

Chapter 2

Literature study

This chapter provides a literature review of the technology and techniques currently applicable to the project at hand.

2.1 Overview

One of the factors that make sustainable alternative energies difficult to implement can be attributed to the multitude of different environments where these alternative energies are harnessed. This is especially true when working with wind energy, where the physical surroundings have a dramatical effect on the probable power output calculations. Calculating the power potential for various system configurations at the different locations can be a time consuming and expensive task and requires substantial knowledge of the resource being analysed as well as the intended equipment.

There are many sources of renewable energy, ranging from geothermal energy to hydro energy harnessing the natural flow of water to generate electricity. However, during the course of this project, only solar and wind energy were investigated as viable

options due to their abundant availability across South Africa.

2.2 Software

2.2.1 Existing simulation packages

Currently there are some discrete simulation packages capable of simulating the potential power output of a wind turbine such as the Etap Power System Software [18], or to simulate the wind probability by using software such as Power Analysis and Sample Size statistical software [19]. Similar software packages can be used to calculate the solar irradiance, but a hybrid simulation package capable of simulating both the wind energy as well as solar power output probabilities has not yet been encountered.

2.2.2 Integrated design environment

The LabView programming environment is the main Integrated Development Environment (IDE) and is ideally suited for a modular programming approach. LabView promotes rapid software development by providing a substantial amount of math and statistical libraries with drag and drop functionality. Furthermore, LabView provides user friendly graphical user interface (GUI) components. By creating an individual Virtual Instrument (VI) for each unit, one will be able to independently design and test each component and ultimately integrate them into the final program. Supporting software used throughout the project includes Matlab and Microsoft Excel.

2.3 Solar

Every day of our lives we encounter solar energy in the forms of light and heat when we wander outdoors. Currently there are two general methods of harnessing this

abundant energy source. The lesser known method called Concentrating solar thermal power (CSP), utilises parabolic mirrors and lenses to focus the solar energy collected over a large area onto a small target. This concentrated thermal power can then be utilised to produce steam for a turbine generator. In order for CSP to be advantageous, it would require a substantial amount of land and water. In contrast, there are a lot of rooftops that can accommodate Photovoltaic (PV) technologies providing power close to where it is needed [20], thus omitting the need for special long distance transmission lines and the losses associated therewith. The more common method known as PV, differs from CSP in that it is capable of converting solar irradiance directly into electrical energy. For the aim of this project, PV panels will be used to harness the solar energy.

2.3.1 Photovoltaic Panels

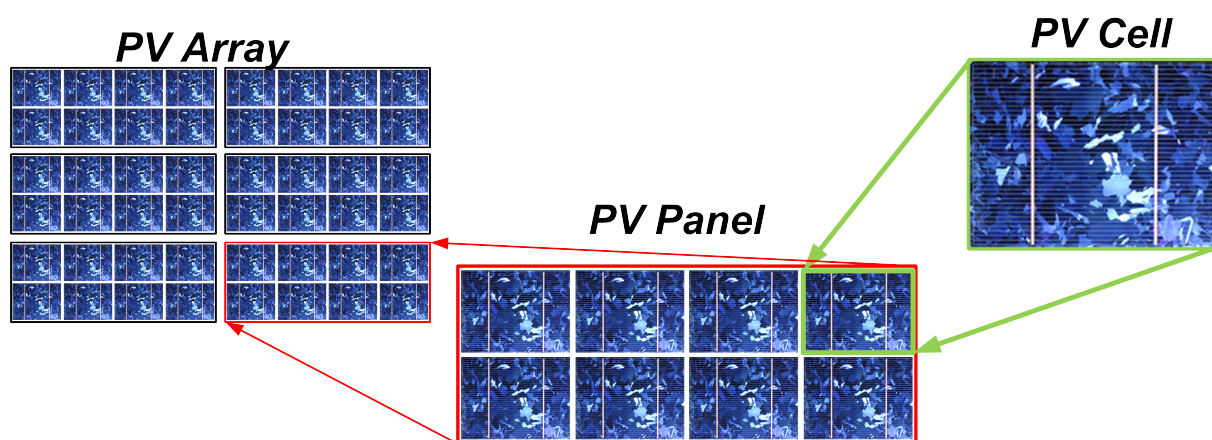


Figure 2.1: Exploded view of a solar array

PV is the technology capable of generating direct current (DC) electrical power when photons in the sunlight hit a semiconductive substrate [3]. Each PV panel is constructed from various smaller solar cells as illustrated in figure 2.1. As illustrated in figure 2.2, each of these cells create electron(e^-)-hole(h^+) pairs when struck by the sunlight and in effect form an electrical current.

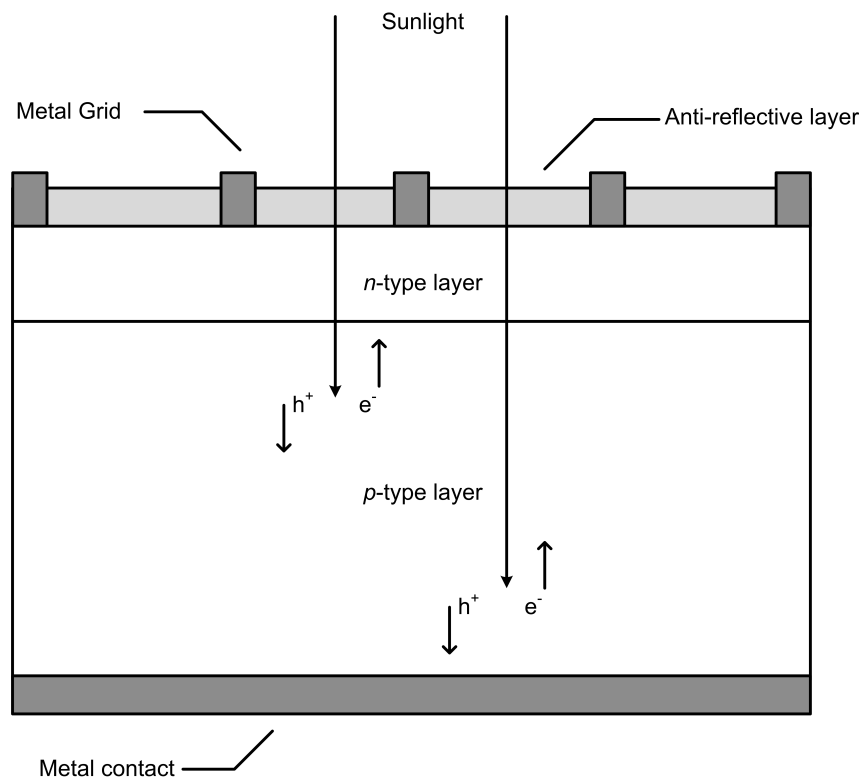


Figure 2.2: Schematic representation of a conventional solar cell [3]

It is important to note that figure 2.2 merely represents a conventional solar cell. There are however various different types of PV cells that operate on the same fundamental principles, but vary in composition and efficiency due to material constraints. There are 4 basic PV cell designs [21]:

- Homojunction devices:

A single material, usually crystalline silicon, is modified to create a p/n junction where one side is dominated by positive holes called the p -type, and the other side dominated by negative electrons which is aptly labelled n -type material;

- Heterojunction devices:

Heterojunction devices are created when contacting different semiconductive materials as is the case with cadmium sulfide and copper indium diselenide;

- p - i - n and n - i - p devices:

Amorphous silicon thin-film cells uses a $p-i-n$ structure while the cadmium

telluride cells uses an $n - i - p$ structure, where i refers to the middle intrinsic layer between the n -type and p -type layers;

- Multijunction devices:

Multijunction devices are constructed of various different individual single-junction cells in a descending order of their bandgaps.

There are currently five key technological areas regarding the construction and materials used in PV cells being researched with the hope of improving the energy conversion efficiencies [21]:

- Crystalline Silicon:

Crystalline silicon PV cells are the most common type of solar cells currently used in commercially available solar panels. The energy conversion efficiency for the laboratory created cells is approximately 25% for single-crystal cells and 20.4% for multi-crystalline cells, while industrially produced modules have average efficiencies ranging from 18% - 24% [21].

- Thin-Film

Thin-film cell construction refers to the manufacturing technique where semi-conductive materials are deposited on a substrate with a thickness ranging from a few nanometer to tens of micrometers.

- Amorphous Silicon (a-Si):

Hydrogenated amorphous silicon ($a - Si : H$) is a type of thin film solar cell that achieve conversion efficiencies of 12.5% on laboratory-scale cells while the high-volume manufactured cells' efficiencies range from 6% to 9%. Despite the lower efficiencies when compared to crystalline silicon cells, the thin-film cells are cheaper, more flexible and lighter.

- Cadmium Telluride (CdTe):

Cadmium Telluride solar cells provide a lower-cost alternative to conventional silicon-based solar technologies due to its fast and inexpensive manufacturing techniques. Laboratory scale CdTe cells have an average efficiency

of approximately 17.3% compared to the commercially available modules with efficiencies ranging from 10% and 12.4%. Following crystalline silicon solar cells, Cadmium telluride solar cells are the second most common PV technology.

- Copper Indium Gallium Diselenide (CIGS):

CIGS solar cells have a high absorption rate capable of absorbing a significant portion of the solar spectrum. The low cost manufacturing technique combined with a laboratory scale efficiency of 20% makes this an attractive option. Commercially available cells have efficiencies typically between 12% to 14%.

- Copper Zinc Tin Sulfide/Selenide (CZTSSe) and Earth-Abundant Materials: CTZS solar cells provide a promising alternative to other resource intensive PV technologies. CTZS solar cells have obtained efficiencies of 10% while using laboratory samples.

- Multijunction (III-V):

The main advantage of multijunction solar cells can be attributed to its cascade design. By combining various individual cells with different band gaps, the multijunction solar cell is able to achieve a higher total conversion efficiency due to the multiple bandgap layers that captures a larger portion of the solar spectrum. These cells have efficiencies of more than 35% when subjected to concentrated sunlight.

- Organic:

Organic PV cells have the aim of using earth-abundant materials in order to provide a less expensive energy technology compared to the previous generations of solar technologies. The efficiencies of these cells are approaching the 10% mark, but suffer from long-term reliability issues.

- Dye-Sensitized:

Dye-sensitized solar cells (DSSC) are made from easy to produce materials and have achieved laboratory efficiencies of 12.3%. DSSCs currently suffer from

low efficiencies and limited durability when compared to some of the other PV technologies.

Table 2.1 provides a summary of the various PV technologies and their associated efficiencies. The outcome of this PV technology survey illustrated that not all PV panels are created equally. Although there are certain cheaper PV panels, they may not be as effective due to the materials used.

Table 2.1: PV technology summary

STRUCTURE	PANEL TYPE	EFFICIENCY		NOTES
		LAB %	IND. %	
Crystalline panels:				
Homojunction	Single crystal	25	18-24	More maturity technology; Higher efficiency when compared to other mass produced single junction devices;
	Multicrystalline	20.4	18-24	Reliability - 25+ years lifespan
Thin Films:				
p-i-n	Amorphous Sil- icon	12.5	6-9	Flexible substrate; Ligter due to less material; Less expensive substrates;
n-i-p	Cadmium Telluride	17.3	10-12.4	Fast and low-cost manufactur- ing;
Heterojunction	Copper Indium Gallium Diselenide	20	12-14	Wide solar spectrum absorbtion rate;
	Earth- Abundant Materials	10	NS	Low cost materials;
Multi-junction III-V:				
Multijunction devices	Organic Photo- voltaics	NS	10	Low cost due to abundant mate- rials; Flexible substrates;
	Dye-Sensitized Solar Cells	12.3	NS	Low cost due to abundant mate- rials;

PV panel power output and efficiency

The power output of any PV panel is directly related to the amount of solar irradiance incident on the PV panel. The amount of solar irradiance incident on the panel can be negatively affected due to dust and dirt. The deposit of dust and dirt reduces the amount of incident solar irradiation incident on the PV panel. This adversely affects the efficiency of a PV panel and is most pronounced on PV panels that have a low tilt angle relative the the horizon.

The efficiency of PV panels can also be adversely affected by solar degradation in which the materials used to construct the PV panel becomes less effective over time.

The last factor that can have a noticeable effect on the the efficiency of a PV panel is temperature. PV panels have a nominal operating cell temperature (NOCT) defined as the temperature of the PV panel at the conditions of the nominal terrestrial environment (NTE) defined as [22]:

- solar irradiance of $800 \frac{W}{m^2}$;
- an ambient temperature of $20^{\circ}C$;
- an average wind speed of $1 \frac{m}{s}$;
- zero electrical load;
- and the panel normal to the solar noon.

When the ambient temperature is high enough, the panel will operate at a reduced efficiency. This effect is accounted for in the PV model described later in section 3.3.1.

2.3.2 Shading

The inherent nature of a PV panel dictates that it requires solar irradiance to operate. Most PV panels will still operate when exposed to a certain amount of shading, but

with reduced efficiency. Even a small amount of shading, as little as 5-10%, can reduce the power output by over 80% [3].

There are two categories of shading that affect the efficiency of PV panels:

- Near-field shading:

Near-field shading is caused by local obstructions that only affects a portion the PV panel usually caused by other panels or trees.

- Global shading:

Global shading, also called horizon shading, is usually caused by distant hills or large objects that block the direct irradiance beam from the whole array.

Depending on the array configuration, even if only one panel is affected by shading within an array of panels, the whole array will operate at reduced efficiency as if each panel is subjected to the same amount of shading.

It is fairly easy to prevent near-field shading but the effects of global shading is very difficult to mitigate, especially when caused by nature - e.g. a hill casting a long shadow.

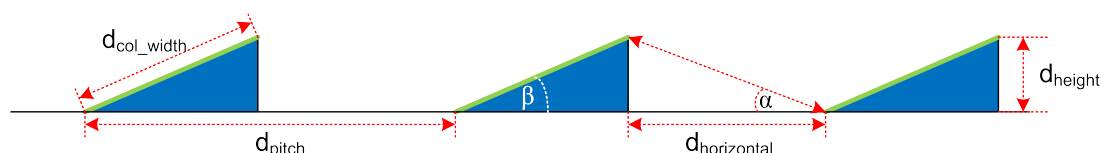


Figure 2.3: PV module array row spacing [3]

Near-field shading becomes a substantial problem when implementing a solar array with multiple rows. This can be overcome by calculating the setback ratio (SBR) which is defined as:

$$SBR = \frac{d_{horizontal}}{d_{height}} \quad (2.1)$$

with the horizontal distance $d_{horizontal}$ between the rows and the vertical distance d_{height} between the high and low sides of adjoining rows as shown in figure 2.3. The norm is

to use a SBR of 2:1 for the lower latitude regions and 3:1 for mid-latitude regions [3]. The various latitude regions are illustrated in figure 2.4.

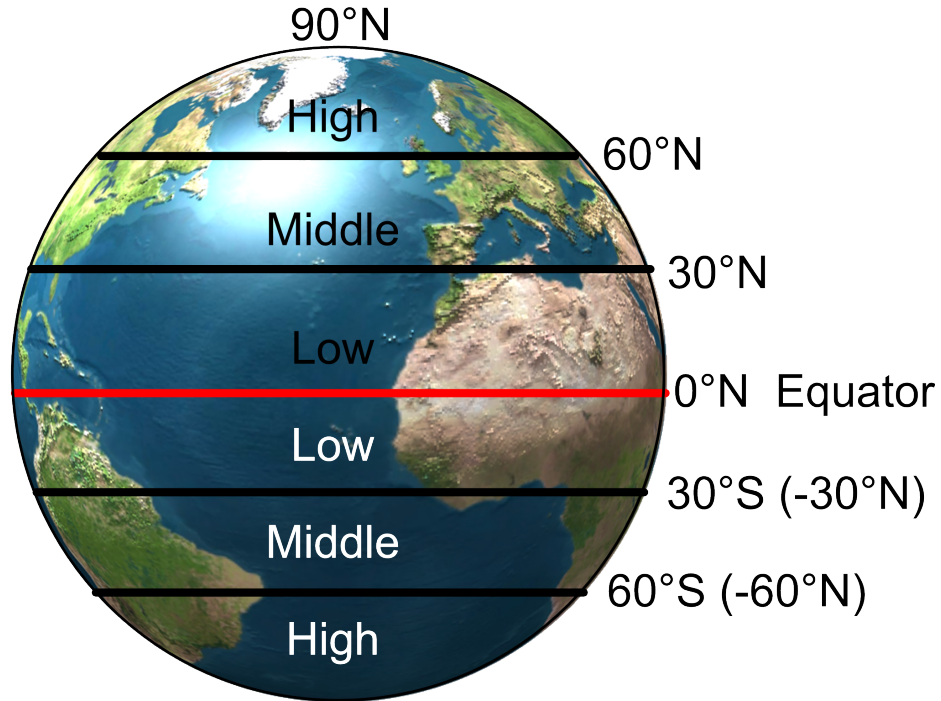


Figure 2.4: SBR Latitude regions [4]

Furthermore the ground cover ratio (GCR) is defined as the array area d_{col_width} divided by the ground area (including the empty row width) d_{pitch} :

$$GCR = \frac{d_{col_width}}{d_{pitch}}. \quad (2.2)$$

2.3.3 Optimal Tilt

The orientation and tilt angle of a PV module has a pronounce impact on the power it will be able to produce. This tilt angle varies with geographical location as well as the changing of the seasons but is also influenced by convenience since it might be cheaper to install a PV panel on a sloped roof.

The various solar angles relative to the observer is shown in figure 2.5. The azimuth angle ψ is defined as the horizontal angle measured in a clockwise direction from the

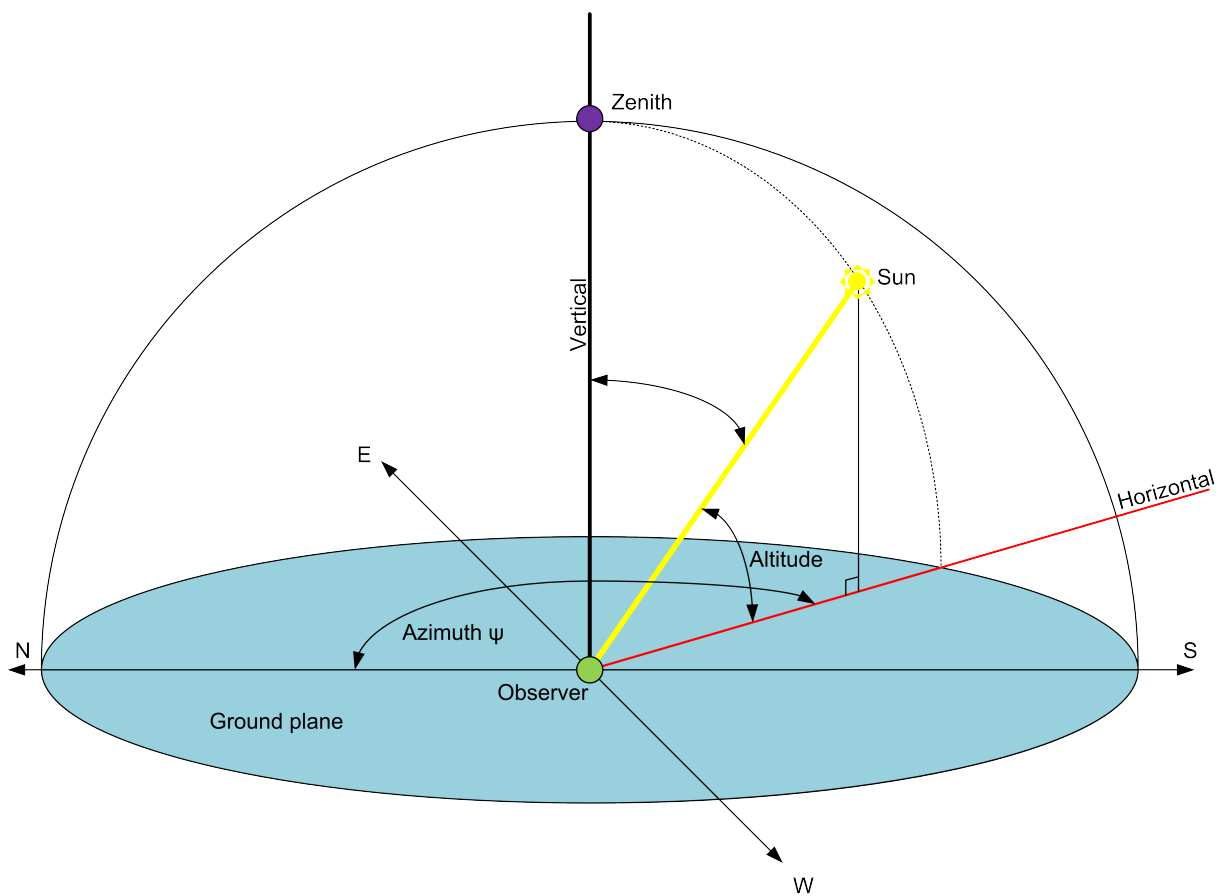


Figure 2.5: Solar angles [5]

meridian line connecting the North and South poles. The point of reference for the azimuth angle is occasionally chosen as the South pole when calculating angles in the northern hemisphere and vice versa for the southern hemisphere. This is due to the fact that PV panels in the northern hemisphere are tilted to face in a southerly direction [23]. The zenith point is an imaginary point directly above the observer, also commonly referred to as solar-noon. A horizontally placed PV panel will receive the optimal solar irradiance when the sun is at its zenith relative to the PV panel.

Depending on the initial capital investment of the solar installation, one can utilize the maximum available solar irradiation with the help of a solar tracking system. This allows the PV panels to track the movement of the sun throughout the day and align the panels accordingly to ensure the maximum amount of incident solar irradiation

reaches the PV panels perpendicularly [23]. According to the case study done by Zhimin Li et al. [24], it was found that by using a dual-axis solar tracker, they achieved a gross radiation gain of 29.3% and a 34.6% power gain for a particular day in July.

2.3.4 Solar Irradiance

In general, when referring to the sun's rays incident on a PV panel, it is called solar irradiation. Solar irradiation is a form of energy measured in $\left(\frac{Wh}{m^2}\right)$, but is commonly confused with solar irradiance which is the power of electromagnetic radiation per unit area incident on a surface measured in $\left(\frac{W}{m^2}\right)$. There is yet another term, solar insolation, that refers to the measure of solar radiation energy received on a given surface area during a certain time duration. When it is recorded for an hour, it is also called solar irradiation. Throughout this document the solar insolation of 1 hour, in effect, solar irradiation, is used.

There are various factors that can influence the radiant energy from the sun before it hits the PV panels. This includes climatological conditions such as cloud density and rainfall for short periods of time. More predictable influences are the earth's atmosphere and changing of the seasons [25].

Surface solar irradiance can be measured with the help of a pyranometer as seen in figure 2.6, but it is only accurate for a small area close to the pyranometer. In order to promote the commercial use of meteorological data, the National Aeronautics and Space Administration (NASA) continually supports the development of the Surface meteorology and Solar Energy (SSE) dataset. The SSE dataset has been specifically formulated for PV system design needs. One of the main advantage of the SSE dataset lies in the fact that the global meteorological and solar radiation data were obtained from the NASA Science Mission Directorate's satellite and re-analysis research programs [26]. The NASA data provides monthly regional averages of the insolation incident on a horizontal surface $\left(\frac{kWh}{m^2 \cdot day}\right)$ for each latitude and longitude.

Figure 2.7 indicates how the incident solar irradiance is divided into 3 sub categories:



Figure 2.6: Hukseflux SR03 pyranometer [6]

- Incident irradiation $S_{incident}$:
Solar radiation directly from the sun;
- Diffuse (indirect) irradiation $S_{diffuse}$:
The diffuse component is caused by reflection and scattering of light in the earth's atmosphere;
- Reflected irradiation $S_{reflected}$:
The sunlight reflected from surrounding objects.

The effective hours of sunshine is a term used to denote the average hours of "full sun" when the solar insolation is $1000 \frac{W}{m^2}$ or more as illustrated in figure 2.8 [5]. It is important to note that the average of effective sunlight hours may vary from location to location as well as the different seasons. It is common practise to approximate the graph in figure 2.8 and calculate an integer value e.g. 5.5 hours of effective sunlight hours per day for the site.

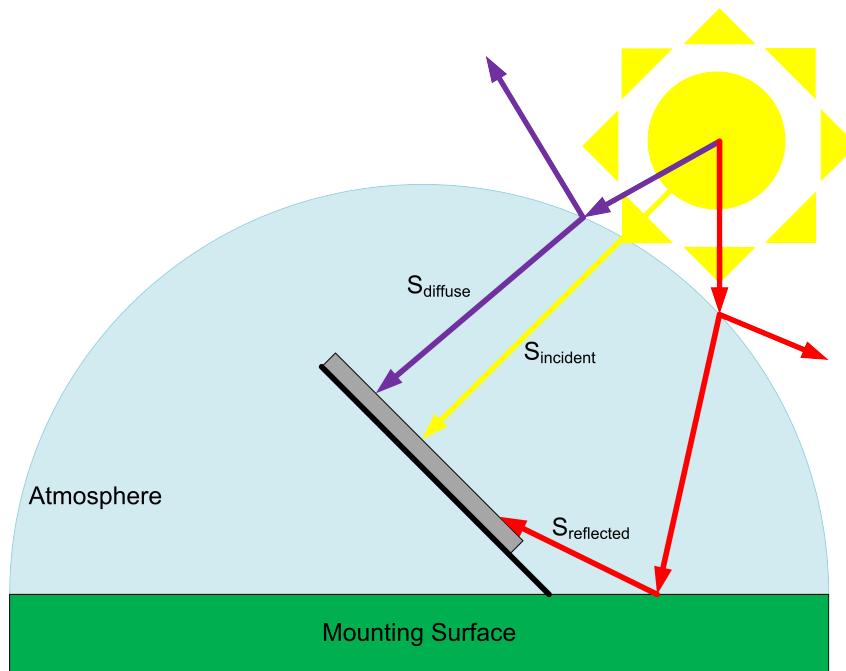


Figure 2.7: Incident solar irradiation angles

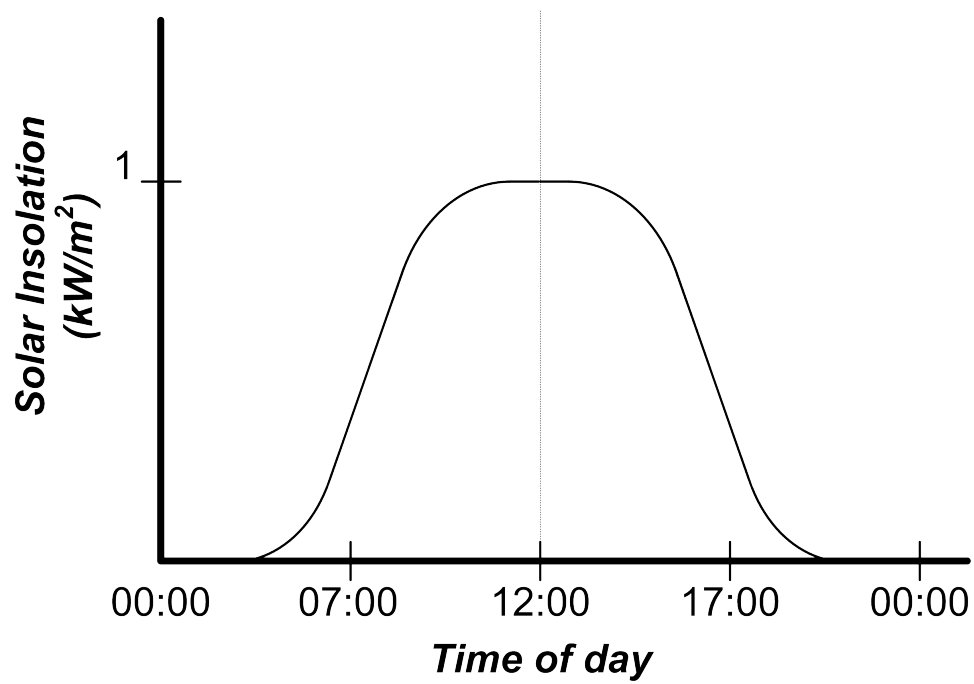


Figure 2.8: Daily variation in solar insolation

2.4 Wind

2.4.1 Wind Turbines

Wind turbine overview

Windmills have been around for many years, mainly used to grind grain or to pump water. Modern day wind turbines, as illustrated in figure 2.9, work on the same basic principles - to harness the winds' kinetic energy by means of blades and convert it into mechanical energy. The main difference between traditional windmills and modern wind turbines, apart from the construction and physical size, lies in how this mechanical energy is applied. Modern day turbines utilise this mechanical energy from the wind to drive an electric generator which in turn generates electrical power.



Figure 2.9: Vestas V112-3MW Wind turbine Courtesy of Vestas Wind Systems A/S [7]

Wind turbine mechanics

Modern wind turbines are constructed from various composite materials in order to endure the rigorous environment and stresses it will be subjected to. The Vestas V164-7MW turbine is an example of one of the larger wind turbines, with a nacelle height of approximately 107m (depending on the site) and a blade length of 80m per blade. Thus the 164m rotor diameter (blade length as well as nacelle diameter) offers a swept area of more than $21,000m^2$ with a total turbine height of approximately 200m [7].

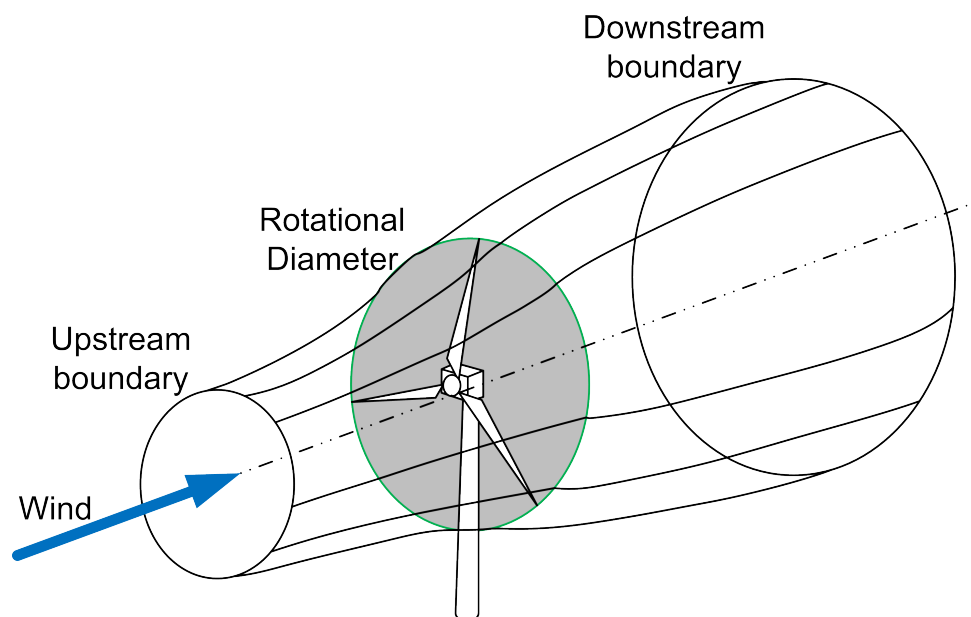


Figure 2.10: The energy extracting stream-tube of a wind turbine [8]

The wind's kinetic energy is converted to mechanical energy when the wind turns the turbine's blades, but in doing so, it slows down the wind. A boundary surface can be drawn that contains the mass of air affected by the turbine blades, assuming that it remains separate from the surrounding air which didn't pass through the rotor disc as illustrated in figure 2.10. Since the air within the tube is slowed down, but not compressed, it occupies a larger area. It is thus very important to take the size of a wind turbine into account when designing a wind farm to ensure each turbine will have a stream of undisturbed air.

Wind turbine types

Wind turbines can be divided into two main categories namely horizontal axis and vertical axis wind turbines as shown in figure 2.11. Both types of turbines harness the wind by means of blades in order to turn a generator, but differ with regard to the axis about which the blades revolve. Vertical axis wind turbines (VAWT) have the advantage of producing less noise than horizontal axis wind turbines (HAWT), but have several drawbacks. The main two are the lower efficiency due to the VAWT's low rotor position close to the ground, as well as the greater material expenditure per square meter of surface covered when compared to HAWTs [27]. The most common turbine type is the HAWTs as shown in figure 2.9. All of the wind turbines in this category consists of the same basic components as listed below:

- Mast, shaft or tower;
- Nacelle - or sometimes referred to as the hub that encloses the gears and electric generator;
- Blades - the blades are connected to the nacelle in order to harness the kinetic energy in the wind.

2.4.2 Wind speed modelling

In order to calculate the probable power output of a wind turbine at a given geographic location, one needs to know what the wind trends are. This is complicated by the variability of the wind speed. There is a common misconception when referring to this variability. Many people refer to the 'intermittent' nature of the wind which would indicate starting and completely stopping. This is however not the case. The wind speed actually fluctuates continuously, thus voiding the use of an average wind speed for accurate analysis of a site. In this section the Weibull Probability Density Function (PDF) technique for wind speed estimation is described.

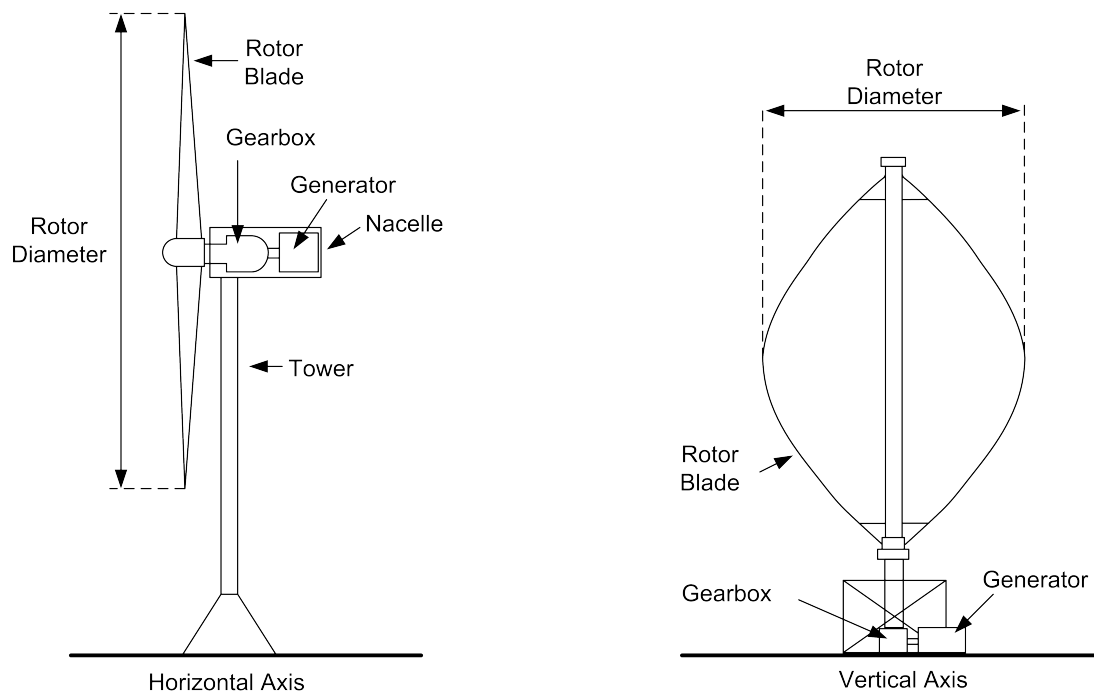


Figure 2.11: Wind turbine type comparison [9]

Data acquisition

An anemometer is a device used to measure the unobstructed flow of wind. The Wind Atlas of South Africa (WASA) project has constructed numerous meteorological masts across South Africa to monitor and record wind related data. The main advantage of these masts as seen in figure 2.12, is that they measure the wind velocity at 5 different heights. The schematic is a generic representation of the masts used at the various sites, which were commissioned at different dates as indicated by xx. The wind data used for the simulation was obtained with permission from WASA [10].

Weibull

Due to the fluctuating nature of wind, it is difficult to predict the wind speed. A simple approach entails using the average wind speed over long periods. This poses a problem of accuracy since wind turbine generators' power output varies with the wind speed.

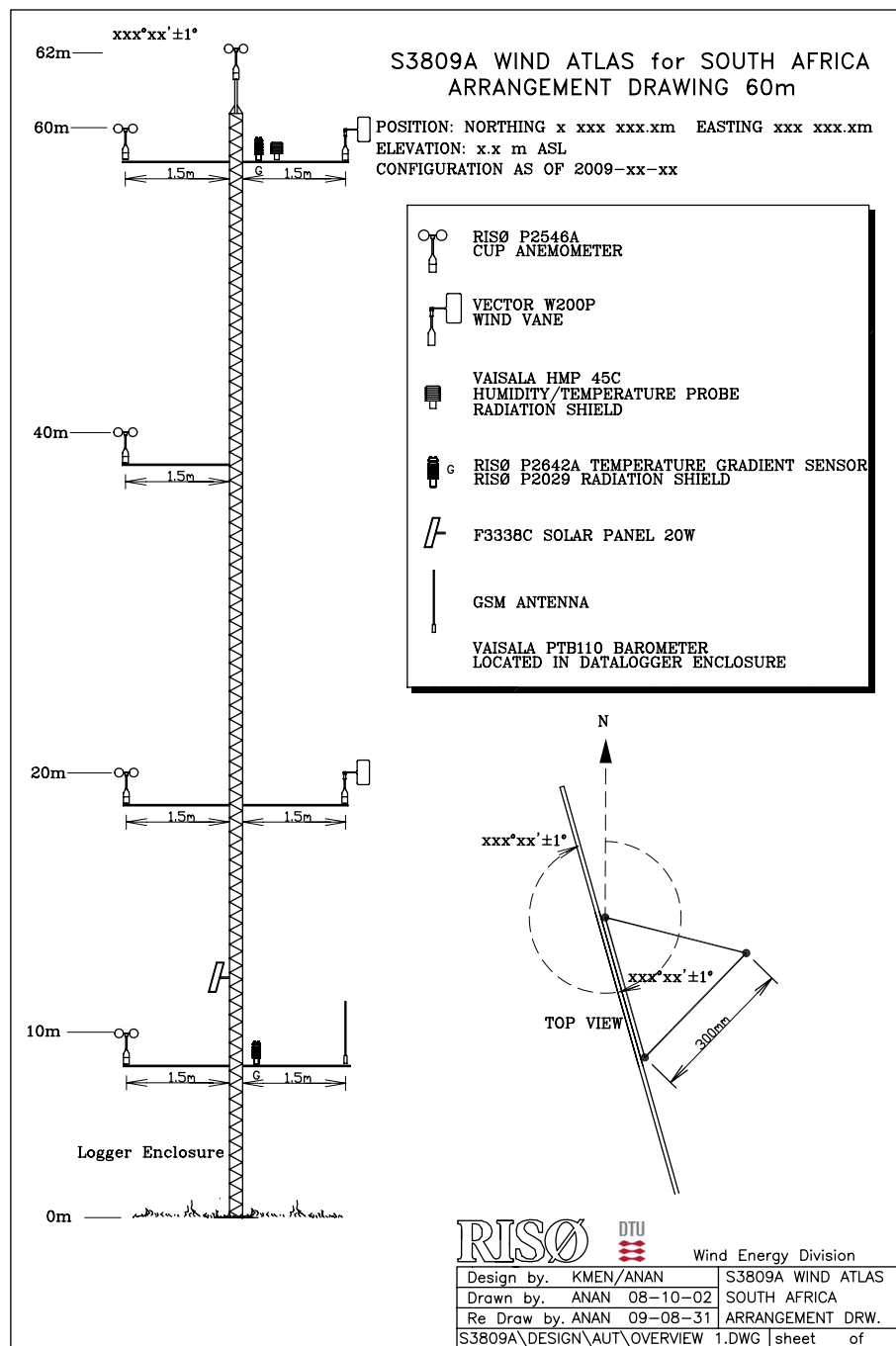


Figure 2.12: Technical document depicting one of the WASA towers [10]

One way of overcoming this hurdle is to implement the Weibull distribution to model the wind speed data. The Weibull distribution provides a statistical distribution depicting the probability of encountering each possible outcome of a random experiment, in this case the probability of encountering a certain wind speed based on historical data. The Weibull PDF does not just provide the average wind speed, but rather the probability of encountering each wind speed. This wind speed probability is later used to determine the probable power output of the wind turbines.

When drawing a histogram of the wind speed data, using an adequate bin width Δx , one is left with a frequency distribution showing how many observations fall within each bin, essentially providing an estimation of the probability distribution of the data.

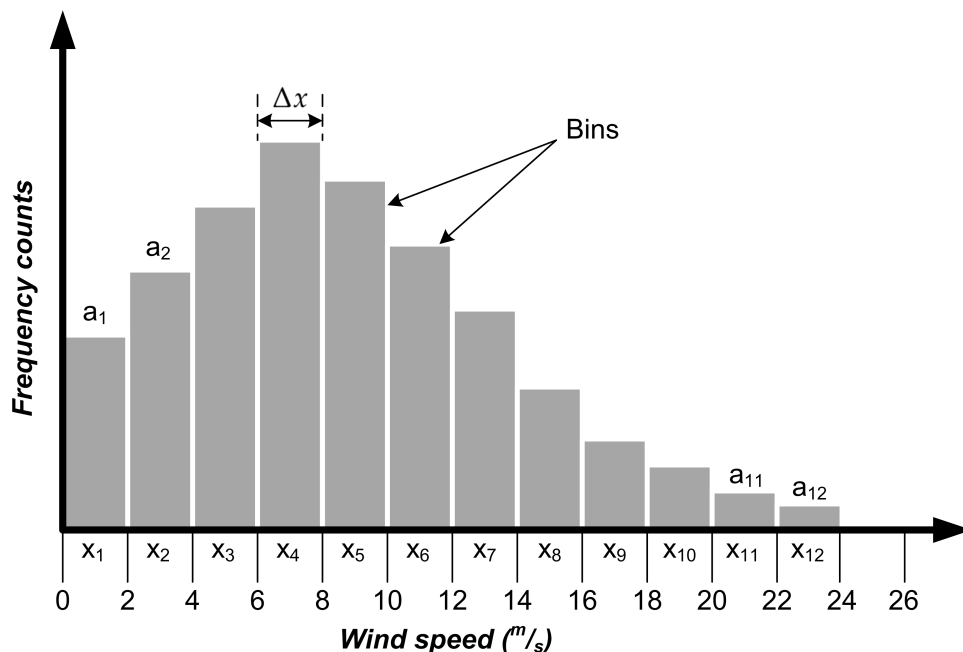


Figure 2.13: Histogram illustration with a bin width Δx of $2\frac{m}{s}$ for 12 bins

Serratos et al. [28] proposed to define the histogram function by letting x be a measurement which can have one of T values which is contained within the set $X = \{x_1, \dots, x_T\}$ as shown in figure 2.13. Considering a set of n elements whose measurements of the value of x are $A = \{a_1, \dots, a_n\}$ where $a_t \in X$, then $H(x, A)$, or simply $H(A)$, is the histogram of the set A along the measurement x , which is a list containing the number of discrete occurrences, of the discrete values of x amongst the

a_t . Thus if $H_i(A)$, with $1 \leq i \leq T$, denotes the number of elements in A that have a value x_i , then $H(A) = [H_1(A), \dots, H_T(A)]$ where

$$H_i(A) = \sum_{t=1}^n C_{i,t}^A \quad (2.3)$$

and the individual costs are defined as

$$C_{i,t}^A = \begin{cases} 1 & \text{if } a_t = x_i \\ 0 & \text{otherwise.} \end{cases} \quad (2.4)$$

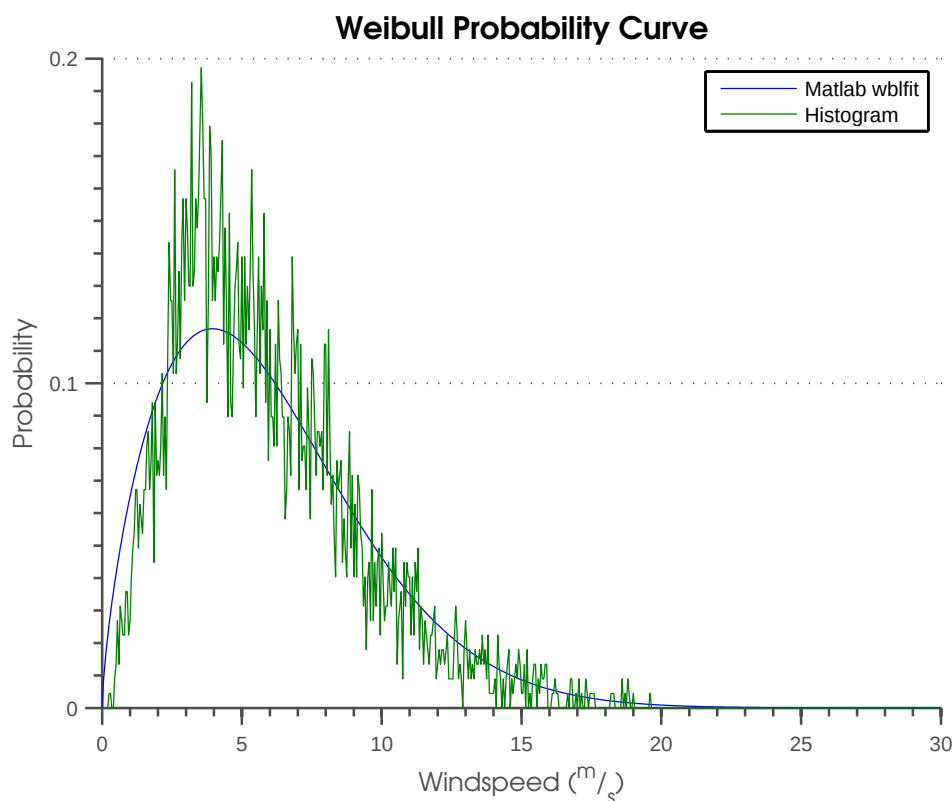


Figure 2.14: Weibull probability curve overlaid on the data's normalised histogram

To summarize and simplify the histogram function, A is a list containing the frequency counts of the values within each bin for the values of X . Histograms are generally graphed using bars to represent each bin, but in figure 2.14 the values have been graphed using a normal line plot in order to compare it with the Weibull distribution of the wind data. It is clear from figure 2.14 that the Weibull probability function is a good representation of the raw wind data.

The Weibull PDF thus provides a statistical representation of the probability that a certain wind speed will occur based on parameters calculated from long term meteorological data.

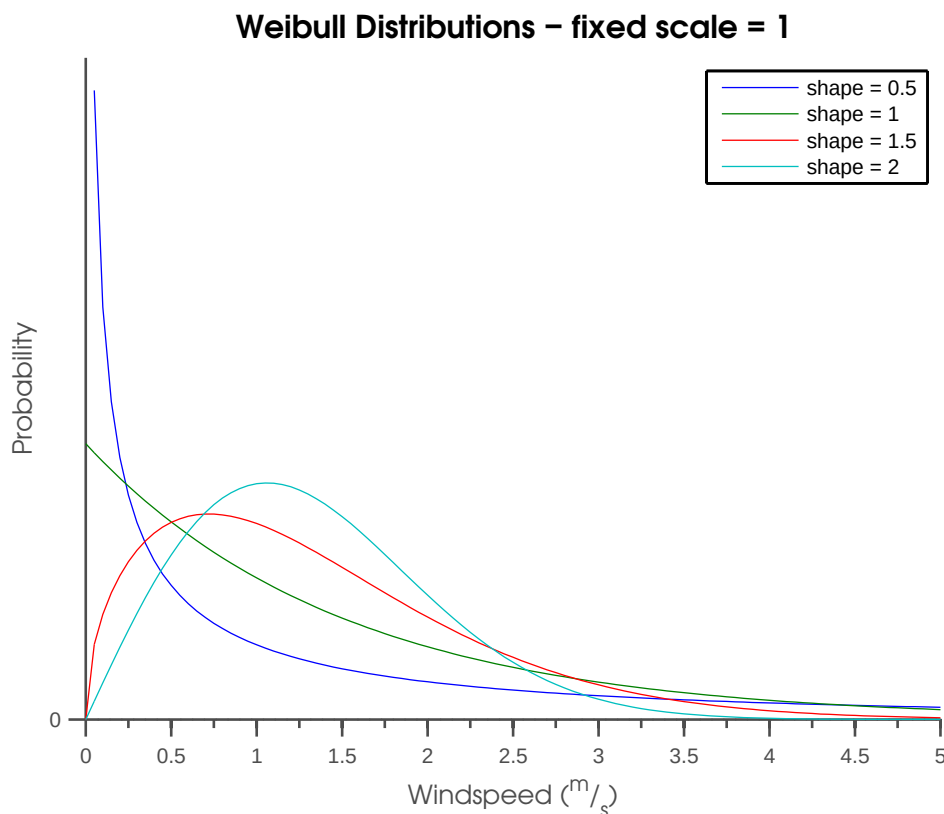


Figure 2.15: Weibull probability curves for a variable shape parameter

The two parameter Weibull probability function $f(v)$ for observing a wind speed v is expressed by:

$$f_{Weibull}(v) = \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} \quad (2.5)$$

where k is a dimensionless shape parameter and c the scale parameter with the same unit as the wind speed [29]. The effects of the shape parameter can be seen in figure 2.15 while the scale parameter was kept constant. A similar analysis of the scale parameter can be seen in figure 2.16.

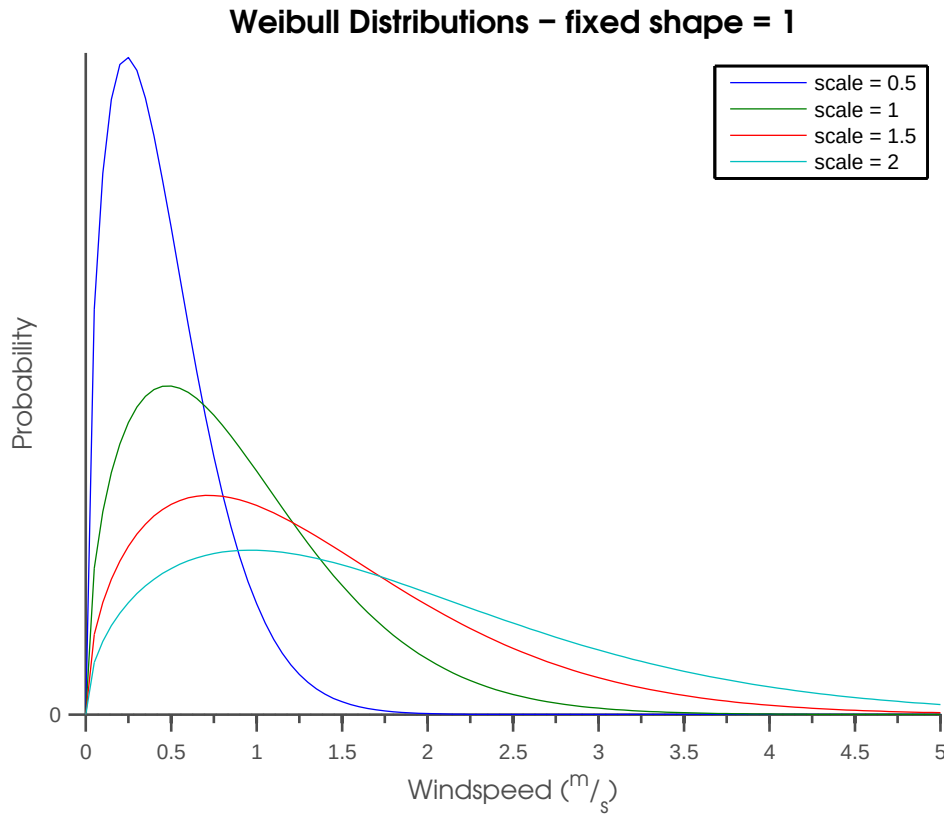


Figure 2.16: Weibull probability curves for a variable scale parameter

There are various methods that can be used to determine the value of these parameters, each with their respective pros and cons [30]:

- Graphical method:

This method is simple to use but involves a great probability of error;

- Analytical methods:

- *Maximum Likelihood Estimation (MLE):*

The MLE method is commonly used in literature and consists of two equations. The shape parameter k can be calculated by iteratively implementing equation 2.6 [31]:

$$k = \left(\frac{\sum_{i=1}^n v_i^k \ln(v_i)}{\sum_{i=1}^n v_i^k} - \frac{\sum_{i=1}^n \ln(v_i)}{n} \right)^{-1} \quad (2.6)$$

with a suitable initial guess of $k = 2$. It is important to note that this method only functions with non-zero data values. Following the shape parameter, one can calculate the the scale parameter c :

$$c = \left(\frac{1}{n} \sum_{i=1}^n v_i^k \right)^{\frac{1}{k}}. \quad (2.7)$$

The MLE method is asymptotically consistent implying that the parameter estimates converges to the right values as the sample size increases, however the method may not be very accurate with small sample sizes [32]. As a rule of thumb, a small sample size is defined as less than 30 observations per parameter [33];

– *Method of moments (MOM):*

The method of moments parameter estimation technique is commonly used and at first glance looks similar to the MLE method's equation 2.7. If the data set contains a series of numbers $v_1, v_2, \dots, v_n$, then an unbiased estimator for the k^{th} origin moment is:

$$\hat{m}_k = \frac{1}{n} \sum_{i=1}^n v_i^k \quad (2.8)$$

where $\hat{m}_k$ is an estimate of the moment m_k . The MOM method has many additional calculations as listed in Al-Fawzan et al. [30], that are computational intensive without necessarily providing a substantial increase in parameter accuracy.

Thus the preferred method for parameter estimation, based on computational time and accuracy thereof, is the MLE method.

Power calculation

The previously calculated Weibull distribution of the wind speeds, can now be applied to help determine the probable power output of the wind turbines. This can be approached by firstly calculating the theoretical amount of power available in the wind

and then how much of that power can be extracted by a wind turbine based on its dimensions.

The theoretical power P (W) available in the wind can be expressed as follows [34]:

$$P = \frac{1}{2} \rho A v^3 \quad (2.9)$$

where ρ is the density of air $\left(\frac{\text{kg}}{\text{m}^3}\right)$ that flows perpendicular to an area A (m^2) with a velocity v $\left(\frac{\text{m}}{\text{s}}\right)$. It is important to note that the density of air varies with altitude and temperature. When using equation 2.9 to calculate the theoretical power available in the wind, one must take the Lanchester-Betz limit into account. The Lanchester-Betz limit states that the maximum amount of energy one can extract from the wind is 59.3% of the power available in the wind under ideal conditions [35].

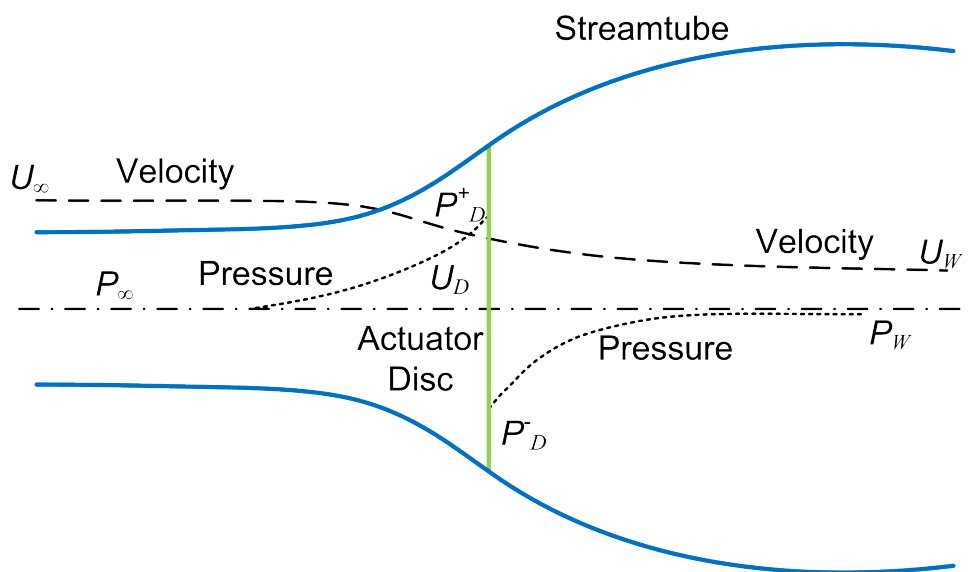


Figure 2.17: An energy extracting actuator disc and stream-tube [8]

Since the mass flow rate of the air must be the same everywhere along the stream-tube as shown in figure 2.17, the following equation holds true:

$$\rho A_{\infty} U_{\infty} = \rho A_D U_D = \rho A_W U_W \quad (2.10)$$

where A is the cross-sectional area of the turbine rotor disc and U the air flow velocity. In effect, equation 2.10 represents a form of the law of conservation of energy which

states that the energy in an isolated system remains constant over time. Thus the derivation in Burton et al. [8] states that the density of the air ρ through a cross-sectional A with an air-flow velocity U stays the same far upstream denoted by the subscript ∞ , at the rotor disc D and in the far wake behind the rotor disc W .

There is an alternate method to calculate the power output of a turbine without having to specifically calculate the Lanchester-Betz limit. The power curve of a wind turbine as shown in figure 2.18, displays the power output for that specific turbine configuration for each corresponding wind speed. There are four main phases of power generation

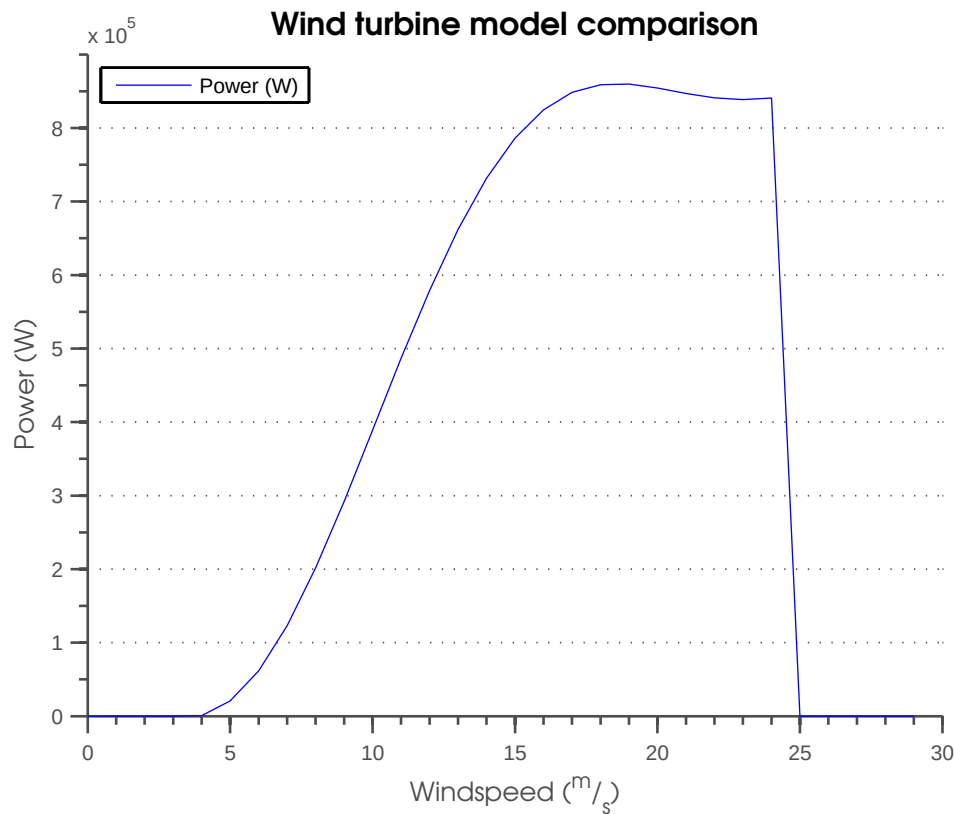


Figure 2.18: Power curve of wind turbine

of a wind turbine:

- $0 \rightarrow v_{ci}$ no generation;
- $v_{ci} \rightarrow v_r$ maximum rotor efficiency;

- $v_r \rightarrow v_{co}$ nominal power generation with reduced rotor efficiency;
- $v_{co} \rightarrow \infty$ no generation.

The cut-in speed of the turbine v_{ci} is the minimum speed at which the turbine will start generating power. The range between the cut-in speed and the rated wind speed v_r is generally proportionate to the cube of the wind speed (v^3). The optimal operation phase of the wind turbine is in the range between the rated wind speed v_r and the cut-out speed v_{co} where the wind turbine will produce its rated power output. It is important to note that when the wind speed is greater than the cut-out speed, the turbine ceases to produce power as a safety precaution.

Since the Weibull PDF provides the probability of each wind speed being present as shown in figure 2.14, and the power curve indicates what power will be available at each wind speed shown in figure 2.18, one can multiply these two graphs to obtain a wind turbine power probability graph [36] as seen in figure 2.19.

2.4.3 Data resolution

Data resolution provides a measure of the observation frequency at which the data is logged. It is widely accepted throughout the literature that a data resolution of 1 hour intervals provides satisfactory accuracy when working with wind data [37]. It is important to note that when working with data that is recorded at such short intervals, might suggest dependence, and in doing so, violate the criteria for the majority of statistical tests and procedures [34]. Dependence implies the statistical relationship between data two random data events, e.g. wind speed. Time dependent data implies that the closer the measurement intervals are, the more likely the data will be resemble the previous data. Most statistical methods require random data samples, hence no dependent data.

The data resolution's effect on the power output of wind turbine as well as the determination of the optimal data resolution is discussed in section 4.2.

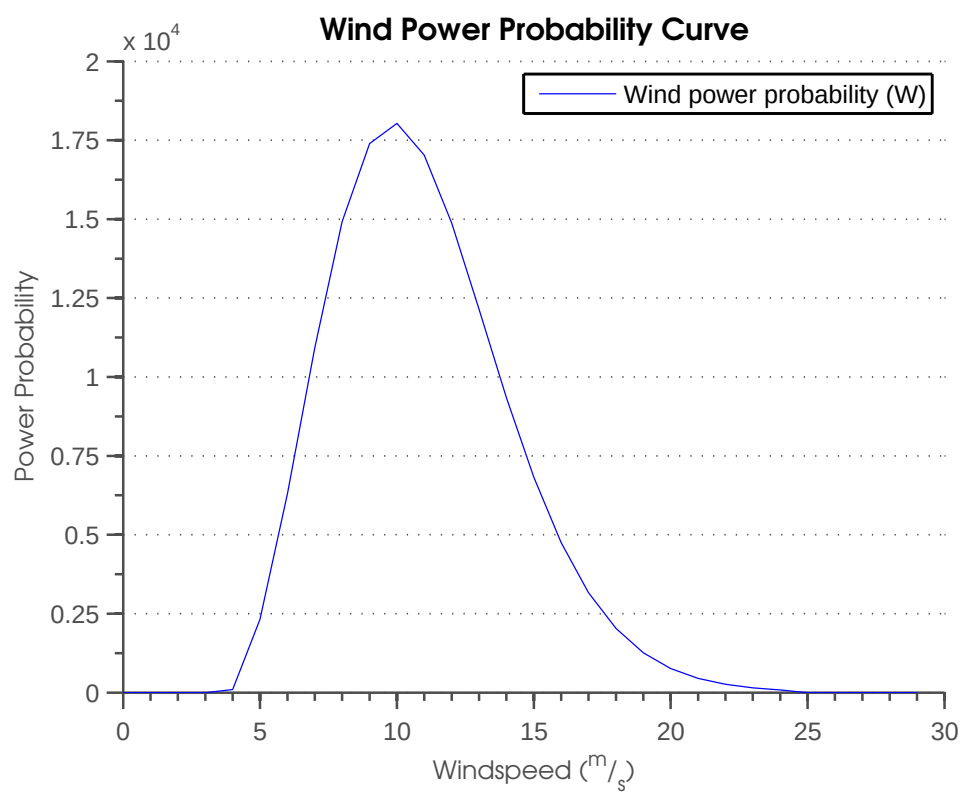


Figure 2.19: Wind turbine power probability graph