Chapter 2

LITERATURE STUDY

The literature study provides the theoretical framework which is used for the development of the specific application entities and functional units. A systematic approach is taken, starting with a brief look at the renewable energy sources applicable to the REHS-plant functional description; this is followed by an overview of available technologies for other constituents of the REHS relating to meteorological measurement and energy storage technologies. Finally, we conclude with a brief overview of optimisation techniques and how they can be applied to the REHS-based engineering problem.

2.1 PHOTOVOLTAIC POWER SYSTEMS

2.1.1 Introduction

Since its inception in the early 1800's [6], photovoltaic's has been cause for major discussion. Today the photovoltaic principle has evolved into a global leader for the provision of clean energy. To briefly describe a PV system, one can say that such a system converts light energy quanta in the form of photons into usable electricity by means of the Photoelectric Effect [7].

PV systems have evolved at a tremendous rate up until today with a continuous increase in efficiency and a systematic reduction in cost.

Modern PV modules are built according to power and/or voltage specification by using a specific amount of basis-unit PV cells. These individual cells have characteristics coherent with the type of material it consists of [8]. *Figure 2.1* illustrates how a PV array is created in terms of these basis units.

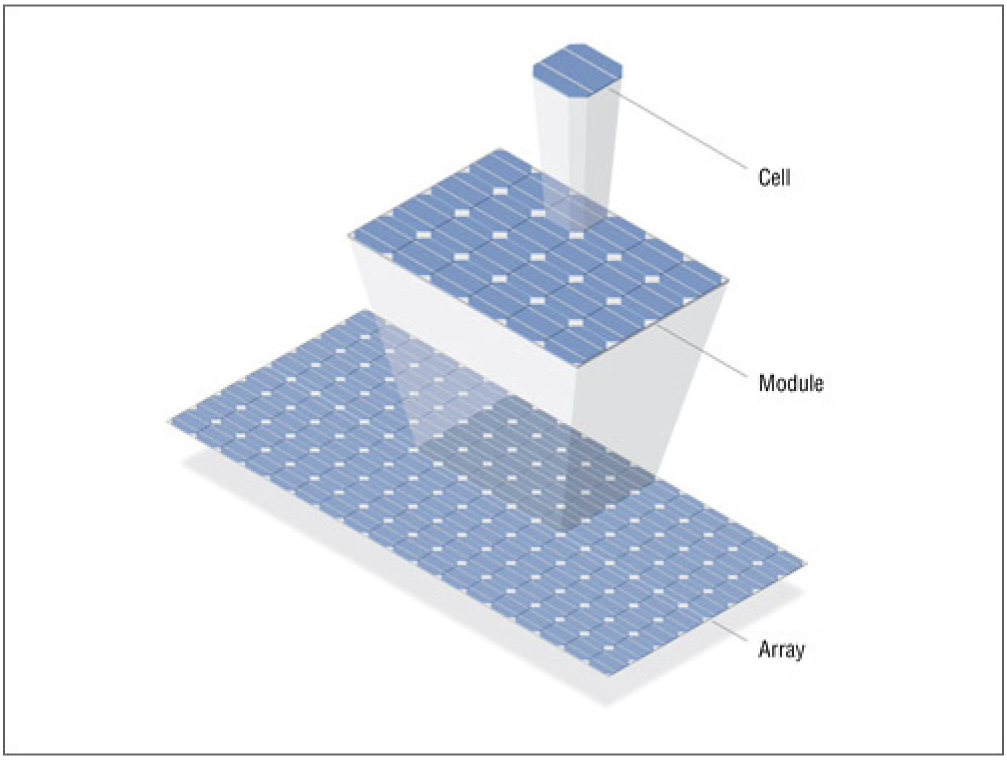

Figure 2.1 – Exploded view of a solar array [9]

For the purposes of this project, an in-depth look at the physics and engineering behind the PV cell is not necessary as we are only interested in developing a mathematical technique for the sizing of PV arrays. We can therefore limit this discussion to how PV module specifications are defined, and how they can be used in a sizing procedure for creating PV arrays.

2.1.2 Photovoltaic modules

PV modules consist out of multiple, interconnected PV cells of the same type. These cells are preferably matched so that consistent outputs can be achieved. An effective technique has also been devised by Lentine et al. [10] which allows the interconnection of non-matched cell groups. The end-result of either approach is that the specific connections of the cells contribute to stable output values as chosen by the manufacturer. The typical current-voltage characteristics of a PV-module are presented in *Figure 2.2*.

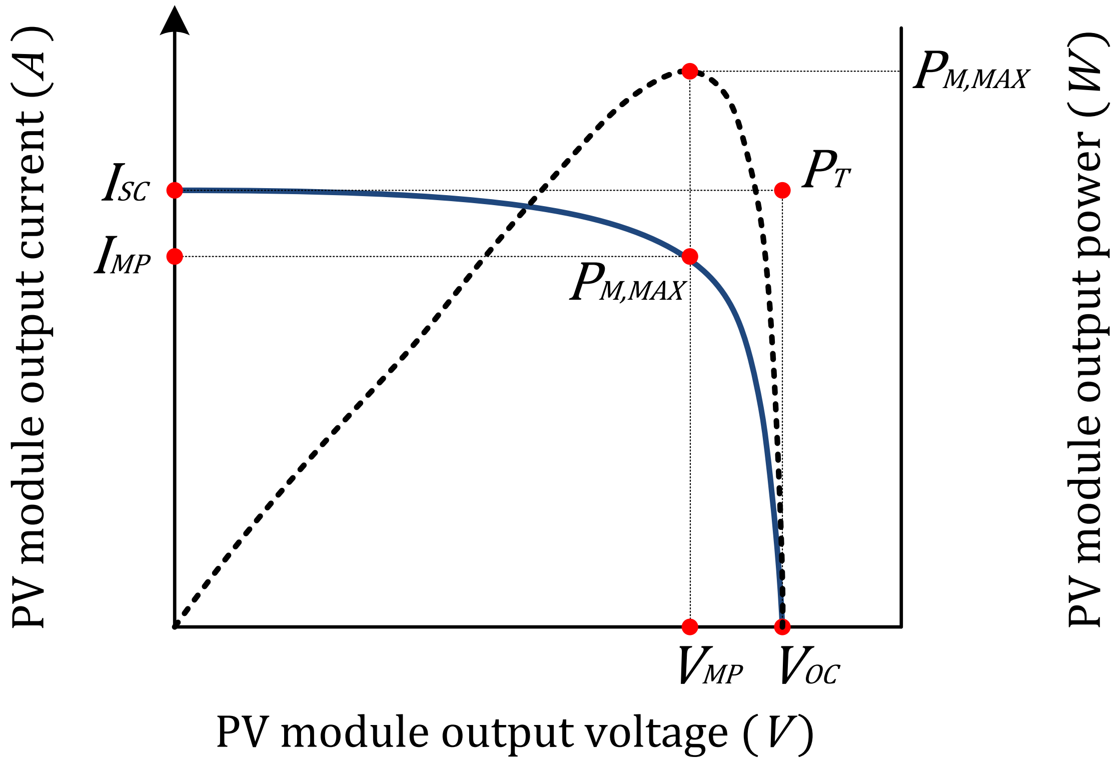

Figure 2.2 – I-V characteristic curve of a typical PV module

For proper model definition, we proceed to define the parameters used in *Figure 2.2*. Two curves are presented by the figure: the solid, blue curve represents the PV module output current versus the output voltage of the module; and the dotted, black curve represents the PV module output power in Watts versus the output voltage of the module. Specific parameters are defined as follows:

I_{SC} is the short-circuit current (A) of the module, which is also the maximum current;
I_{MP} is the current output of the module at the maximum power point (A);
V_{MP} is the voltage output of the module at the maximum power point (V);
V_{OC} is the open-circuit voltage (V) of the module, which is also the maximum voltage;

$P_{M,MAX}$ is the power output of the module (W) at the maximum power point; and
P_T is an indication of the maximum theoretical power output of the module (W).

The significance of the parameter P_T lies in the determination of the Fill Factor (FF) of the module in question. This parameter is discussed later in *section 2.1.2.4.* We now continue to derive models for the specified parameters for further analysis.

According to Hegedus [11], in order to identify all of the PV module characteristics which are important for sizing procedures, we must first define mathematical equivalents of the base parameters as given by the manufacturer. Firstly, we look at the maximum power output $(P_{M,MAX}(t,\beta),(W))$ at a specific time of the day (t) when the PV module is placed at a tilt angle of β° which is determined by:

$$P_{M,MAX}(t,\beta) = V_{OC}(t) I_{SC}(t,\beta) FF(t,\beta) \tag{1}$$

where $V_{OC}(t)$ is the open-circuit voltage (V), $I_{SC}(t,\beta)$ is the short-circuit current (A) at a specific time of the day (t), and $FF(t,\beta)$ is a parameter known as the Fill Factor, at a specific time of the day (t) when the PV module is placed at a tilt angle of β°.

To properly define *(1)*, we define its individual constituents by looking at a system-specific combination of the analytical procedures derived by Kornelakis [12] and Zhou [13].

2.1.2.1 *Open-circuit Voltage*

The open-circuit voltage produced at the terminals of a PV module is the maximum voltage that the module is capable of delivering, when tested under standard test conditions (STC). As the term suggests, this voltage is measured when no current flows between the terminals of the module.

Using the two techniques shown in [12] and [13] we find that the open-circuit voltage of the PV module is given by:

$$V_{OC}(t) = V_{OC,STC} + k_V\left[T_C(t) - T_{C,ref}\right] \tag{2}$$

where $V_{OC,STC}$ is the open-circuit voltage (V) under STC;

k_V is the open-circuit voltage temperature coefficient ($\frac{mV}{°C}$);

T_C is the PV module operating temperature ($°C$), defined under *section 2.1.2.3 and*

$T_{C,ref}$ is the PV module operating temperature ($°C$) under STC.

2.1.2.2 *Short-circuit Current*

The short-circuit current of the module is the maximum amount of current which the PV module can produce when tested under STC. We find that the short-circuit current of the PV module is given by:

$$I_{SC}(t,\beta) = \{I_{SC,STC} + k_I[T_C(t) - T_{C,ref}]\}\frac{G_T(t,\beta)}{G_{ref}} \tag{3}$$

where $I_{SC,STC}$ is the PV module short-circuit current (A) under STC;

k_I is the short-circuit current temperature coefficient ($\frac{mA}{°C}$);

G_T is the irradiance ($kW.m^{-2}$) incident on the PV module placed at tilt angle $\beta°$;

G_{ref} is the irradiance ($kW.m^{-2}$) incident on the PV module under STC and

T_C is defined under *section 2.1.2.3.*

2.1.2.3 *PV Module Temperature*

In both *sections 2.1.2.1* and *2.1.2.2* there is mention of the parameter T_C which corresponds to the PV module operating temperature. This is not an arbitrary value which is only dependant on the ambient temperature, but is also a function of the irradiance incident on the PV module. This parameter is given by:

$$T_C(t) = T_A(t) + \frac{NCOT - 20°C}{800W.m^{-2}}G_T(t,\beta) \tag{4}$$

where T_A is the ambient temperature ($°C$) of the site;

$NCOT$ is the Nominal Cell Operating Temperature ($°C$);

2.1.2.4 *Fill Factor*

When referring to the Fill Factor (FF) of a PV module, we specifically look at the ratio between the actual maximum obtainable power $(P_{M,MAX})$ and the product of the module's short-circuit current (I_{SC}) and the open-circuit voltage (V_{OC}), which is referred to as the theoretical power, P_T. In order to properly define this term, we refer to the illustration in *Figure 2.2.*

As is stated in *section 2.1.2*, this curve represents the current-voltage characteristics of a typical PV Module. The maximum power point is usually measured using a technique known as Maximum Power Point Tracking (MPPT), which will be elaborated on in *section 2.1.4.* Using the value for the maximum power $(P_{M,MAX})$ the values for the current at the maximum power point (I_{MP}) and the voltage at maximum power point (V_{MP}) may be determined. Consequently, the Fill Factor is given by:

$$FF = \frac{P_{M,MAX}}{P_T} = \frac{I_{MP} \times V_{MP}}{I_{SC} \times V_{OC}} \tag{5}$$

This parameter is one of the key parameters when measuring the performance of solar cells. Typically for commercial solar cells, the fill factor > 70%. These cells exhibit low parasitic losses due to internal resistivity.

2.1.3 Photovoltaic arrays

PV arrays can simply be described as units comprising of multiple PV modules, connected in specific electrical configurations such that a given specification is met. This description is graphically shown in *Figure 2.3*.

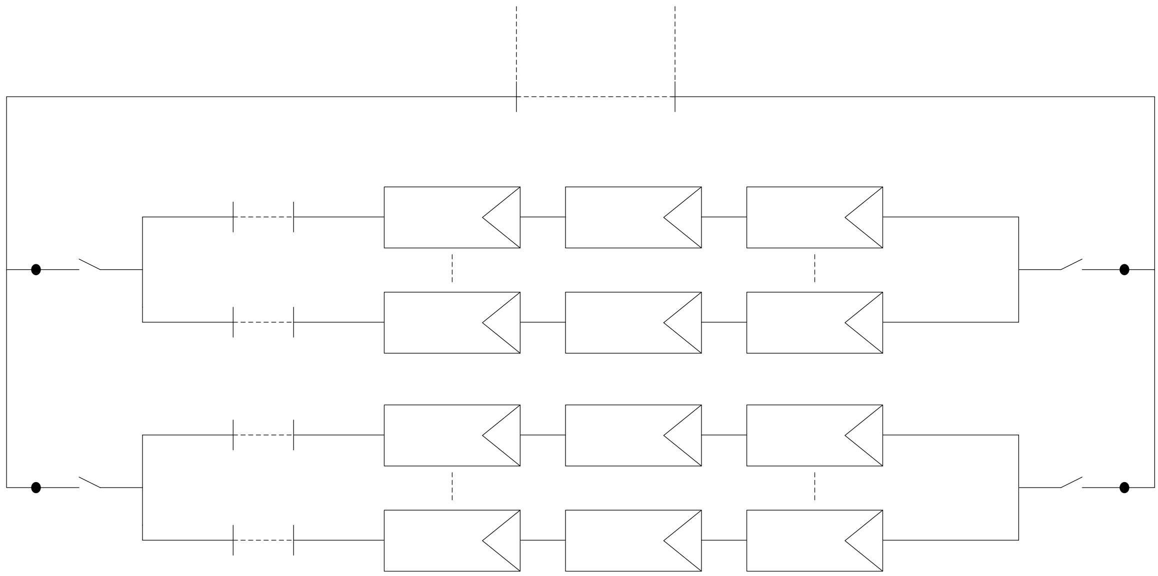

Figure 2.3 – PV Array example

These configurations include series and parallel connections between multiple PV modules to satisfy system voltage, current and power requirements.

2.1.4 Output converter topologies

When a PV array is introduced into a system, the outputs of the array must be matched to the input requirements of the system. This may be achieved through the introduction of different power electronics systems, the type of which depends on the integration requirements and specifications. Since the REHS-based concept features the possibility of introducing either a DC or AC bus, we must look at different converter topologies which can be implemented in each case. This is necessary since the component configuration and hence the cost is dependent on the type of topology. To this end, we look at two different components: the DC-DC converter and the DC/AC inverter and comment on the implementation characteristics.

2.1.4.1 *DC-DC Converter*

In the DC-DC converter stage, there are multiple converter types which may be implemented into a system, each performing a specific function, or a combination of functions. To that end, we discuss two basic types, and conclude with a converter which utilises both these basic types into one efficient converter.

- **Buck converter**

  The functional description of a buck converter comes down to the fact that it is used for voltage step-down. This is achieved by varying the duty cycle which switches a MOSFET in the circuit [14] – the ratio between the output voltage (V_{out}) and input voltage (V_{in}) is equal to the duty cycle (D):

$$\frac{V_{out}}{V_{in}} = D \tag{6}$$

  It can also be noted that the current ratio is, as expected, the reciprocal of the voltage ratio stated in *(6)*. In this converter type, losses of up to 10% may be introduced during the conversion phase, as must be taken into consideration for systems-integration.

- **Boost converter**

  The functional description of a boost converter comes down to the fact that it is used for voltage step-up. The basic principle behind a boost converter is no more complicated than that of the buck converter, as the same components are used in the design, but with a different configuration. The step-up process is also achieved by varying the duty cycle which switches a MOSFET in the circuit [15] – the ratio between the output voltage (V_{out}) and input voltage (V_{in}) is shown in *(7)*:

$$\frac{V_{out}}{V_{in}} = \frac{1}{1-D} \tag{7}$$

  The duty cycle is continuously adjusted by the MPPT controller, which continuously monitors the solar panel voltage and current outputs so that the maximum power can be extracted [16].

- **Buck-Boost converter**

  The buck-boost converter is a very common converter type for photovoltaic applications. The use of this type of converter ensures constant power characteristics, while keeping system complexity to a minimum [17]. According to Weiping et al [18] it is also very effective at finding the MPPT, and is therefore ideal for applications where maximum power output is preferred. It also provides a good response-speed and its controlling schemes are flexible. Overall efficiency is improved as opposed to a system using combinations of boost and buck converters, due to the integrated nature of the buck-boost converter. Considering the voltage characteristics, the output voltage can be given by:

$$V_{out} = -V_{in}\frac{D}{1-D} \tag{8}$$

  Since the duty cycle is less than one in this converter-type, the converter can operate in both buck and boost modes, depending on the requirements of the system.

2.1.4.2 *DC/AC Inverter*

When the renewable energy sources providing DC power must be connected to an AC destination, a power electronics device knows as a DC/AC inverter must be introduced. In hybrid renewable energy projects, the DC/AC inverter is one of the most fundamental components of the system configuration. These come in many forms, and are classified according to four distinct categories. The first is the number of power processing stages incorporated in the design; the second refers to the location of the power decoupling capacitors in the inverter; whether they incorporate transformers into the design forms the third category; and finally the types of grid interfaces implemented forms the last. [19].

The description of each category requires extensive study and application of inverter technologies and electrical systems. For the scope of this project, it is therefore sufficient to describe the first category, as it is closely linked to MPPT.

To illustrate the concept of power processing stages, the reader is referred to *Figure 2.4.* Three cases of single- and multiple-stage inverters are presented in this figure. *Figure 2.4*(*a)* represents a single stage inverter. In this type of configuration, the inverter must handle all related power tasks like MPPT and voltage amplification by itself. This topology has been mostly phased out of modern inverter technologies, due to design requirements that require expensive auxiliary components like high-voltage DC cables, and the introduction of high losses in many stages of the design.

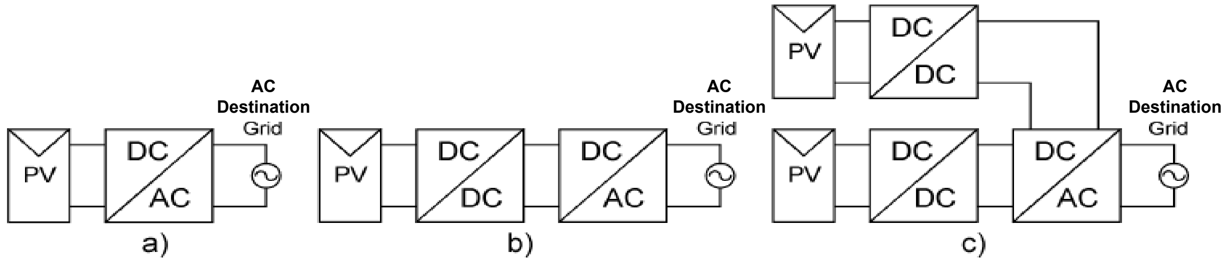

Figure 2.4 – Three types of PV inverter topologies [19]

Figure 2.4(*b)* shows the topology of a dual-stage inverter. Here, the DC-DC converter is introduced to be solely responsible for the MPPT. As noted in [19], a high efficiency can be reached for this solution if the nominal power is low, as DC losses increase exponentially when DC current is increased. A solution for this drawback is illustrated in *Figure 2.4*(*c)*, which represents a solution for the multi-string inverter (inverter system used when the PV array becomes larger). Here, each PV module string (with multiple series strings in an array) is connected to a DC-DC converter, and all the converters are connected to the DC-link of a common DC-AC inverter. This enables good modularity for the PV array, and reduces final component requirements.

2.2 WIND POWER SYSTEMS

2.2.1 Introduction

Wind energy as an applied concept has been used in many forms from very early in the history of man. The entering of the industrial age saw a marked decrease in the significance of wind in the role of energy generation with the gradual introduction of fossil fuel-based technologies. As we progressed into the modern age however, a clear reversal of this trend could be discerned, as the focus on non-polluting energy supplies became more apparent. By the late 1990's there was a marked shift to the implementation of larger wind turbines, and this increasing trend has continued well into the 21st century [20].

Amidst the larger scope of wind energy usage, there is also an increasing trend for the implementation of smaller wind turbines for off-grid specialist applications [21], specifically in the range of 1kW and 30kW [22] and [23]. The REHS is a very good example of such an application, where wind turbines may be used as an energy source if the location of the REHS-based plant allows for efficient wind energy conversion. For the purposes of this thesis, we briefly investigate the performance and operating characteristics of wind turbines in general relating to how wind turbines may be used for power supply in an off-grid application; we also look at the economics of wind energy, and how this impacts REHS-based plant concepts.

2.2.2 Wind turbine design

Many types of wind turbine designs have been experimented with in the past, but none have had the commercial success of the horizontal axis wind turbine (HAWT) design [24]. This turbine features an axis of rotation that is parallel to the ground plane, with auxiliary components introduced appropriately to this design. *Figure 2.5* shows a diagrammatical summary of components with which the HAWT is constructed. This turbine type features a three-bladed rotor connected to a drive train which consists out of a low speed drive shaft connecting the rotor to a gearbox, which in turn drives a generator [25]. This assembly, referred to as the "nacelle" is connected to the tower by means of a yaw system, which keeps the rotor oriented into the wind. Without going into specific design details, we continue to discuss how these turbines may be integrated into a system.

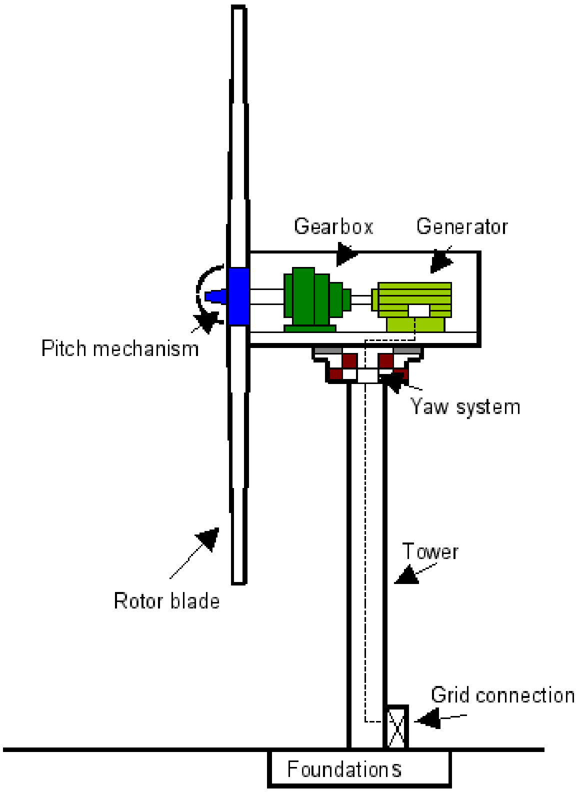

Figure 2.5 – Major components of the HAWT [25]

2.2.3 Wind turbine integration

The integration of wind turbines into a hybrid system such as the REHS is very similar to the methods described in detail in *section 2.1.4.* Since a wind turbine outputs AC power (in larger turbine designs) or DC power (in smaller turbine designs), a reciprocal technique may be implemented between the energy source and system bus entities. This enables the application to implement a modular method for the sizing of the renewable energy sources, by changing the component topologies dependant on the system's and turbine's power specification.

2.2.3.1 *Power characteristics*

There are several factors which determine the output power of a wind turbine. These factors include (i) turbine speed, (ii) rotor blade tilt, (iii) rotor blade pitch angle, (iv) size of turbine, (v) wind speed. For the purposes of turbine integration into the sizing procedures of the ESM, we do not need an in-depth formulation of the mathematical equivalent of the output wind turbine power, as this model has already been incorporated into the TSM. What we do need however, is an equation which can relate the effective power output of the turbine, versus the wind speed. By following the detailed derivation in Manyonge [26], we find that the actual mechanical power P_w is given by:

$$P_w = \frac{1}{2}\rho A V_u^3 C_p \,, \tag{9}$$

where ρ is the density of air $(kg.m^{-3})$;
A is the area through which the wind is flowing (m^2);
V_u is the upstream wind velocity $(m.s^{-1})$; and
C_p is the Betz limit, which is elaborated upon in *equation (10).*

The Betz limit is used to specify the fraction of upstream (total incoming towards the turbine) wind captured by the turbine blades as the downstream (resultant outgoing from the turbine) wind velocity changes (as function of the rotor speed). This limit is used in *equation (9)* and is given by:

$$C_p = \frac{\left(1 + \frac{v_d}{v_u}\right)\left(1 - \left(\frac{v_d}{v_u}\right)^2\right)}{2} \,, \tag{10}$$

where v_d is the downstream wind velocity $(m.s^{-1})$; and
v_u is the upstream wind velocity $(m.s^{-1})$.

As discussed, further investigation into this topic is beyond the scope of this dissertation. We refer the reader to the detailed modelling of the TSM by De Klerk [2] for further elaboration on the topic.

2.3 SENSORY APPARATUS

2.3.1 Introduction

The physical properties of the atmosphere have a great influence on both the type of renewable energy source that should or could be used for a system, as well as the size of such a renewable energy system. In order to perform efficient systems integration with renewables, large quantities of applicable meteorological information is required for the specific site. When the system sizing is complete, it is also important to keep track of meteorological events. These events can be used for many purposes including triggering safeguards in a system or efficiency evaluations [27]. Since the REHS implements a combination of wind and solar energy sources, the monitoring of natural phenomena relating to both technologies is important. We will therefore discuss all relevant measurement techniques in brief, to provide for a good basic understanding of how the technologies can be implemented, and what purposes they may serve to improve the applicable system.

2.3.2 Solar irradiance

Solar irradiance refers to the emission of radiation across the entire frequency spectrum by the sun. As solar radiation traverses the space between the sun and a station on the ground, it is attenuated by scattering, absorption and reflection effects in space and in the atmosphere [28]. The effective solar radiation that reaches the surface is used for PV module systems modelling. It is thus important to be able to measure this value in a real-time basis for system prediction and performance evaluation.

Figure 2.6 – Kipp & Zonen pyranometer

A widely used apparatus which can accurately measure broadband solar irradiance is called the pyranometer, shown in *Figure 2.6*. This sensor measures the flux density of incoming solar irradiance over a broad range of incident radiation wavelengths (280nm to 2800nm) in watts per metre square, the accuracy of which is dependent on the wavelength-range of the sensor [29]. Commercially available pyranometers are standardised according to the ISO9060 standard, which classify the sensors according to three standards (from highest to lowest): secondary standard, first class and second class. These classes are distinguished by the amount of error introduced in the measurement, as well as the sensitivity specifications of the devices [30]. In terms of systems integration, the choice of pyranometer class comes down to cost and system accuracy requirements. For the purposes of an REHS-based plant, precise solar irradiance measurement is not of cardinal importance.

2.3.3 Wind speed

When sizing hybrid renewable energy systems, incorporating wind and solar sources, the speed and direction of wind present on the site is a parameter that is important to both technologies. When considering PV modules, the main attribute that wind can alter, is the temperature of the modules. Although the direction of the wind has a minimal effect on the temperature, the speed of the wind is an important consideration due the convection coefficient [31]. In terms of wind turbine technology, the measurement of the speed and direction of the wind is very important for both operational and observational purposes.

The measurement of wind is thus critical for the effective functioning and maintenance of a REHS-based plant. Three commonly used apparatuses for the measurement of wind are the cup and propeller sensors for wind speed measurement, wind-direction vanes for the determination of wind direction through the use of potentiometers, and the ultrasonic anemometer, shown in *Figure 2.7(b)*, which determines wind speed by calculating the propagation speed of an emitted ultrasonic pulse [32]. Wind speed and direction sensors are sometimes combined into a single unit, as shown in *Figure 2.7(a).*

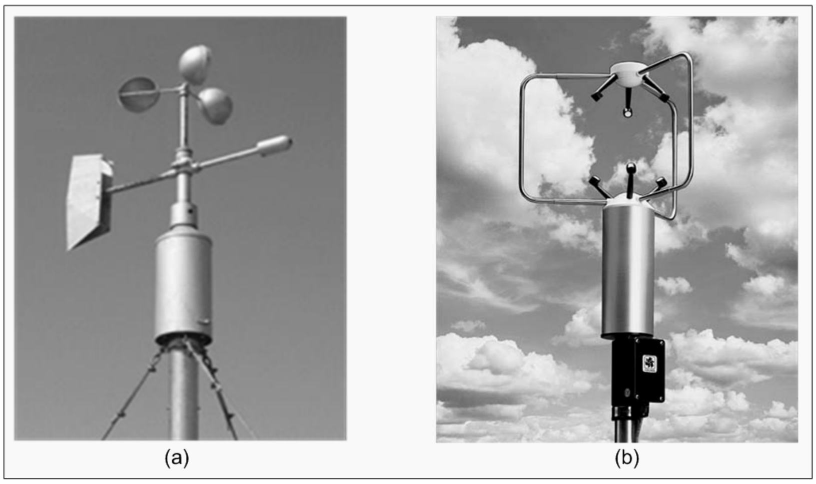

Figure 2.7 – (a) Combination of wind speed and wind direction sensors. (b) Ultrasonic wind sensor

2.3.4 Temperature

Temperature is a collective term used to describe the average kinetic energy of atoms in a given substance. Since the photoelectric effect is a process that happens on the atomic level of a PV module, the temperature of the modules is a significant quantity. A detailed discussion of the correlation between temperature and the photovoltaic conversion process is given by Skoplaki et al. [33]. Here it is shown that for proper model prediction, the accurate measurement of temperature is of vital importance for system predictive control and maintenance. Large variations in temperature also have an influence on the air density, which in turns influences the performance of wind turbines [34].

According to [35], the measurement of temperature is extremely sensitive to exposure. Therefore specific installation guides must be followed to ensure that accurate data sets can be obtained. The option of including temperature measurements in the ESM must thus include the necessary equipment for proper sensor functioning.

2.3.5 Humidity

Humidity describes the amount of water vapour per unit volume in the air with specific dependence to the air temperature. A more commonly used term is relative humidity, which describes the humidity as a ratio between the partial pressure of water vapour per volume, and the saturated pressure of water vapour per volume at a given temperature.

According to a study by Sozen [36], humidity has no influence on solar potential prediction, but Mekhilef [37] shows that this is not the case for the actual power extraction potential in the field. Two specific effects that the humidity can have on solar-based sources, relate to the water vapour particles on the effective solar irradiance incident on the cells, and the ingression of vapour into the panels, which may cause device failure. The effects of humidity in wind-based applications are also substantial. Baskut [38] found that with increasing humidity, the exergy (available energy) efficiency of a wind turbine decreases linearly.

These effects contribute directly to the total plant efficiency numbers, which is an important index that must be presented to the client by the ESM. The sizing application will allow for the custom selection of measurement tools for humidity.

2.4 SYSTEM OPTIMISATION

In many engineering projects, the goal is to develop efficient, cheap and effective solutions to problems encountered in the specific industries of application. The optimisation of system entity functioning, layout definition and component configuration can be a major hurdle in the developmental phases due to the potentially large amounts of individual constituents present. To overcome these performance issues, optimisation techniques have been developed over the past few decades, which specifically serve to minimise time requirements, and maximise system performance. Due to the nature of the required optimisation functionality of the application being developed in this project, we look at an algorithm which may be used for the optimal sizing procedures.

2.4.1 Metaheuristic approach

The field of metaheuristics has been established as one of the most practical approaches to optimisation problems [39]. Even though these methods are generally designed for combinatorial optimisation, various forms of metaheuristic optimisation techniques have been developed to be applicable to most fields. For the ESM, a brief look at a metaheuristic technique will suffice.

2.4.1.1 *Genetic algorithm*

The theory behind the genetic algorithm is based on the popular theory of natural selection by Charles Darwin [40]. The theory states that individuals within a specific population of species which exhibit certain favourable characteristics are more likely to survive and reproduce, consequently passing on their specific characteristics to their offspring. Individuals with less favourable characteristics on the other hand, will gradually disappear from the population. These characteristics are contained within the genetic code of the species and individuals. The genetic code is passed on to the offspring of the individuals during reproduction. Random mutation in the genetic code may occur during this transference process, which may have beneficial or non-beneficial impacts on the offspring's characteristics.

Using the bases of this principle, John Holland and his associates developed the genetic algorithm for systems optimisation [41]. The idea behind the genetic algorithm, is to model the natural evolution of individuals, which may refer to space-elements, configurations etc., by using genetic inheritance and mutations.

As with most optimisation techniques, an objective function, which forms the basis of the algorithm's functioning, must be defined. This function can be minimised or maximised, depending on the system requirements.

2.5 REVIEW

In this literature review, an overview of the different proponents of an REHS-based plant was given. This was done by first looking at renewable energy sources, specifically solar and wind power, and how such systems are characterised. Hereafter background information for other physical components needed for correct REHS-specification was given. In order to fit all the proponents together, different optimisation techniques were investigated. Based on the information gathered, the following decisions have been made with regards to ESM specific development tools:

- For the sizing of PV and wind systems, the integration of two-stage inverters will be compulsory for the ESM sizing algorithm, as it has been found that for the REHS-based approach, this inverter type provides most benefits. Thus the ESM will provide an array of component models based on this technology for user selection.

- To aid in programming methods, two phases of optimisation must be introduced. The first will be used to create permutations of functional renewable energy source configurations, which can be transferred to the rest of the system. The second is the implementation of a simpler algorithm for the final system configuration.

- An optimisation technique based on the genetic algorithm seems to be most fitting for this application, since we need an algorithm which can determine local optima, while still being able to determine global optima. Due to the vast amount of theory on different implementations of the genetic algorithm, a specific technique has been devised in conjunction with the application that is to be developed. The details of this process are set out in *Chapter 4* of this dissertation.