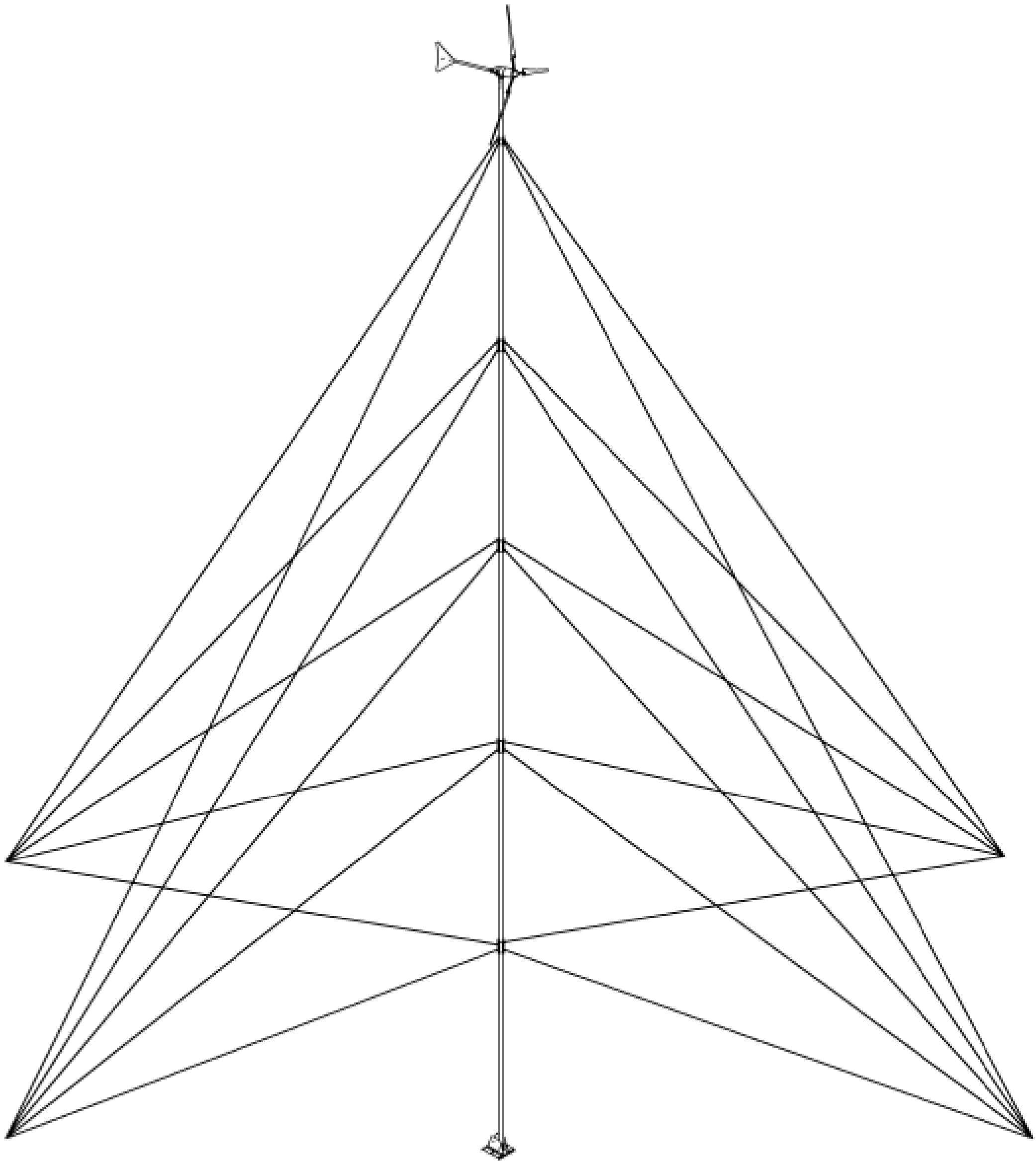
1. No advantages in standards compliance.
2. Free-standing tower up to double the cost of the other options.
3. The minimal footprint gives the free standing a large advantage.
4. All units are modular so no variation in transportability.
5. Fixed guyed and free-standing installations are both machinery intensive, tilt-up only requires a standard vehicle or a lever-winch.
6. No component advantages.
7. No innovation advantages.
8. A slight advantage to the free-standing tower due to the absence of guy wires.
9. Maintainability is a key advantage of the tilt-up tower due to not having to climb the tower.
10. No materials advantages.
11. Manufacturing is more complex with the free-standing design, the tilt-up design being the simplest manufacturing.

APPENDIX D – Vendor Information

D.1 Southwest Windpower 25 m Tilt-up Tower Installation Manual

Note: Only pages 1 to 8 of this 27 page installation manual are included here.

80 FOOT LAND TOWER KIT
For WHISPER 100 AND 200 WIND TURBINES



Made in the USA by:
Southwest Windpower
1801 W. Route 66
Flagstaff, AZ 86001
(928) 779-9463
Whisper is a trademark of Southwest Windpower Inc.

80 FOOT WHISPER LAND TOWER KIT

CONGRATULATIONS! You have just received the simplest, most economical 80 foot tower kit available for your Whisper 100 or 200 wind turbine. This kit is designed to be very easy to assemble and erect, however it is important that you read this manual thoroughly before beginning assembly. If you have any questions on proper installation or usage, please call either Southwest Windpower or your dealer for more information.

Notice: This information is believed to be accurate, however, Southwest Windpower assumes no responsibility for inaccuracies or omissions. The user of this information and product assumes full responsibility and risk. All specifications are subject to change without notice.

CONTENTS		**Page**

Introduction

This tower kit is designed specifically for the Southwest Windpower Whisper 100 and 200 wind turbines. To our knowledge this is the most economical and user friendly tower kit available for the Whisper wind turbines. Five level, guy wire supported construction allows the use of lightweight tubing while providing plenty of strength, even in high wind conditions. With the help of a winch, beast of burden or vehicle, two people can easily erect the tower in a few hours. All that is required is the necessary tubing, the proper anchors for your soil type and a few common tools. At least two people must be present to safely erect the tower.

This 80 foot (25 m) tower uses a gin pole to assist in raising the tower. The basic principle of gin pole use is described on the next two pages. This Whisper tower kit includes a galvanized steel base with separate pivots for both the tower and gin pole. The tower base has a footprint of 16 inches square. In many cases a concrete pad for the tower base is not necessary.

Simple extruded aluminum coupling clamps allow the use of different wall thickness of tubing, depending on site requirements. Threaded coupling joints are eliminated, allowing lighter materials to be used with the same or greater strength than a threaded pipe tower. The top guy wire attachment clamps onto the upper mast section. This reduces the number of pieces of tubing used to construct the tower and reduces the stresses concentrated at this point. Pre-cut and swaged guy wires eliminate wire measuring and cutting.

Thank you for purchasing our products and for your interest in renewable energy. We are confident that you will enjoy the benefits of your wind powered electrical system for many years to come. If, after reading this manual, you have any further questions please contact your local dealer or Southwest Windpower and we will do our best to assist you.

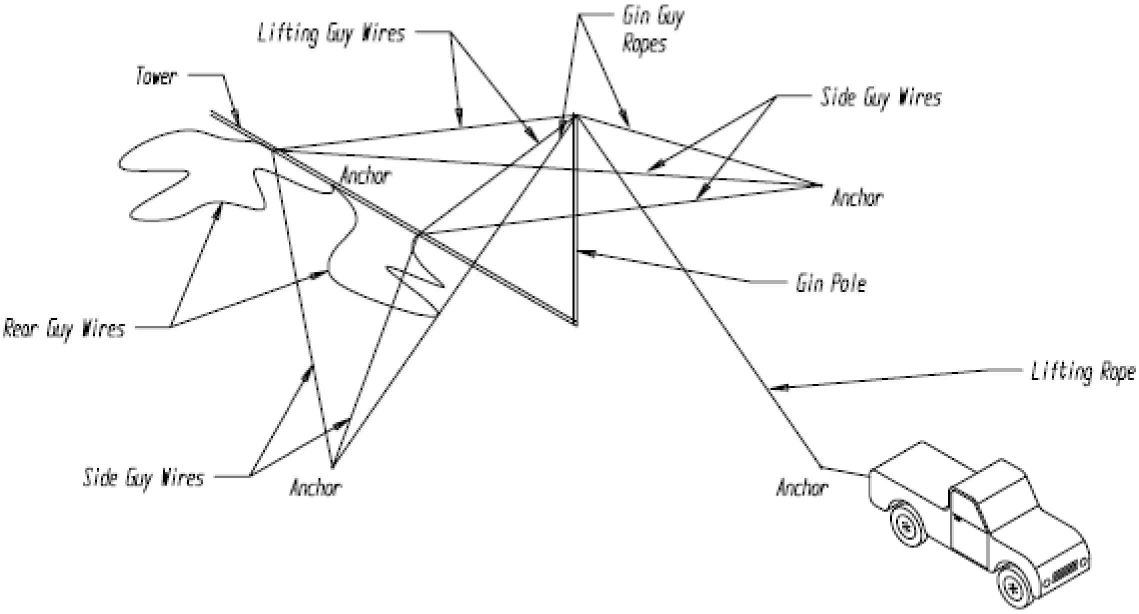
Safe Installation

Safety is the most important consideration to take into account when installing a tower and wind turbine. It is very important to remember that any wind turbine has high speed spinning parts and can be very dangerous if not installed properly! Be sure that the tubing or pipe used for the tower is of adequate strength, that all bolted connections are tightened to the proper torque and that the guy wire anchors are suitable for your conditions, terrain and size of tower. All of these elements are explained in further detail later in this manual. **Important! Choose a very calm day to do your installation. A gust of wind at the wrong moment could cause SERIOUS PROBLEMS!**

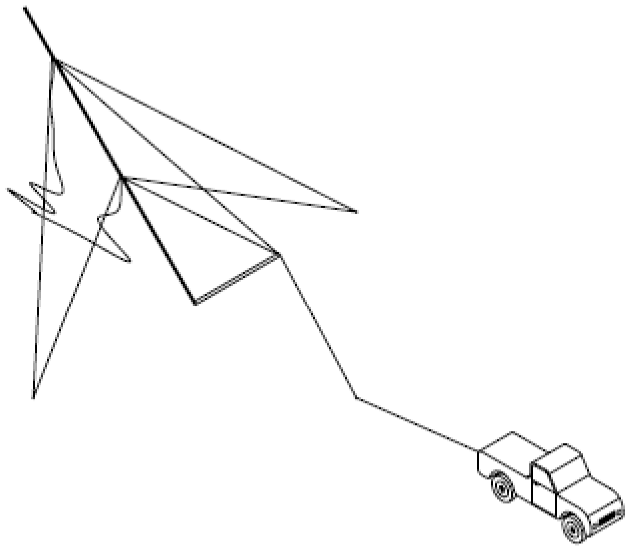
PLEASE….READ ALL OF THIS MANUAL BEFORE DOING ANYTHING !

Raising a Tower With a Gin Pole

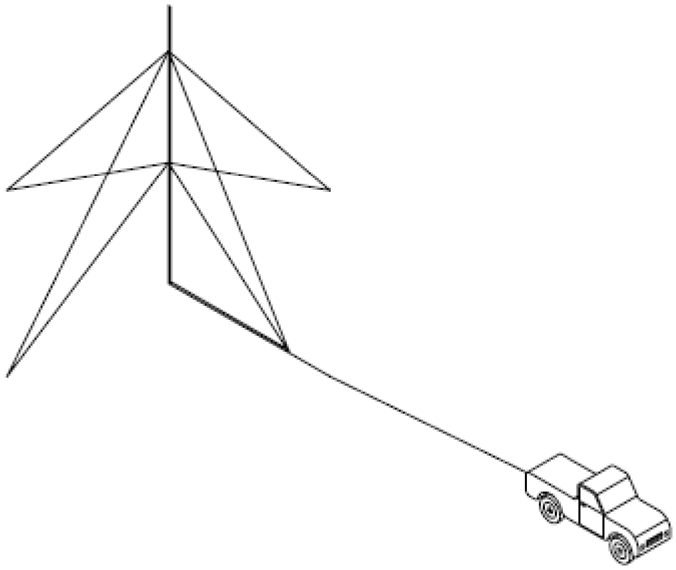
A gin pole is essentially a smaller second tower that is used to gain the mechanical advantage necessary to raise your tower off the ground. The gin pole is raised first, with all of the guy wires on the front side of the tower (Lifting Guy Wires) attached to it. Ropes ("gin guy ropes") are tied to the side anchors to stabilize the gin pole.



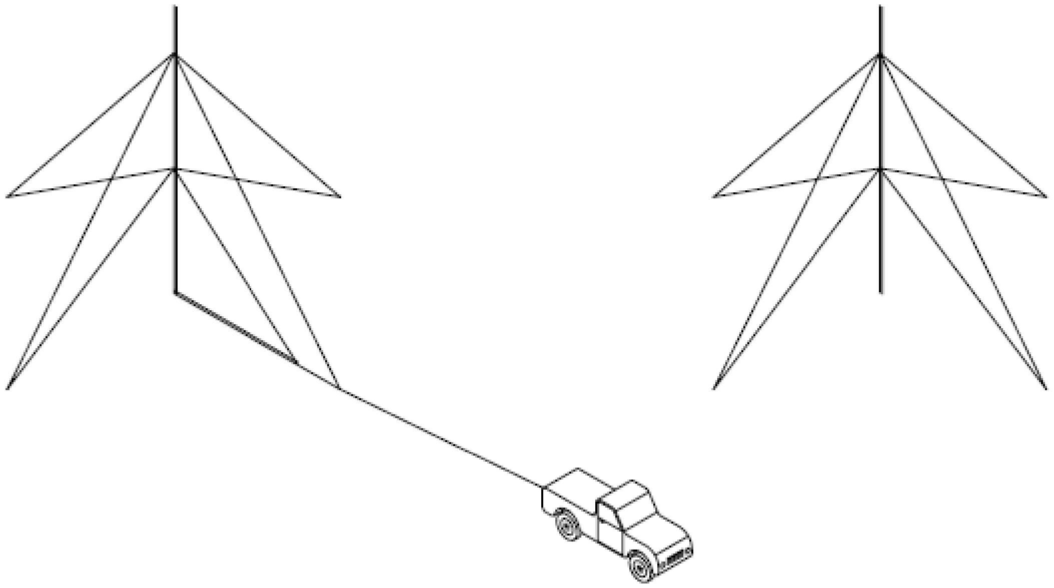
As tension is applied to the lifting rope (or cable) the tower will be raised off of the ground.



Pulling continues until the tower is vertical.

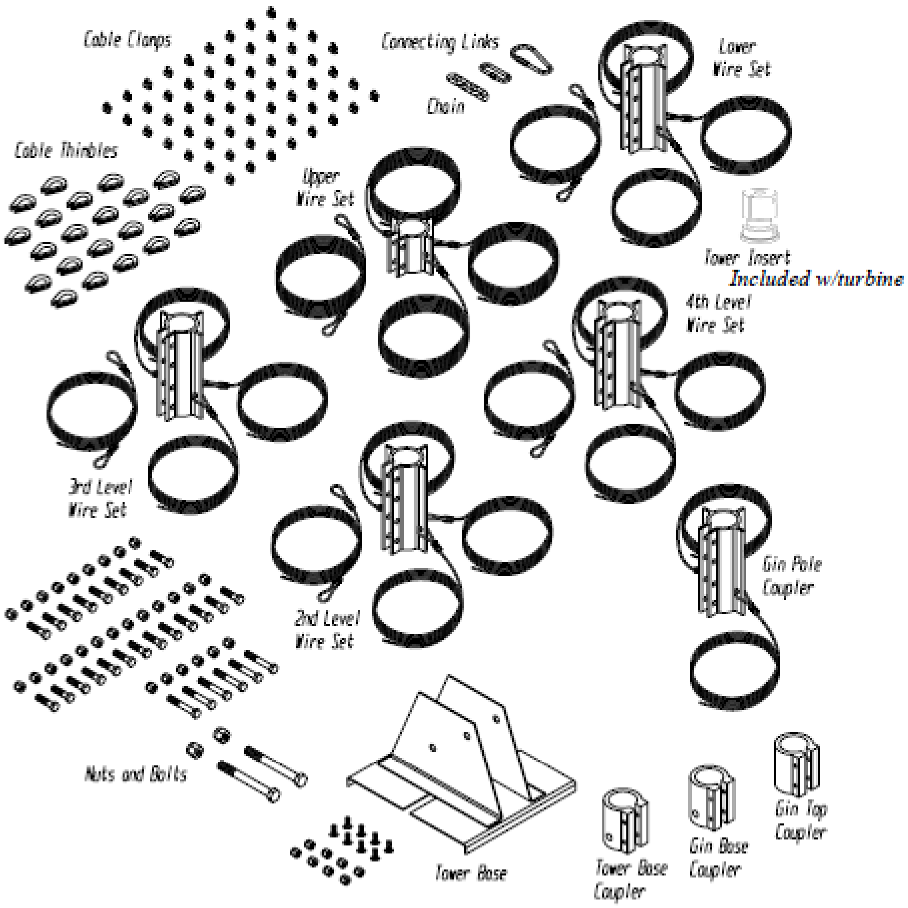


One at a time, the lifting wires are then removed from the gin pole top and attached to the lifting side anchor. The gin pole can be removed and used to erect other towers, stored until needed later or simply left in place.



80 Foot Whisper Tower Kit Parts List

Part	Quantity	Part	Quantity
Tower Base	1	3/8" Carriage Bolts	8
Upper Guy Wire Set	1	Tower Insert (included w/turbine)	1
4th Guy Wire Set	1	3rd Guy Wire Set	1
Pivot Bolt and Nut	2	2nd Guy Wire Set	1
Pear Connecting Link	1	Lower Guy Wire Set	1
Tower Base Coupler	1	3/8" x 2" Bolts	22
Gin Base Coupler	1	3/8" x 3 ½" Bolts	6
Gin Pole Top Piece	1	3/8" Lock-nuts	36
4 link Chain	1	Cable Thimbles	22
Straight Connecting Link	1	Cable Clamps	66
Gin Pole Coupler	1		



Please inspect the contents to see that all parts are present and to familiarize yourself with the pieces before beginning assembly.

Necessary Items Not Included In This Kit:

Anchors (explained further in the "Anchors" section of this manual.)
Tubing or Pipe for Tower
Ground Rod and Clamp
Lightning Arrestor*
Electrical Wire
Wire Connectors (preferably copper split bolts)
Pipe Insulation (to prevent wire "rattle" inside pole) *
Electrical tape or heat shrink tubing
Lifting Cable or Rope (2,000 lb. (950 kg.) strength x 150 ft. (45m))

* optional items (these are explained in more detail in their relevant assembly sections)

Tools Needed:

Round or Half Round File	Pliers
Carpenters Level (optional)	(2) 9/16" or 15mm Wrenches/Sockets
Torque Wrench	Sledge Hammer
15/16" Wrench	Large Adjustable Wrench
Sawhorse	Ladder or 10 foot (3 m) 2x6 or 2x8
3/8" or 10mm Corded or Cordless Drill Motor	3/8" or 10mm Metal Cutting Drill Bit

Step 1: Site Selection

Site selection is the most important factor affecting the performance of your wind turbine!

The energy in the wind is the kinetic energy of the moving air mass. What a wind turbine does is convert some of that kinetic energy into rotational energy that can then be converted to electricity. The formula for the amount of power in the wind is a cube function of the wind speed. This means basically that an increase in wind speed of 10% (say from 9 mph to 10 mph) will result in approximately a 37% increase in the power available from the wind and a similar increase in turbine performance. In almost all locations the wind speed increases as you get higher off the ground. This is why a tall tower is very important at most wind sites. As a rule, the turbine should be mounted as high in the air and as far away from obstructions as is possible.

To find the best location to erect your tower and wind turbine, study the available area and take note of how the prevailing (most common) winds blow through it. If there are trees, buildings, hills or other obstructions take note of how high they are and where they are in relation to the prevailing wind direction. The best site for your tower and turbine will be upwind and above any obstructions that may exist. If there are houses or trees in the surrounding area a good rule of thumb is to mount the turbine at least 15 feet above any obstructions within 500 feet (150 m) of it.

The next consideration in siting your tower and turbine is the distance from the turbine to your batteries. The shortest distance will require the least amount of wire, allow use of the most economical (smallest) wire and reduce the amount of power lost. If a long distance is required between your tower and the batteries it will be necessary to use a heavier gage wire to reduce the resistance of the wire. The power consumed by the wires can be calculated using the formula:

Power = Current x *Current* x *Resistance*

Since the resistance of the wire is directly proportional to its length, making the run shorter will dramatically reduce the amount of power "lost" in the wires.

Please refer to the section on "Tower, Base and Anchor Layout". The amount of space available to assemble and raise the tower may also affect where your tower can be placed.

Step 2: Tower Pipe Selection

Because of the high cost of shipping and the widespread availability of the tubing or pipe used for our towers, these materials are not provided by Southwest Windpower. These materials are readily available through most chain link fence suppliers or plumbing companies and will cost much less when purchased locally than if we were to try to ship them from our factory.

The "Whisper" land tower kit is designed to use a 2.875 in. (73 mm) outside diameter pipe. This is the same outside diameter as 2 ½ in. steel water pipe where the "2 ½" is a nominal size indicating an outside diameter that is actually 2.875 in.. Whether the pipe is "schedule 20", or "schedule 40", the outside diameter will be the same and the schedule number determines the wall thickness of the pipe. *Use only structural steel for this tower! Never use electrical conduit!*

The design of this tower kit allows steel pipe (or tubing) of various different wall thickness to be used depending on its availability and on the severity of the wind at your site location. Use the following table to determine the acceptable pipe size(s) for your tower and wind severity. In most locations structural pipe with a wall thickness of .120 inches (3 mm) is sufficient for the conditions and preferable in terms of cost and ease of assembly. We recommend either "CQ-40" or "S-40" fence pipe available from any chain link fence supplier. Electrical conduit or plastic tubing must never be used in your tower assembly, since it is designed to be bent easily, not for strength.

Use the following table for Pipe / Tubing wall thickness guidelines:

Maximum Wind Speed	Recommended Wall Thickness	Pipe Schedule
80 mph. (135 kph)	.120 inch (3 mm)	CQ-40
100 mph. (160 kph)	.140 inch (3.6 mm)	S-40

Pieces of Pipe Needed:

(4) 15 foot (4.57 M) lengths of pipe for tower (wall thickness selected for local conditions)
(1) 20 foot (6.1 M) length of pipe for tower (wall thickness selected for local conditions)
(1) 20 foot (5.8 M) length of pipe for gin pole (.065" (1.6mm) or greater wall thickness)
(1) 13 foot (4.0 M) length of pipe for gin pole (.065" (1.6mm) or greater wall thickness)

D.2 Ginlong Technologies Inc. GL-PMG-1800 Specification Sheet

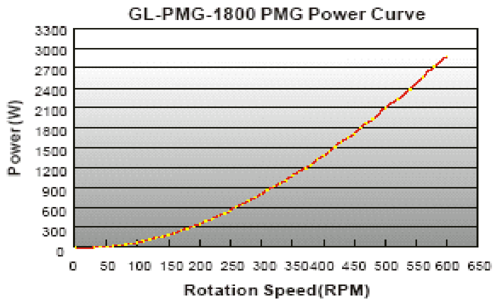
Wind Turbine Permanent Magnet Generator/ Alternator

Ginlong Technologies GL-PMG-1800

World Leading Professional Wind Turbine Parts Supplier

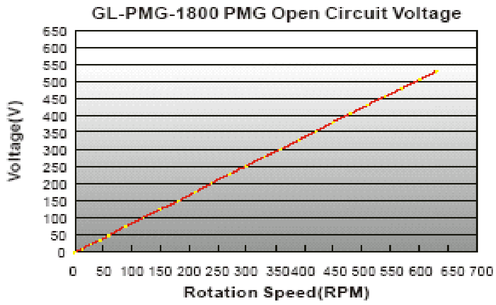
Electrical Specification

Rated Output Power(W):	1800
Rated Rotatoin Speed (RPM):	480
Recified DC Current at Rated Output (A):	6
Requied Torque at Rated Power:	44.5
Phase Resistance (Ohm):	5.0
Output Wire Square Section (mm2):	4
Output Wire Length (mm):	600
Insultation:	H Class
Generator configuration:	3 Phase star connected AC output
Design Lifetime:	>20 years



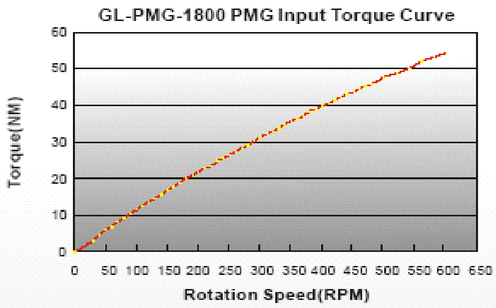
Mechanical Specification

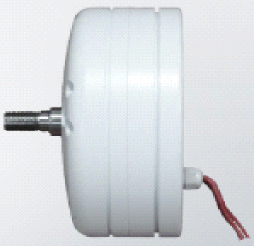
Weight (Kg):	18.3
Starting Torque (NM):	<0.9
Rotor Inertia (Kg.m²):	0.013
Bearing Type:	High standard NSK 6207DDUC3 (Front) NSK 6207VVC3 (Rear)

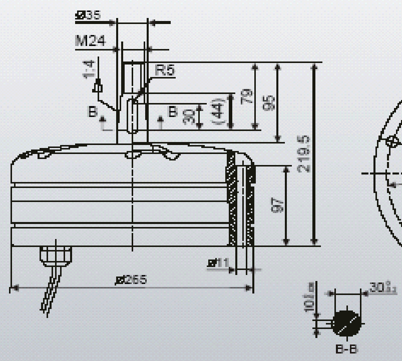


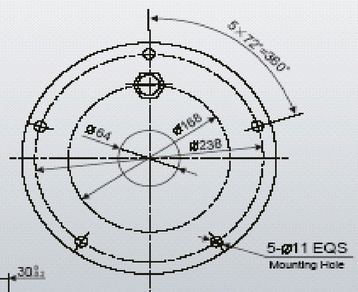
Material Specification

Shaft Material:	High standard Stainless Steel
Shaft Bearing:	High standard SKF or NSK bearing
Outer Frame Material:	High standard Aluminium alloy with TF/T6 heat treatment
(TF/T6 full heat treatment for increasing the performance of aluminium alloy as follows. Heat 4-12 hours at 525-545 degrees Celsius, quench with hot water, and precipitation heat treatment for 8-12 hours at 155-175 degrees Celsius.)	
Fasteners (nuts and bolts):	High standard Stainless Steel
Windings Temperature Rating:	180 degrees Celsius
Magnet Material:	NdFeB (Neodymium Iron Boron)
Magnets Temperature Rating:	150 degrees Celsius
Lamination Stack:	High specification cold-rolled Steel









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