

Chapter 3

Component modelling

This chapter provides a breakdown of the various functional units and their associated interfaces that comprise the simulation application. Furthermore this chapter provides a technical assessment of the mathematical models and procedures implemented within these functional units as to simulate the various system components.

3.1 System modelling

A functional flow analysis of the simulation software helps to identify the system's behaviour while taking into account the possible branches in the primary process flow due to choices made by the user by means of input variables. The simplified functional flow analysis of the system, as seen in figure 3.1, indicates a linear program flow with a recursive loop being formed for the system optimization. The financial module does not form part of the main program flow, but can be interfaced to provide additional criteria for the system optimization.

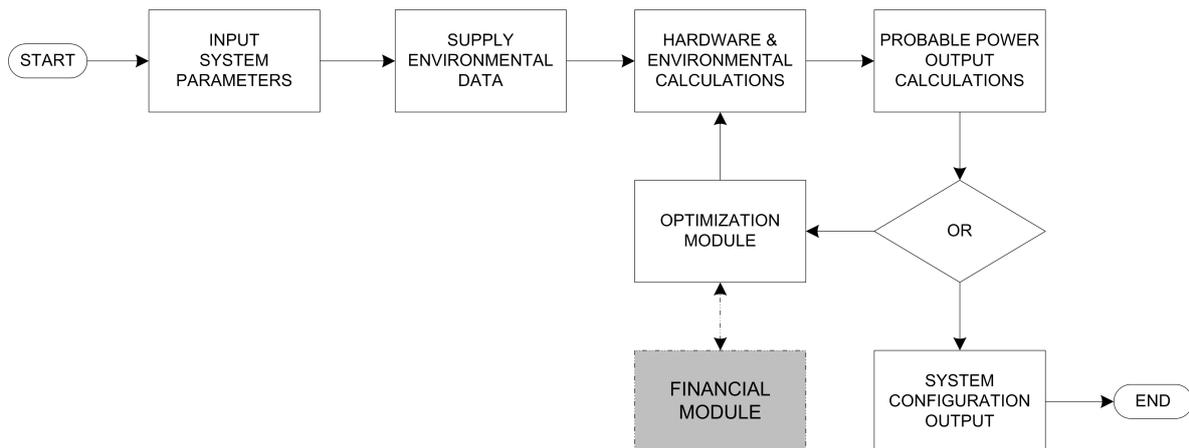


Figure 3.1: Simplified functional flow of the simulation program

3.2 Functional Architecture

The functional architecture analysis of the system divides the system into the various functional units (*F/U*) and identifies the interfaces (*I/F*) associated with them as illustrated in figure 3.2.

F/U 1 - User Input

F/U 1 contains all the GUI units that provide the user with a means to specify various operating parameters for the simulation. This includes the following parameters:

- 1.1 - Power requirements of the main system components e.g. PEM electrolyser as well as control and ventilation components;
- 1.2 - The losses module allows the user to specify the losses in the wires, the loss factor due to dust and dirt with regard to the PV panels, turbine mechanical losses and other general losses;
- 1.3 - System autonomy refer to the system's ability to remain functional in the absence of input power;
- 1.4 - PV panel parameters of a specific PV panel are required to calculate the probable power output of a certain PV panel. This is done due to the general

difference between the manufacturers' specified power output, and the actual power output of the PV panel;

- 1.5 - The wind turbine parameters entails the technical parameters pertaining to the physical dimensions (hub height, blade length, etc.) as well as the power output of the wind turbine generator (turbine power curve);
- 1.6 - The solar data functional unit reads a text file containing the global horizontal radiation solar data. It is not required by the user to manually enter the data, merely to supply the model with the updated data file as found on
<http://eosweb.larc.nasa.gov/cgi-bin/sse/global.cgi?> ;
- 1.7 - Unlike the solar data, there is no *universal* source of wind data containing adequate wind observations in existence. Wind data is very site specific and needs to be specifically supplied to the model in the form of .csv files. This data is ideally measured at the intended location for a long term (minimum of 1 year), or as previously stated, this data can be obtained from meteorological or similar institutions.

F/U 2 - Calculations

F/U 2 contains the subroutines that perform the majority of the calculations in the simulation program:

- 2.1 - The total power requirements module calculates the power required by the main system components while factoring in the power required to account for losses due to e.g. hardware degrading;
- 2.2 - Battery bank calculations entails the sizing and configuration of the battery bank based on the system autonomy specifications;
- 2.3 - The solar calculations module calculates both the probable power output of the PV panel as well as the optimal tilt angle for maximum efficiency;
- 2.4 - The wind calculations process the wind data while creating the power curve of the wind turbine generator.

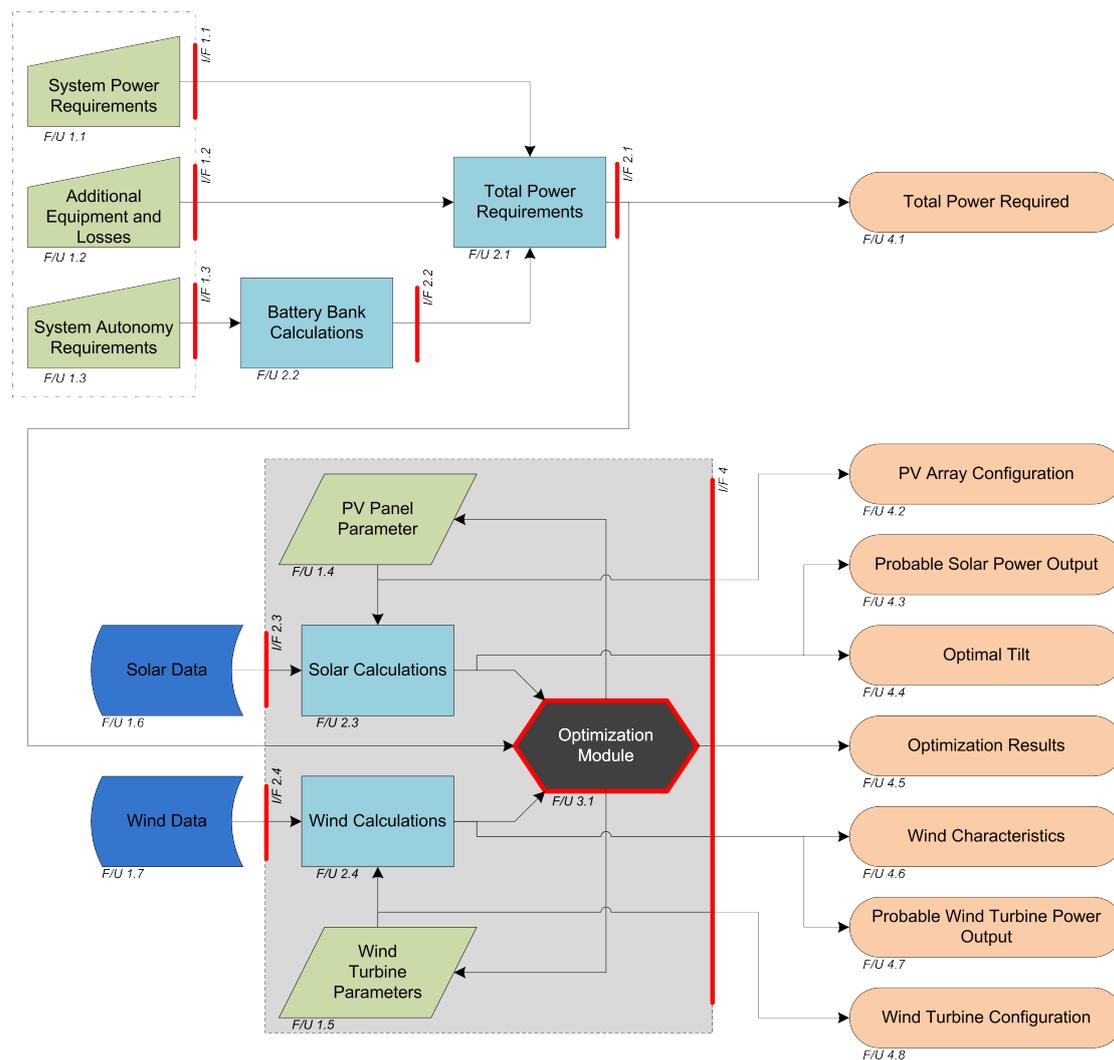


Figure 3.2: Intermediate level functional architecture diagram

F/U 3 - Optimization module

The optimization module is tasked with optimizing the renewable energy system's wind-to-solar ratio. This optimization is based upon the premise of supplying the maximum amount of energy while occupying the least amount of space while trying to minimize the cost of the system. Figure 3.3 provides a more detailed view of the optimization module.

F/U 4 - Output module

Rather than having only one final output module for the simulation model, the outputs will be displayed where they are relevant during the simulation.

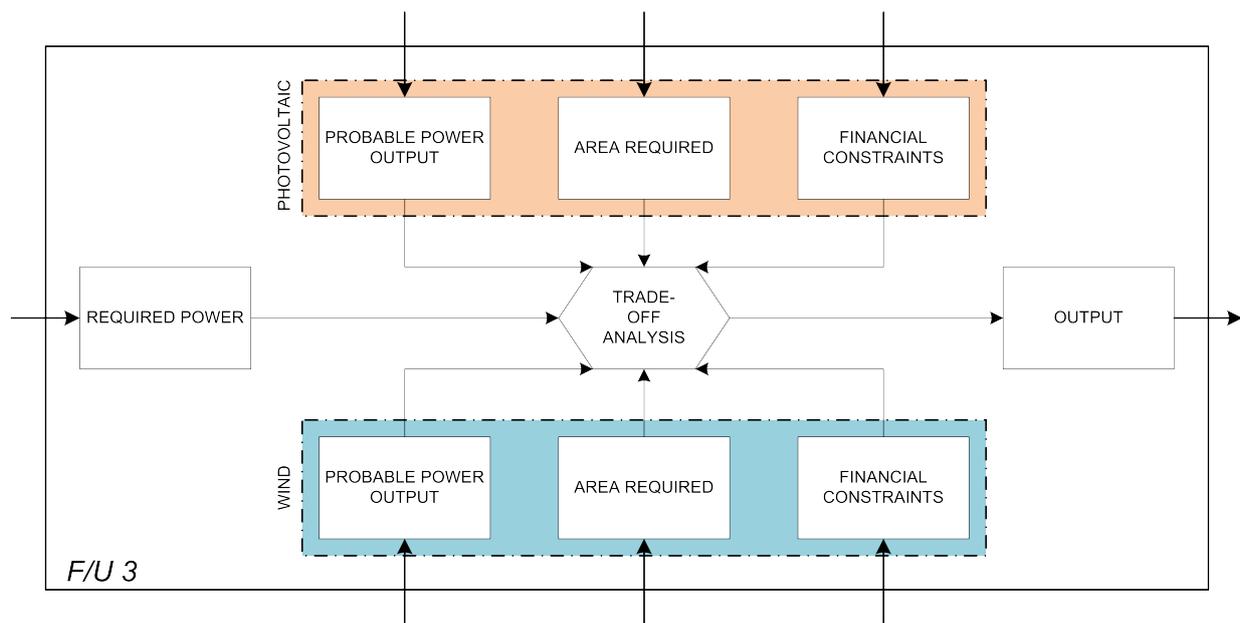


Figure 3.3: Architectural analysis of F/U 3 - Optimization module

3.3 Hardware modelling

3.3.1 PV panel

The rapid expansion of the renewable energy market has brought forth many new PV panel producers world wide. Although there are standards to govern the manufacturing and testing of these PV panels, it has been observed that the PV panels' power output may vary from the manufacturers' specifications. This variance can likely be attributed to the differences in operating conditions.

The model for the PV panels as presented by Belfkira et al. [1], was selected to simulate the PV panels due to the fact that it accounts for the losses incurred due to temperature. Other models such as the two-diode model proposed by Ishaque et al. [38] was considered for the simulation, but was decided against due to its overwhelming mathematics that require technical data of the PV panels that are not readily available. In order to calculate the PV panel's power (P_{mpp}) at the maximum

power point denoted by the subscript $_{mpp}$, one needs to calculate the PV panel current I_{mpp} and PV panel voltage V_{mpp} as shown in the following equation:

$$P_{mpp} = I_{mpp} \cdot V_{mpp} \quad (3.1)$$

where

$$V_{mpp} = V_{max} + \mu_{v,oc} \cdot \Delta T. \quad (3.2)$$

All the parameters required for these calculations can be found in the PV panel's datasheet, with the nomenclature discussed in table 3.1.

The subsequent equations have been factorised to simplify the equations resulting in the following:

$$C_1 = \left(1 - \frac{I_{max}}{I_{SC}}\right) \cdot \exp\left(-\frac{V_{max}}{C_2 \cdot V_{OC}}\right) \quad (3.3)$$

and

$$C_2 = \left(\frac{V_{max}}{V_{OC}} - 1\right) \cdot \left[\ln\left(1 - \frac{I_{max}}{I_{SC}}\right)\right]^{-1}. \quad (3.4)$$

Table 3.1: PV Panel nomenclature

SYMBOL	UNIT	DESCRIPTION
I_{max}	A	The maximum PV panel current under reference conditions
I_{SC}	A	The short circuit current of a PV panel
V_{max}	V	The maximum voltage of a PV panel under reference conditions
V_{OC}	V	The open circuit voltage of a PV panel
G_T	$\frac{W}{m^2}$	Hourly irradiance on a tilted surface
G_{ref}	$\frac{W}{m^2}$	The irradiance at the reference operating conditions equal to $1000 \frac{W}{m^2}$
$\mu_{v,oc}$	$\frac{V}{^\circ C}$	Open circuit voltage temperature coefficient
$\mu_{I,SC}$	$\frac{I}{^\circ C}$	Short circuit current temperature coefficient
T_c	$^\circ C$	Operating temperature of the PV panel
$T_{c,ref}$	$^\circ C$	Temperature of the PV panel under reference operating conditions ($25^\circ C$)
T_a	$^\circ C$	Ambient temperature of the site
$NOCT$	$^\circ C$	Nominal Operating Cell Temperature

The current variation due to the temperature effects can then be calculated by

$$\Delta I = I_{SC} \cdot \left(\frac{G_T}{G_{ref}} - 1 \right) + \mu_{I,SC} \cdot \Delta T \quad (3.5)$$

where the temperature difference between the operating temperature T_c and the reference temperature $T_{c,ref}$ of the PV panel is calculated by

$$\Delta T = T_c - T_{c,ref}. \quad (3.6)$$

Markvar et al. [39] expressed the operating temperature of the PV panel as:

$$T_c = T_a + \frac{NOCT - 20}{800} \cdot G_T \quad (3.7)$$

where the normal operating cell temperature (NOCT) is defined as the mean solar cell junction temperature with an open back, rack mounted module in a standard reference environment (SRE) [40]. This provides a reference of how the PV panel will operate under actual conditions. The SRE refers to an environment satisfying the following conditions:

- tilt angle normal to the incident solar beam at solar noon;
- $800 \frac{W}{m^2}$ irradiance;
- ambient temperature of $20^\circ C$;
- wind speed of $1 \frac{m}{s}$;
- no electrical load.

Finally one can calculate the PV panel's current I_{mpp} at the maximum power point as follows:

$$I_{mpp} = I_{sc} \cdot \left\{ 1 - C_1 \cdot \left[\exp \left(\frac{V_{max}}{C_2 \cdot V_{OC}} \right) - 1 \right] \right\} + \Delta I. \quad (3.8)$$

One draw back of this model is that it doesn't account for shading on the PV panels. It is beneficial to account for PV panel placing in order to ensure that the alignment of the

PV panels do not cause shading on the other panels. In order to prevent shading of the PV panels as discussed in section 2.3.2, one can place the PV panels in a strategic grid layout by calculating the setback ratio (SBR) with equation 2.1 and the ground cover ratio (GCR) with equation 2.2.

It is important to note that the calculations require the amount of direct solar irradiance perpendicular to the PV panels as an input. This can be determined by calculating the optimal tilt angle for the PV panels as mentioned in section 2.4.2.

3.3.2 Wind turbine

The wind turbine model will allow the user to generate a representation of a wind turbine's power curve. A power curve provides a visual representation of the power output of the given generator for a corresponding wind speed. There are various functions that represent this power curve, with varying degrees of accuracy. The power curve is later used to estimate the probable power output of the wind turbine based on the location's wind speeds as modelled by the Weibull curves discussed later in section 3.4.2.

The wind module is capable of generating a wind turbine power curve using one of the methods listed below:

- Polynomial:

Most wind turbine manufacturers provide a power curve graph illustrating the power output for a corresponding wind speed. By fitting a polynomial curve to the data, one is left with an accurate mathematical representation of the turbine's power curve. Based on simulations in Matlab and approximations done in Microsoft Excel, it has been found that a 6th order polynomial provides the best approximation of the manufacturers' power curve as illustrated in figure 3.4:

$$P_i(v) = \left(b_i v^i + b_{i-1} v^{i-1} + \dots + b_3 v^3 + b_2 v^2 + b_1 v + b_0 \right) \quad (3.9)$$

where $b_i \in \mathbb{R}$ for any $i \in \mathbb{Z}^+$. The 6th order polynomial's output in figure 3.4 is the closest to the actual wind turbine's power curve. This figure illustrates the difference between the various methods of representing the power curve.

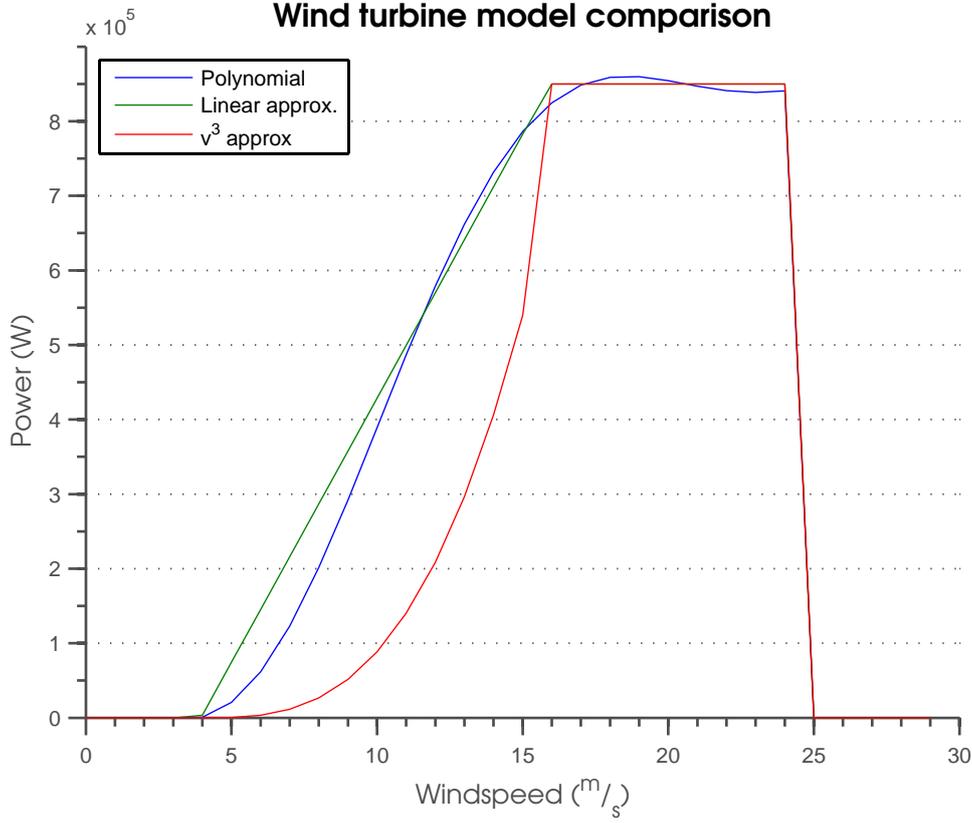


Figure 3.4: Wind turbine power curve comparison

- The hourly power output (P_{WT}) of a wind turbine generator can be determined for the various sections of the turbine power curve as described in section 2.4.2, with the help of the following equation [1]:

$$P_{WT}(v) = \begin{cases} \left(\frac{P_R}{v_r^3 - v_{ci}^3} \right) \cdot v^3 - \left(\frac{v_{ci}^3}{v_r^3 - v_{ci}^3} \right) \cdot P_R & v_{ci} < v < v_r \\ P_R & v_r < v < v_{co} \\ 0 & \text{otherwise} \end{cases} \quad (3.10)$$

- The ratio of the average power output to the rated power output of a wind turbine is called the capacity factor (C_{fM_i}) and expressed as follows:

$$C_{fM_i} = \frac{1}{P_R} \cdot \int_{v_{ci}}^{v_r} M_i \cdot f(v) \, dv + \int_{v_r}^{v_{co}} f(v) \, dv \quad (3.11)$$

where M_i can be any of the following power curve models [41]:

$$M_1 = P_R \cdot \left(\frac{v - v_1}{v_r - v_{ci}} \right) \quad (3.12a)$$

$$M_2 = P_R \cdot (c_1 v^2 + c_2 v + c_3) \quad (3.12b)$$

$$M_3 = P_R \cdot \left(\frac{v^2 - v_{ci}^2}{v_r^2 - v_{ci}^2} \right) \quad (3.12c)$$

$$M_4 = P_R \cdot \left(\frac{v^3}{v_r^3} \right) \quad (3.12d)$$

$$M_5 = P_R \cdot \left(\frac{v - v_{ci}}{v_r - v_{ci}} \right)^3 \quad (3.12e)$$

$$M_6 = P_R \cdot (a_1 v^3 + a_2 v^2 + a_3 v + a_4) \quad (3.12f)$$

$$M_7 = P_R \cdot (b_1 v^4 + b_2 v^3 + b_3 v^2 + b_4 v + b_5) \quad (3.12g)$$

where a_i, b_i and c_i are regression constants. It is important to note that equations 3.12a to equation 3.12g only represent the transient phase of the power curve where $v_{ci} \leq v < v_r$.

Thus to summarize, the power curve can be calculated using the above mentioned models by implementing the following function:

$$P_{WT}(v) = \begin{cases} M_i & v_{ci} < v < v_r \\ P_R & v_r < v < v_{co} \\ 0 & \text{otherwise} \end{cases} \quad (3.13)$$

It is important to note that the wind speed required for all the models listed above, refers to the wind speed at the hub height. The wind speed at a reference height h_r can be scaled to the hub height h_{hub} with the help of the following equation [42]:

$$v = v_{h_r} \cdot \left(\frac{h_{hub}}{h_r} \right)^\alpha \quad (3.14)$$

where v_{h_r} is the wind speed ($\frac{m}{s}$) at the reference height (m) and α representing the wind-shear power law exponent.

The wind-shear power law exponent is a numerical representation of the terrain surrounding the wind turbine with common values listed in table 3.2 [43].

Table 3.2: Typical power law exponent values for varying terrain

<i>TERRAIN DESCRIPTION</i>	<i>POWER LAW EXPONENT α</i>
Smooth, hard ground, lake or ocean	0.10
Short grass on untilled ground	0.14
Level country with foot-high grass, occasional tree	0.16
Tall row crops, hedges, a few trees	0.20
Many trees and occasional buildings	0.22 - 0.24
Wooded country small towns and suburbs	0.28 - 0.30
Urban areas with tall buildings	0.4

3.3.3 Battery bank

The variable nature of renewable energy sources, such as the daily cycle of the sun, causes variable breaks in power output. This intermittent energy problem is addressed by incorporating a battery bank into the system. A battery bank is designed in such a way as to provide the system with enough energy, to continue normal operation, in the absence of the renewable energy sources. This property of the battery bank is referred to as system autonomy, usually specified in days.

One of the most important parameters with regard to a battery bank is the current state of charge SOC of the battery bank as expressed by

Table 3.3: Battery bank nomenclature

<i>SYMBOL</i>	<i>UNIT</i>	<i>DESCRIPTION</i>
SOC	Ah	State of charge of the battery bank
DOD	Ah	Depth of discharge of the battery bank ($0 \Leftrightarrow 1$)
C_n	Ah	Nominal capacity of the battery bank
C_B	Ah	Nominal capacity of each battery
I_{sys}	Ah	System current requirements
P_{sys}	W	System power requirements
P_B	W	Battery bank power rating
T_{days}		System autonomy in days
Δt	h	Hourly time step
η_{bat}		Round-trip efficiency of the charging process
N_{bat}		Total number of batteries in the battery bank
$N_{bat,s}$		Number of batteries connected in series
V_{bus}	V	DC bus voltage
$V_{bat,nom}$	V	Nominal voltage of an each individual battery

$$SOC(t + \Delta t) = SOC(t) + \eta_{bat} \cdot \left(\frac{P_B(t)}{v_{bus}} \right) \cdot \Delta t \quad (3.15)$$

where the previous SOC at time t is used along side the round trip charging efficiency η_{bat} . In order to ensure that the battery bank has sufficient storage capacity, one can calculate the nominal storage capacity C_n with the help of [1]:

$$C_n = \frac{N_{bat}}{N_{bat,s}} \cdot C_B \quad (3.16)$$

where

$$N_{bat,s} = \frac{v_{bus}}{v_{bat,nom}} \quad (3.17)$$

calculates the number of batteries required in series and parallel configurations. The battery capacity C_B is discussed under battery cycling characteristics.

A lower limit for the SOC has been defined as the SOC_{min}

$$SOC_{min} = (1 - DOD) \cdot SOC_{max} \quad (3.18)$$

which specifies the minimum state of charge that should remain on the batteries at all times based on the prescribed depth of discharge DOD in order to extend the batteries' life span.

Battery cycling characteristics

The batteries' cycling characteristics describe the rates at which the batteries are charged or discharged. The first step is to determine the required battery capacity C_B depending on the system's current requirements I_{sys} for a prescribed period of days T_{days} by:

$$C_B = \frac{I_{sys} \cdot T_{days} \cdot 24}{DOD} \quad (3.19)$$

where the system's current requirements I_{sys} are determined by

$$I_{sys} = \frac{P_{sys}}{V_{bus}} \quad (3.20)$$

where P_{sys} represents the system's power rating for the system's DC bus voltage V_{bus} . A DC voltage bus is simpler to implement since the PV panels and batteries work with

DC voltage by default. It is important to note that P_{sys} has to be calculated for the whole system and specified in terms of the inverters' requirements if the system uses AC voltage.

3.4 Environmental data

3.4.1 Solar

Optimal tilt

The tilt angle of a PV panel determines the amount of solar irradiance that the PV panel will receive, in turn effecting the power output thereof. If one had a PV panel system feeding the maximum amount of energy into an electricity grid, one would choose a tilt angle to provide the maximum accumulative power output per year. The problem with this approach is that the output of the PV panels will vary dramatically during the year.

The optimal tilt angle in this simulation model is selected on the premise of producing the maximum amount of power during the worst month of the year. The aforementioned optimal tilt angles are subject to a fixed PV installation. If one is able to implement a solar tracker, that will in effect tilt the PV panel to the optimal tilt angle for each month, one will produce the maximum amount of power throughout the year.

Rentech et al. [44] showed that one can calculate the effective irradiance I_{eff} for a specified tilt angle b with the help of equations 3.21, 3.22 and 3.23:

$$A = \text{sign}(\delta - \phi) \times \cos^{-1}((\sin(\delta_{rad}) \times \sin(\phi_{rad})) + (\cos(\delta_{rad}) \times \cos(\phi_{rad}))) \quad (3.21)$$

$$I_{tr} = \frac{1}{2} \times r_g \times (1 - \cos(\text{rad}(-b))) \times I_{irr} \quad (3.22)$$

and finally the effective irradiance I_{eff} for the selected tilt angle b

$$I_{eff} = \left(\left(\frac{\cos(\text{rad}(-b) + A)}{\cos(A)} \right) \times I_{irr} \right) + I_{tr} \quad (3.23)$$

with the relative nomenclature for equations 3.21 to 3.23 described in table 3.4.

Table 3.4: Optimal tilt nomenclature

SYMBOL	UNIT	DESCRIPTION
δ	°(degrees)	Solar declination
ϕ	°(degrees)	Site latitude
b	°(degrees)	PV panel tilt angle
I_{eff}	$\frac{Wh}{m^2}$	Effective irradiance
I_{tr}	$\frac{Wh}{m^2}$	Terrain reflected irradiance
I_{irr}	$\frac{Wh}{m^2}$	Incident irradiation perpendicular to a flat horizontal surface
r_g		Ground reflectivity

Consequently the optimal tilt for the specific location can be determined by iteratively calculating these equations for different tilt angles ranging from 0° to 90° and determining the maximum I_{eff} corresponding to a tilt angel.

The sign function refers to a function that returns merely a -1 or $+1$ based on the input value and is given by equation 3.24.

$$\text{sign}(x) = \frac{x}{|x|} \quad (3.24)$$

3.4.2 Wind

Weibull curves

As previously mentioned in section 2.4.2, the Weibull distribution can be used to represent the probability of each wind speed being present at the intended location.

In order to generate the Weibull PDF using equation 2.5, one has to determine the shape k and the scale parameter c . This was accomplished using the MLE method with equations 2.6 and 2.7.

A secondary method was implemented in LabView in order to determine these parameters. By drawing a histogram of the data with a sufficient bin width Δx , one is left with a crude approximation of the wind speed frequencies.

The sufficient bin width and number of bins are relative terms. The number or bins in the histogram should be sufficient to produce a distinguishable envelope of the data. As a rule of thumb, the number of bins n_b can be approximated by [45]:

$$n_b \approx \sqrt{n_o} \quad (3.25)$$

where n_o is the number of observations.

It is necessary to normalize all the frequency counts $H(A)$ in each bin relative to the number of observations in the original data set:

$$H_{norm}(A) = \frac{H(A)}{(n_o \cdot \Delta x)} \quad (3.26)$$

where $H_{norm}(A)$ is the normalized histogram frequency counts as seen in figure 2.14.

The next step is to fit a curve to the histogram envelope using the built in non-linear curve fit VI in LabView's mathematics toolbox. The non-linear curve fit VI generates a Weibull curve and compares it to the normalized histogram curve and the error is calculated. This procedure is repeated until the error is minimized, resulting in a pair of shape and scale parameter that provides the best fit.

Both of these methods have been implemented in the module to allow the user to decide what method to use. There is a slight compromise in accuracy when using the latter method but a massive gain in processing speed, especially when working with large data sets. The usage characteristic for both methods are compared in table 3.5 based on a case study using the data from WASA's WM01 site based in Alexander bay, South Africa.

The final step is to supply the shape and scale parameters to equation 2.5 to generate the Weibull curve.

Table 3.5: Parameter estimation method comparison

	<i>MLE</i>	<i>Curve fit method</i>	<i>Difference</i>
Execution time			
Large data set	159.453s	0.570s	156.738s
Accuracy			
Shape	1.88862	1.9391	2.67%
Scale	6.59943	6.2266	5.64%

Probable power

There are different ways to calculate the probable power output $P_{prob}(v)$ of the wind turbine generator at intended locations. The first method is very computational intensive where each data value is supplied to one of the wind turbine power curve polynomials and the final result is averaged:

$$P_{prob} = \frac{1}{n} \cdot \sum_{i=1}^n P(i) \quad (3.27)$$

where n is the number of entries in the data set.

Alternatively, following the calculation of the Weibull curves $f_{Weibull}(v)$ and the turbine power curve $P(v)$ (equations 3.9, 3.10 or 3.13), one can calculate the probable power output by:

$$P_{prob} = \int_0^{\infty} f(v) \cdot P(v) dv. \quad (3.28)$$

The latter method is advantageous due to its processing speed. Once the Weibull curves have been generated, one can change the wind turbine's parameters and re-calculate the probable power output almost instantaneously by implementing equation 3.28, while equation 3.27 would have required one to re-evaluate the power polynomial for every single data entry.

An additional advantage of working with Weibull curves is that once the curves have been calculated, the original data is not required any more, thus reducing the required

storage space from multiple thousands of entries to a simple array.

3.5 Verification and validation

Verification

In order to verify the accuracy of each module created in LabView, a corresponding module has been created in the Matlab environment as well as Microsoft Excel in some instances. Each module utilises the most basic forms of the equations to prevent any '*behind the scenes*' calculations. The accuracy of each module is evaluated in both environments and furthermore compared to the results of known data sets. The data used in the simulations have been sourced from reputable sources to ensure the accuracy thereof [26].

The ideal method of verification would be to compare the simulation results with that of an actual facility that has been operating for a minimum of 1 year.

Validation

Each individual module, as well as the final integrated collection of modules will be evaluated to ensure its validity. This evaluation process will compare the functionality of each module to the functional architecture diagrams in section 3.1.