The Formulation and Validation of PV inverter efficiency under South Africa climate conditions

by

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A Thesis Submitted in Partial Fulfilment of
the Requirements for the Degree of

Master of Technology: Electrical Engineering (Energy)

In the Department of Electrical, Electronic and Computer Engineering

**At the Cape Peninsula University of Technology
South Africa**

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Cape Town
September 2018

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DECLARATION

I, Byamungu Cirhuza Alain, declare that this thesis and the contents of this document represent my own work – save for that which is acknowledged appropriately – and that it has not previously been submitted for academic examination towards any qualification.

Signed _____   **Date** _____

ABSTRACT

In photovoltaic power systems, the DC/AC conversion efficiency depends on weather conditions causing PV inverters to operate under fluctuating input power from PV modules. The peak efficiency stated by the inverter manufacturers are often used by project designers to estimate how much power PV plants can produce. However, the varying nature of the DC input power to the inverters, occasioned by varying irradiation and temperature, leads to deviations of the actual efficiency from the peak efficiency.

Literature surveys prove that inverter efficiencies must be evaluated against local irradiation profiles to get more precise annual energy yield estimations, since meteorological conditions and solar irradiation profiles vary from one site to another around the planet.

This method of using different weights for different irradiation ranges has led to the development of two standard weighted average efficiency models, the European efficiency η_{EURO} and the California Energy Commission efficiency η_{CEC}.

Both the η_{EURO} & η_{CEC} formulas address the problem by weighting the major DC input power levels that the inverter is likely to operate in with respect to their frequency of occurrence and energy contributions within the year. By considering the annual irradiation distribution over the entire sunny time, the ranges are selected with their respective weight factors. But these figures are based on climate conditions from Trier (Germany) and Sacramento (California). To get an accurate estimate of the yearly energy output, the inverter efficiency is measured against the weights of the probable power ranges representing the different irradiation values at the selected site.

This paper analyses solar irradiation data of the city of Cape Town (South Africa) and simulates the behaviour of a 1 kWp grid-connected PV inverter and the annual energy yield under local climate conditions. A software model of a solar power plant's inverter efficiency and its electrical energy output are computed to assess the validity of η_{EU} & η_{CEC} for the selected site.

The results provide data and graphs describing the relationship between site meteorological data, PV inverter efficiency and AC energy output to help simulate the annual energy yield and irradiation-temperature distributions, for each range of irradiance and the frequency of their occurrence.

A brief overview of the results shows that:

- Cape Town annual irradiation-temperature distribution is different from Trier, Ispra and Sacramento, in Euro & CEC efficiency standards.
- 33.63% of annual energy yield would be harvested at and below 500 W/m^2 irradiation levels, 30.99% between 500 and 750 W/m^2 and 35.38% above 750 W/m^2.
- The validity of European efficiency can be challenged for Cape Town since it assumes 79% of annual yield would be harvested at and below 500 W/m^2 irradiation levels
- CEC efficiency shows a closer match with Cape Town irradiation profile at lower levels, assuming 42% energy yield at and below 500 W/m^2 but does not match properly for medium and high irradiation levels for it assumes 95% of annual yield would be harvested below 750 W/m^2 irradiation levels.
- The selected inverter's datasheet assumed η_{EURO} = 96.0% & η_{CEC} = 96.0% but when evaluated against Cape Town climate conditions, η_{EURO} = 93.08% & η_{CEC} = 92.94% (respectively 2.92% and 3.06% discrepancy) whereas the corrected formulas proposed in this study give $\eta_{\text{CPT\_EURO}}$ = 96.35% & $\eta_{\text{CPT\_CEC}}$ = 94.83%, closer to the intended efficiency.

These findings highlight the shortcomings of the Euro efficiency and demonstrate the importance of an alternative formula for weighted average efficiency of inverters operating under climatic conditions in Cape Town. These have a measurable impact on the formulation and calculation of PV inverter efficiency.

The study introduces a more reliable figure η_{CPT} or η_{SA}, a South African weighted efficiency model, derived from Cape Town (Western Cape) irradiation profile. The proposed formula was recalculated to improve its capability to correctly predict site-specific annual energy yield with weights that represent local weather data better than η_{EU} & η_{CEC}.

Based on this, future research is recommended using multiple year data on a several PV system configurations for an even more accurate figure. This research could be extended by surveying other sites across South Africa and the influence of local irradiation and temperature effect.

ACKNOWLEDGEMENTS

DEDICATION

This thesis is dedicated to God Almighty and to all the persons acknowledged above

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1. INTRODUCTION

In recent years, renewable energy (RE) sources have sparked a substantial interest worldwide and in South Africa. There is an economic reason for this trend, because an ever-increasing energy demand to sustain industrial and demographic growth is quickly depleting reserves of fossil fuels like coal (Hartnady, 2010). As these energy sources become rarefied and less accessible, their cost will keep rising. The second reason is environmental and ethical. Due to global warming and pollution from CO_2 (and other greenhouse gases or GHG) emissions are having a detrimental impact on Earth's ecosystems (NASA, 2018a; NASA, 2018b).

As a result, a total of 195 countries, including South Africa, signed and ratified the Paris Agreement, adopted in Paris in December 2015 at the twenty-first session of the Conference of the Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCCC) (UN, 2018). This accord seeks to limit the increase in global temperature below 2 degrees Celsius above pre-industrial levels (before the 1850 industrial revolution). It is the governments' answer to many surveys that have found a link between human activities and climate change (Cook, et al., 2016). In fact, seventeen of the eighteen warmest years on record (137 years) have all occurred since 2001 (NASA, 2017). There is an implicit necessity to decarbonise the energy sector since it represents two-thirds of GHG emissions (IEA, 2015). This is illustrated for example in the German energy transition, *Energiewende* (Kreuz & Müsgens, 2017).

Beyond environmental concerns, the question of energy efficiency is a very relevant subject. Addressing it will be beneficial when adapting RE power supply to localized demands for optimal performance, yield and socio-economic benefits (IRENA, 2017).

Solar Photovoltaics (PV) use the Sun as an energy source. The resource is abundant, the amount of energy reaching the Earth's surface in the form of sunlight being around 10 000 times the world's energy requirements (DGS, 2009). Also, the cost of generating power has decreased significantly in the past few years (Feldman, et al., 2012). South Africa boasts one of the best local solar energy resources worldwide, with sunshine through the whole year (DoE, 2017). This represents an attractive opportunity to encourage research and advances in solar power technologies in order to increase their contribution to the electricity grid while reducing GHG emissions (IEA, 2014).

In 2011, in South Africa, the Integrated Resource Plan (IRP) demonstrated the government's commitment to RE sources as it allowed Independent Power Producers

(IPP's) to bid portions of its targeted RE installed capacity for 2030. For this new energy mix, the Department of Energy (DOE) pledged to commission 8.4 GW of PV capacity through the Renewable Energy Independent Power Producers Programme (REIPPPP), which boosted investments into RE technologies (DOE, 2011).

Among the essential components of solar PV systems are PV modules – solar panels at fixed angle or tracking the sun –, inverters, batteries (for off-grid systems), DC and AC cabling, switchgear, surge protection and metering devices (Mertens, 2014a). The PV inverter converts the DC power (direct current) from the array of modules to AC power (alternating current) used in the electricity grid and domestic appliances.

Studies have shown that PV inverters performance depends on the weather profile in which they operate, i.e. factors like temperature and irradiation, affecting DC input voltage (Fesharaki, et al., 2011). Solar power – unlike conventional fossil fuels – is dependent on weather patterns, and the electricity production is characteristically intermittent. Therefore, the incorporation of PV power plants into SA energy nexus requires that the efficiency of this conversion is formulated accordingly. This is essential to predict the output or energy yield of PV systems as accurately as possible (Vignola, et al., 2008).

PV inverter efficiency has been formulated according to meteorological variations to provide more realistic estimations for the energy yields of PV systems. This approach produced two standards: The European and the California Energy Commission (CEC) efficiencies, developed respectively for regions with lower and higher insolation (Newmiller, et al., 2014). Despite their widespread use, referenced on PV inverter datasheets, the two formulas are based on European and Californian climates which do not match SA irradiation profiles.

There are studies in the literature that have tackled this subject in countries like Brazil, India and Turkey but a similar endeavor has yet to be been done for South Africa. Previous implementations of this approach have produced a number of alternative efficiency formulas:

- Kellermann, et al. (2015) analyse the weather profile of three cities in Brazil: Indaial, Itajai and Florianopolis (Santa Catarina state), using data from climatic stations.
- In India, Panwar et al., (2017) use irradiation profiles from various cities in Northern and Southern India to produce two distinct weighted efficiencies for the country.

- In Turkey, Ongun and Özdemir (2013) calculate a weighted conversion efficiency based on the irradiation profile of the city of Izmir collected from the Meteonorm software.

This study proposes, for the first time, a formula for inverter efficiency that is based on a local South African climate. This means that, the amount of time that the PV inverter and system spends operating under given climatic conditions and DC inputs is based is calculated under an exclusively South African weather. The energy simulations and analyses are carried out in PVSYST software with data from Meteonorm (version 7). An assessment of the results through MS Excel reveals the limitations of the EU and CEC models in predicting output for the chosen location.

Rather than relying on the Euro and CEC efficiencies, this method determines the unique variations, distribution and frequency of occurrence of DC input power, conversion efficiency and energy output under SA's climate. It also shows that using the standard efficiencies can reduce the accuracy of real energy yield estimations.

Furthermore, the characteristics of a nominal waveform can also be altered from prescribed limits by factors such as phase imbalance and harmonic distortion. A cost-effective assessment of PV harmonic current emissions based on PV power output level, rarely provided by PV inverter manufacturers, is an effective way of addressing the issue (Hernandez & Ortega, 2014; Rodriguez & Hernandez, 2015)

1.1. Aim

The aim of this dissertation is to quantify the effects that SA climate conditions have on how DC-AC conversion efficiency is expressed. This is done by first simulating a grid-connected PV system under Cape Town weather to determine its annual energy yield. Then the best efficiency formulas are determined for a PV inverter based on how it behaves under site-specific occurrences of input powers weighted by their respective contributions to the overall energy output.

1.2. Research problem statement

Weighted efficiency is generally accepted worldwide for comparing PV inverters performance and energy yields. However, the Euro and CEC benchmarks are based on German and Californian irradiation profiles that do not cover different geographical locations. This is important because different climate patterns would result in different distributions of DC inputs (Hotopp, 1990; Newmiller, et al., 2014). This questions the ability of both formulas to provide precise estimates of annual energy yields of PV

systems. There are studies that have proposed to solve this problem in some countries like Brazil, India or Turkey (Kellermann, et al., 2015; Panwar, et al., 2017; Ongun & Özdemir, 2013) but a similar endeavour has yet to be been done for South Africa. The research problem is therefore to assess the validity of Euro & CEC efficiency formulas under local climate conditions and propose an alternative model. This new formula uses weighting factors matching SA temperature and irradiation data, with Cape Town as a reference. This research sets the stage for the development of a SA-based efficiency model.

1.3.   Research questions and sub-questions

Research main question:

How can PV inverter efficiency be formulated and validated for South Africa climate conditions?

Research sub-questions:

1. How does PV inverter efficiency relate to climate data? How are η_{EURO} & η_{CEC} formulated?

2. How are temperature and irradiation distributed over a typical year in Cape Town (South Africa), compared to Trier (Germany) and Sacramento (California)?

   What is the frequency of occurrence, per year, of each irradiation class measured in Cape Town?

3. How can DC-AC conversion efficiency of a PV inverter be simulated for a 1000 W_p PV system operating under Cape Town's climate?

4. What energy – for each band of solar radiation – is available per year to be injected into the grid?

5. What influence does the use of long-term rather than 5-minute or hourly irradiation and temperature data sets have on PV energy output estimation?

6. How accurate are yield estimations based on European efficiency for Cape Town (South Africa) irradiation profile?

7. Are energy yield assumptions made by CEC efficiency valid for Cape Town (South Africa) irradiation profile?

8. Which weights can be proposed for Cape Town PV inverter efficiency formula corrected for on-site climate conditions?

1.4.   Thesis statement

Grid-connected solar PV can be a beneficial addition to the capacity of South Africa's power system. But because of the intermittency of their electricity generation, a more appropriate formula for PV inverter efficiency, with weighting factors based on local weather profile, will provide better estimates of PV system yearly energy yield.

1.5.   Objectives

The main research objective of this dissertation is to present the results of simulated analyses assessing the validity of standard PV inverter efficiency formulas under South African weather conditions, using climate data from Cape Town (Western Cape).

From this primary objective branch out a series of secondary objectives, to help accomplish the aim of the study:

- To review the methodology for expressing and assessing standard PV inverter efficiency models used by manufacturers. To review existing research on alternative PV inverter efficiency models.
- To compare Cape Town climate conditions with those considered in assumptions made by η_{EURO} & η_{CEC}.
- To compare η_{EURO} & η_{CEC} assumptions with actual DC-AC conversion efficiency of (grid-connected) inverter using η_{EURO} & η_{CEC} in the climate of Cape Town, South Africa.
- To compare the distribution of energy output among irradiation classes with those used for η_{EURO} & η_{CEC}.
- To justify the use of hourly irradiation, temperature, energy input & output and efficiency figures in this study hint at the need for further & even more detailed research using higher resolution data over a longer period.
- To determine the validity of CEC efficiency η_{CEC}, for the site of Cape Town.
- To deduce the best reformulation and adaption of η_{EURO} & η_{CEC} to Cape Town local irradiation profile.
- To draw valid and useful conclusions from the results and research findings.
  To make recommendations for future research based on these conclusions.

Research problem	Despite documented efforts to develop innovative weighted efficiencies by adapting CEC & Euro to site-specific irradiation profiles in some countries, as of today, none has been proposed for local climate conditions found in SA.	
Research main question	How can PV inverter efficiency be formulated and validated for South Africa climate conditions?	
Research sub-questions (RSQ)	Research approach(es)	Objectives
RSQ 1: How does PV inverter efficiency relate to climate data? How are η_{EURO} & η_{CEC} formulated?	Literature review	To review the methodology for expressing and assessing standard PV inverter efficiency models used by manufacturers. To review existing research on alternative PV inverter efficiency models.
RSQ 2: How are temperature and irradiation distributed over a typical year in Cape Town (South Africa), compared to Trier (Germany) and Sacramento (California)? What is the frequency of occurrence, per year, of each irradiation class measured in Cape Town?	PVSYST software analysis & simulation MS Excel data entry, computations & graphical model	To compare Cape Town climate conditions with those considered in assumptions made by η_{EURO} & η_{CEC}.
RSQ 3: How can DC-AC conversion efficiency of a PV inverter be simulated for a 1000 W_p PV	PVSYST software analysis & simulation	To compare η_{EURO} & η_{CEC} assumptions with actual DC-AC conversion efficiency of (grid-connected) inverter using

system operating under Cape Town's climate?		η_{EURO} & η_{CEC} in the climate of Cape Town, South Africa.
RSQ 4: What energy – for each band of solar radiation – is available per year to be injected into the grid?	PVSYST software analysis & simulation MS Excel data entry, calculations & graphical representation	To compare the distribution of energy output among irradiation classes with those used for η_{EURO} & η_{CEC}.
RSQ 5: What influence does the use of long-term rather than 5-minute or hourly irradiation and temperature data sets have on PV energy output estimation?	Literature review	To justify the use of hourly irradiation, temperature, energy input & output and efficiency figures in this study hint at the need for further & even more detailed research using higher resolution data over a longer period.
RSQ 6: How accurate are yield estimations based on European efficiency for Cape Town (South Africa) irradiation profile?	Graphical interpretation MS Excel data entry, calculations	To determine the validity of Euro efficiency η_{EURO}, for the site of Cape Town.
RSQ 7: Are energy yield assumptions made by CEC efficiency valid for Cape Town (South Africa) irradiation profile?	Graphical interpretation MS Excel data entry, calculations	To determine the validity of CEC efficiency η_{CEC}, for the site of Cape Town.
RSQ 8:	MS Excel data entry & calculations	To deduce the best reformulation and

Which weights can be proposed for Cape Town PV inverter efficiency formula corrected for on-site climate conditions?		adaption of η_{EURO} & η_{CEC} to Cape Town local irradiation profile.

Table 1.1. Summary of research questions, approaches and objectives

1.6.   Conceptualisation of the research

This study was conducted under key research concepts that are expanded in the next chapters.

Delimitation of the research:

This is a case study limited to Cape Town as a reference to test the suitability of η_{EURO} & η_{CEC} under South African weather. It therefore does not account for other regions within the country itself but seeks to justify the need for SA-based efficiency model, η_{SA}. Irradiation profiles vary, even within South Africa itself. Nevertheless, future studies can adjust the results for other locations like Durban, Pretoria or East London, with results specific to their own weather profile. Although this study uses hourly data, higher resolution 5-minute data could be used for even greater precision.

1.7.   Thesis organisation

This thesis comprises seven chapters and subsequently references and appendices. Chapters are structured coherently and link with each other in elaborating the thesis argument. The thesis displays the following organisation:

Chapter One: introduces and offers a descriptive explanation of the thesis title (i.e. introduction and contextualization). The problem statement, research questions, aims and objectives, delineation of the research, and the theoretical concept are indicated. The chapter concludes with a brief recapitulation of the research design.

Chapter Two: defines the key concepts and notions that are necessary to understand the origin and importance of the research problem. It explores the physics and the technical parameters linked to the operation of PV inverters, benchmarks and the status of their integration in the photovoltaic market.

Chapter Three delivers a comprehensive literature review on the current status of PV inverter efficiency formulation. It describes the development and design of both the Euro and CEC efficiency models, then explore studies that have sought to redefine these

models under different climate conditions in various countries. The availability of reliable weather data upon which a model can be simulated for a particular site is discussed. The conclusions are used to define the subsequent research methodology.

Chapter Four lays out the research design and methodology of the study, collecting meteorological data from Meteonorm 7.1 station for the site of Cape Town, and why these are the most accurate for this stochastic simulation approach. The research strategy and techniques employed for PVSYST software design and analysis of PV systems are described. Hourly data resolution and MS Excel calculations are explained for PV yield simulation.

Chapter Five describes how the weather profile, solar irradiation and temperature distribution can be simulated for the site of Cape Town to infer the correlation with evaluation classes from DC input power portions and their respective energy contributions to the simulated annual yield. The methodology for calculating weighting factors is detailed.

Chapter Six presents the research findings, the irradiation and temperature distribution and frequency of occurrence, their power and energy contributions to the overall yield. The results of calculations and simulations is interpreted to evaluate the values of the Euro and CEC efficiency at the site and deduce alternative weights more representative of the local climate.

Chapter Seven brings to the conclusion of the research by once again contemplating the research problem. A summary of the findings and solutions is presented to confirm that the main and secondary research questions have been answered and recapitulates the implications. A series of recommendations is offer in light of both the contribution and the limitations of the research, prospects and opportunities for further research are discussed.

1.8. Research methodology

To meet the objectives outlined in Section 1.5., a research methodology shown in Figure 1.2. is followed in this dissertation.

1. Review available η_{EURO} & η_{CEC} literature

2. Establish adequate methodology for η_{CPT}

3. Select input data for software analysis

4. Run PVSYST models & simulate scenarios

5. Analyse the data, recalculate η_{EU} & η_{CEC}

6. Evaluate the results & Fix weights for η_{CPT}
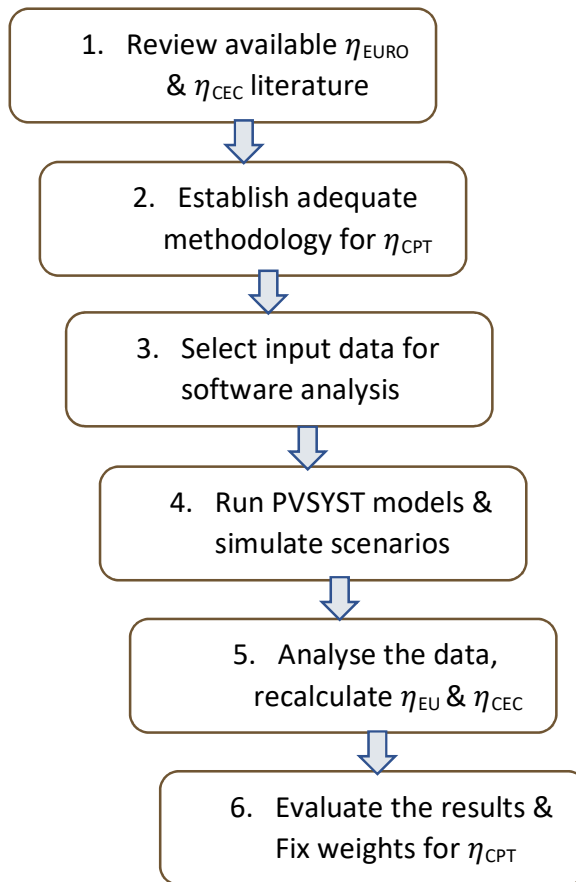
Figure 1.1. Research methodology and design

2. CONTEXT: THEORY AND BACKGROUND

Solar PV technologies rely on energy from the Sun as a source of fuel. The amount of sunlight reaching the surface of the Earth at given location and time is dependent on atmospheric conditions at the site at that moment. This intermittency of solar PV generation affects its reliability. The subsequent need to more accurately predict the annual energy yield that can be expect from PVPS – dependent on DC-AC inverter efficiency – can facilitate their incorporation into electricity grids.

This chapter explores key notions relating to PV inverters efficiency, recapitulates the physics behind their technology and outlines the context of global and South African markets. This is followed by an overview of the background of the performance of these DC-AC PV devices.

2.1. Theoretical context

A combination of the Greek word *"phós, photos"* meaning *"light, of the light"* and the name of Italian physicist *Alessandro Volta*[1] (1745-1825), the term photovoltaics implies the conversion of sunlight (photons) into electricity (flow of electrons) with semiconductor technology, using solar cells as basic components, switched together in series as the PV module (Mertens, 2014b).

PV systems can be stand-alone (off-grid) or grid-connected (on-grid). AC loads are designed to operate at prescribed voltage, phase and frequency. So, the inverter is needed to convert direct output of 12 VDC, 24 VDC or 48 VDC from solar panels or batteries to supply alternating power to 220 VAC domestic electronic devices and appliances. As critical components of PVPS, their performance directly impacts the system's efficiency and reliability. It is therefore necessary to understand how meteorological parameters can influence the performance of these devices.

2.1.1. Definitions:

Reflecting on the purchase of a solar inverter based on its efficiency, users will come across three values expressed as: peak efficiency, Euro efficiency and CEC efficiency (Martin, 2011). This study explores the dependency of PV inverter efficiency on weather

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[1] The Volt, unit of electricity, is also named after him.

conditions, making use of key terms like weighted efficiency, temperature, solar irradiance and irradiation.

a) Temperature:

In thermodynamics, temperature is the measure of warmness or coldness in a system. The Celsius scale (°C) is the most commonly used to express temperature (Al-Shemmeri, 2010).

b) Solar irradiance:

Solar irradiance is the measure of the power density of sunlight per unit area [W/m^2] (Brosz, et al., 2012). On the surface of the planet, irradiance depends on the tilt of the measuring surface, the sun's height over the horizon, and conditions in the atmosphere (Stickler, 2016). In favourable weather conditions, solar irradiance may reach 1000 W/m^2 or more at midday. Counterintuitively, the highest levels of irradiance occur on partly cloudy days as the radiation is reflected off passing clouds. In those instances, insolation levels can then reach up to 1400 W/m^2 (DGS, 2008).

c) Solar irradiation:

Solar irradiation (also called solar exposure or insolation) is the measure of the energy density of sunlight, in units of kWh/m^2 (Brosz, et al., 2012). It is essentially the solar irradiance integrated over time, i.e. measured over a month or a year.

Global horizontal irradiance (GHI) is the combination of perpendicular or direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI) dispersed by molecules and particles in the atmosphere (Brosz, et al., 2012). This is the total amount of shortwave radiation that a horizontal surface on the ground receives from above and relates to both irradiance [W/m^2] and irradiation [kWh/m^2].

$$GHI = DNI + DHI$$

d) DC-AC conversion efficiency:

The efficiency of solar PV inverters is the measure, in percent, of the conversion of DC-AC conversion and can be expressed as follows (Mertens, 2014c)

$$\eta_{INV} = \eta_{DCAC} = \frac{P_{AC}}{P_{DC}}$$

Where:

P_{AC} = alternating current (AC) power at PV inverter's output, expressed in watts [W].

P_{DC} = direct current (DC) power at PV inverter's input, expressed in watts [W].
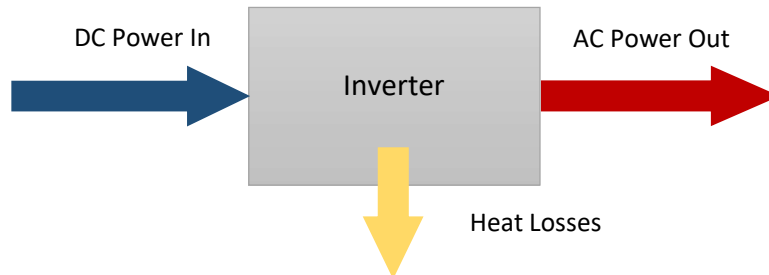
The input power P_{DC} is dependent on the current irradiation conditions, changing constantly throughout the day and DC-AC conversion efficiency varies with climate characteristics at the site's location (Rodrigo, et al., 2016). η_{DCAC} can also vary with technical characteristics: internal temperature of inverters (heat losses), the ratio between PV array peak power and the inverter's nominal power. Another factor is the stability of P_{AC} (Allet, et al., 2011a).

e) Maximum Power Point Tracking (MPPT) efficiency:

The Maximum Power Point Tracker (MPPT) is a device incorporated into the PV inverter that imposes on the PV panels the suitable voltage required to extract from them the maximum DC power P_{MPP} (Demoulias, 2010).

$$P_{MPP} = V_{MPP} \cdot I_{MPP}$$

Where V_{MPP} [V][2] and I_{MPP} [A][3] refer respectively to the voltage and current generating P_{MPP} from the PV modules.

The short circuit current I_{SC} and the open circuit voltage V_{OC}, are produced respectively when $V = 0$ and when $I = 0$. I_{SC} is dependent on the photocurrent I_{PH} which is determined by solar irradiance, the number of incident photons that the solar cells absorbed.

V_{OC} also varies according to irradiance. The quality of the solar cell or fill factor $FF = \frac{I_{MPP} \cdot V_{MPP}}{I_{SC} \cdot V_{OC}} = \frac{P_{MPP}}{I_{SC} \cdot V_{OC}}$ (Mertens, 2014d).

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[2] V = Volts (unit)
[3] A = Amperes (unit)
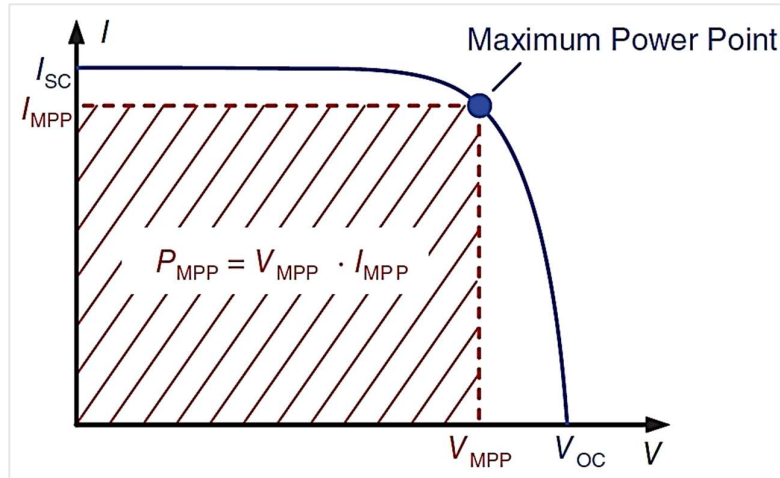
Figure 2.1. Maximum Power Point (MPP). The solar MPP-Tracker allows PV modules to receive the maximum solar radiation for optimal power.

The method to track the Maximum Power Point (MPP) can be expressed separately for stable and variable irradiance, this suggests two definitions for MPP-tracking efficiency (Maranda & Piotrowicz, 2014):

● Static MPPT efficiency ($\eta_{MPPT-static}$) applies to the inverter operating under stable weather conditions. In this case, the MPP position is fixed.

● Dynamic MPPT efficiency ($\eta_{MPPT-dynamic}$): is used under highly variable irradiance (variation of more than 100 W/m^2/s), there is an increase in the deviation between inverter DC input and the true MPP, with its location constantly moving. Depending on the quality of the tracking algorithms or the MPPT functions, it can take up to several seconds to identify the new MPP (Maranda & Piotrowicz, 2014).

MPPT functions are available for certain charge controllers; nevertheless, it is not the norm for battery-based inverters to include MPP-Tracking. The total efficiency is the product of MPP tracking efficiency η_{MPPT} and DC-AC conversion efficiency η_{DCAC} (Burger & Ruther, 2005). While DC-AC conversion efficiency can be determined solely from measurements of the generator power (P_{DC} & P_{AC}), tracking efficiency can only be approximated (Allet, et al., 2011).

f) Peak inverter efficiency:

The peak efficiency of a solar PV inverter indicates its performance at optimal power output. It is the highest figure the inverter can achieve. It shows the MPP for a specific inverter and can be used as an indication of its quality. But in practice, it is not as important as the actual efficiency when operating the system (Fedkin, 2017).
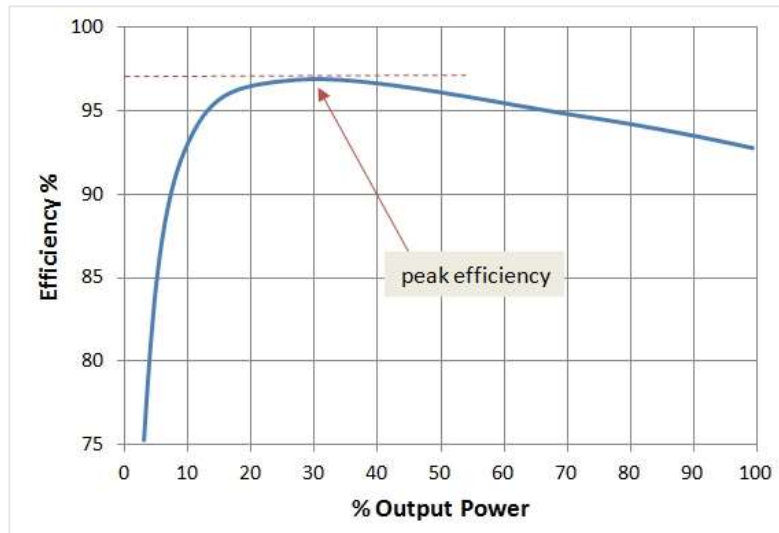
Figure 2.2. Archetypal basic inverter efficiency curve. Efficiency is rather low under 10-15% of power output. At high output power, however, efficiency gradually increases but with some minor deviations.

g) Weighted efficiency:

Weighted efficiency, calculated for a PV inverter, is a formula in which some DC input levels are selected as values in percent relative to the inverter's rated capacity. These are coefficients that "weigh" the importance of inverter performance at each level, based on assumptions about how often the inverter will operate at each one of them (Fedkin, 2017).

From a practical point of view, inverter's average efficiency over a whole year is more conclusive than the peak efficiency. The measure of the frequency with which various classes of radiation occur at a given PV plant site show the energy portions that these respective radiation classes contribute to overall annual energy yield (Mertens, 2014e).

For example, in Fig. 2.4., weather data from Freiburg (Germany) show that low radiation classes observed over the year 2000 at that site provide relatively high-power portions (Burger & Ruther, 2005). With radiation measurements taken at close intervals as "momentary values" (10 seconds averaged), vertical bars represent the energy portions that the respective radiation classes contribute to the overall annual solar energy. The first bar, for instance, shows that the irradiance between 0 and 50 W/m^2 contribute almost 1.5% to the annual energy. The irradiance up to 500 W/m^2 over the year amounts to approximately 30% of the overall energy.
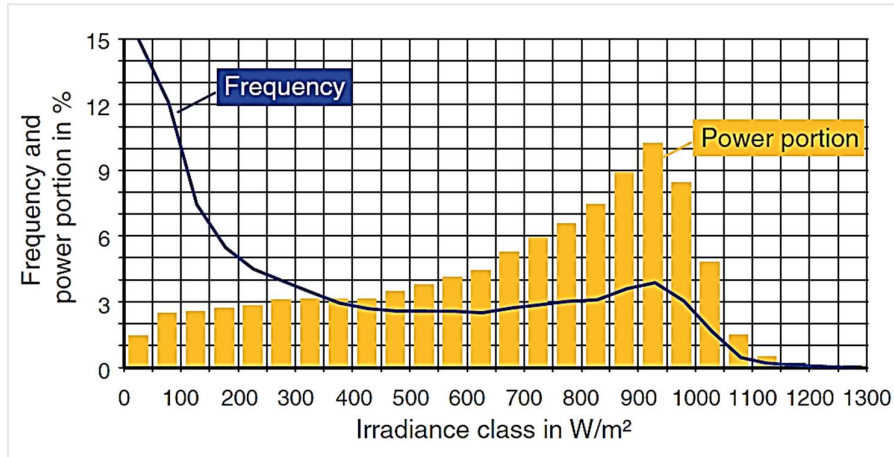
Figure 2.3. A graph showing relative frequencies of solar radiation in the year 2000 as well as annual energy portions of the individual radiation classes in Freiburg (Germany)

h) Euro efficiency & CEC efficiency

On the inverter market, there are two main standard weighted efficiencies, widely used to compare PV inverters: The Euro weighted efficiency η_{EURO} and the CEC weighted efficiency η_{CEC}, with weighted formulas structured as follows (Ongun & Özdemir, 2013):

- $\eta_{EURO} = a_{EU1} \cdot \eta_{MPP1} + a_{EU2} \cdot \eta_{MPP2} + a_{EU3} \cdot \eta_{MPP3} + a_{EU4} \cdot \eta_{MPP4} + a_{EU5} \cdot \eta_{MPP5} + a_{EU6} \cdot \eta_{MPP6}$

- $\eta_{CEC} = a_{CEC1} \cdot \eta_{MPP1} + a_{CEC2} \cdot \eta_{MPP2} + a_{CEC3} \cdot \eta_{MPP3} + a_{CEC4} \cdot \eta_{MPP4} + a_{CEC5} \cdot \eta_{MPP5} + a_{CEC6} \cdot \eta_{MPP6}$

a_{EUi} et a_{CECi} represent the weighting factors and η_{MPPi}, the static MPPT efficiency at partial MPP power, P_{MPP}/P_{STC} [%], where P_{STC} is the rated power at Standard Test Conditions (Solar irradiance = 1000 W/m^2 and Temperature = 25°C).

2.1.2. PV inverter electronics

An understanding of PV inverter performance in PV systems presupposes a comprehension of the underlying electronics behind the conversion of DC power from batteries or solar cells into AC power. The following segment recapitulates basic electrical concepts essential to the understanding of inverter technology.

Direct current (DC) is a unipolar electric current, i.e. a flow of electrical charge in one direction, with no variation in polarity (or poles) between positive and negative values over time. Most electronic circuits operate on DC power.

Alternating current (AC) is bi-polar electric current, i.e. an oscillating flow of electrical charge. With each cycle, the two poles fluctuate between positive and negative values, periodically reversing the direction of the flow (Dunlop, 2012a).

DC and AC circuits have characteristic waveforms, electrical signals that varies over time and can be periodic, repeating themselves in cycles. Inverters are characterized by their AC output waveform (Dunlop, 2012b).

DC waveforms can be constant like in the case of battery voltage or current, or time-varying, like in a rectifier circuit. DC waveforms can be broken down into a constant component (DC), that represents the average value of the voltage (or current) over time, and a time-varying component (AC) with an average value equal to zero. DC waveforms have therefore no definable cycle, and their frequency is zero (Dunlop, 2012a).
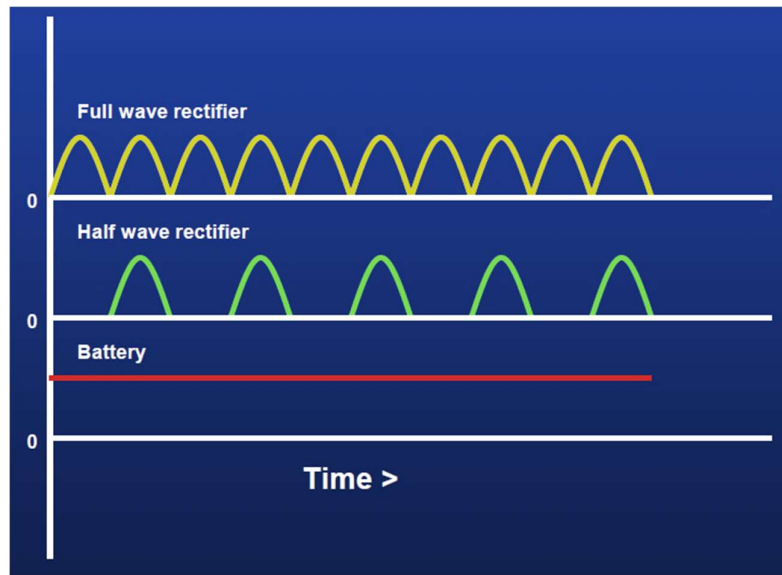
Figure 2.4. DC Waveforms

Common examples of AC waveforms include sine waves, square waves and modified squared waves. The catalogued interactive inverters produce utility-grade sine wave output whereas certain smaller and lower-cost stand-alone inverters yield modified square wave or square wave output (Dunlop, 2012a).

The PV inverter's electrical power is the rate at which it transfers energy to the grid, expressed in units of watts [W], kilowatts [kW] or Megawatts [MW].

Electrical energy E is the total amount of work performed – the average power transferred – by the device over time. It is expressed in units of watt-hours [Wh] or kilowatt-hours [kWh].
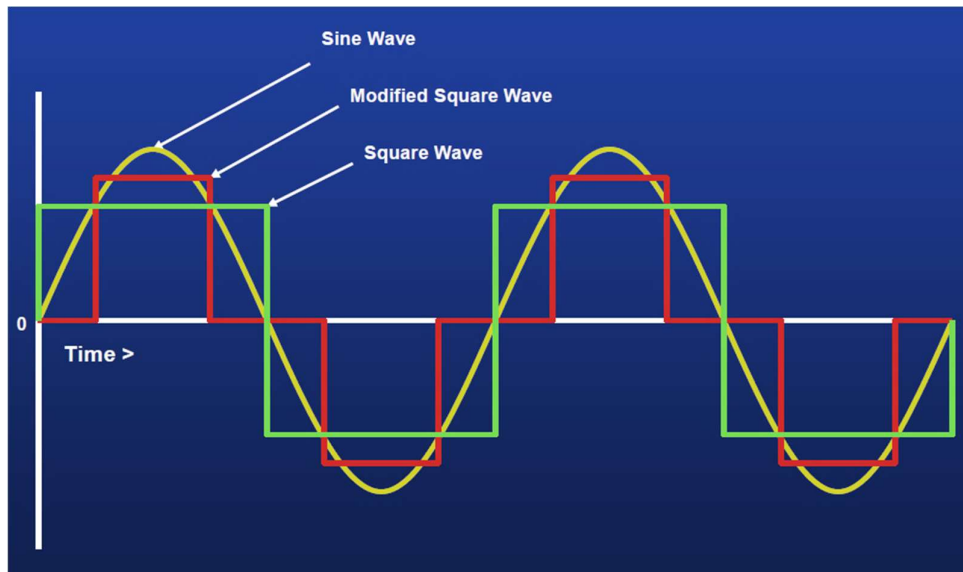
Figure 2.5. AC Waveforms

$$E \ [\text{Wh}] = P_{AVG} \ [\text{W}] \times T \ [\text{h}]$$

For instance, if a household's electrical energy consumption is 30 kWh/day. This corresponds to an average electrical power demand of:

30 kWh/day ÷ 24 hours/day = 1.25 kW.

In AC circuits, the calculation of real power [W] is relative to the phase angle difference between the current and voltage waveforms. Also called true power or active power, it defines the AC power component that produces useful work. Root Mean Square (RMS) is a statistical parameter representing the effective value of a waveform signal or other time-varying function. It is commonly used as a measurement of for AC voltage and current waveforms. It is defined as the square root of the mean (average) of the squares of the waveform values but is not necessarily the "average" value of the waveform since the relationship depends on the type of waveform. The AC RMS voltage is equivalent to the DC voltage that will deliver the same power as the AC voltage waveform (Dunlop, 2012b)

Reactive power [VAR][4] is the component of AC power that generates magnetic fields or stores energy in equipment but performs no useful work. Apparent power [VA] is the combination of active and reactive power. It is the product of RMS voltage V_{RMS} and current I, expressed in volt-amperes. The power factor PF represents the ratio of the active power to the apparent power and equal to the cosine of the phase angle. Some

---

[4] Volt-ampere reactive

inverters can produce reactive power, therefore their power output is often given in VA or kVA, instead of W or kW.

$$P_{APPARENT} = \sqrt{P_{ACTIVE}{}^2 + P_{REACTIVE}{}^2}$$

$$P_{APPARENT} = V_{RMS} \times I$$

$$P = V \times I \times \cos\theta$$

$$P = V \times I \times PF$$

Where

P = power [W]

V = voltage [V]

A = current [A]

θ = phase angle [deg]

In 3-phase circuits;

$$P = V \times I \times \cos\theta \times \sqrt{3}$$

Frequency, the number of AC waveform cycles that repeat in one second, is important when synchronizing AC electrical systems. It is expressed in units of Hertz (Hz). The frequency of the U.S. electric grid is sustained at 60 Hz. In South Africa – like in Europe and Asia – the standard frequency at which power generators are synchronized to the national grid is 50 Hz (Eskom, 2017).

The period T, the inverse of frequency ($F = \frac{1}{T}$), is the time (seconds) it takes a waveform to complete one complete cycle before it repeats itself (Dunlop, 2012b). Amplitude (or peak) is the maximum absolute value of the signal of the AC voltage waveform, the maximum deviation from zero during one cycle. The difference between the positive and negative maximum values of the waveform is called peak-to-peak.

For a pure sine wave, the ratio between the peak voltage and the RMS voltage is the square root of 2:

$$V_{PEAK} = V_{RMS} \times \sqrt{2} = V_{RMS} \times 1.414$$

$$V_{RMS} = V_{PEAK} \times 0.707$$
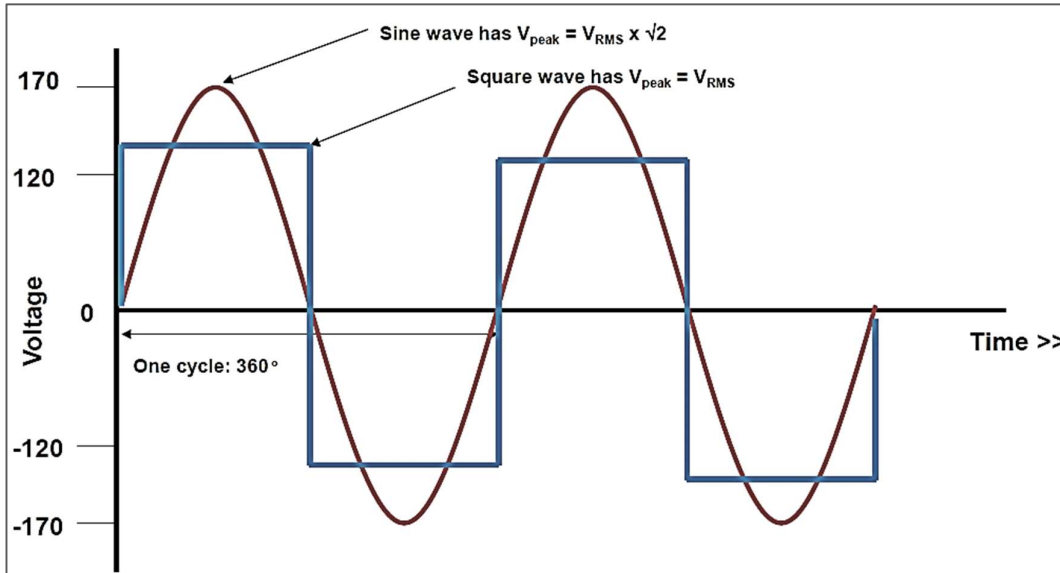
Figure 2.6. Peak and RMS voltages

A typical AC voltage sine wave with a peak voltage of 170 V, for example, has an RMS voltage of 170 × 0.707 = 120 V

For pure sine waves, the average voltage is also related to RMS and peak voltage by:

$V_{RMS} = 1.11 \times V_{AVG}$ or $V_{AVG} = 0.9 \times V_{RMS}$

$V_{AVG} = 0.637 \times V_{PEAK}$ or $V_{PEAK} = 1.57 \times V_{AVG}$

Among periodic waveforms frequently associated with AC power systems is the characteristic sine wave.
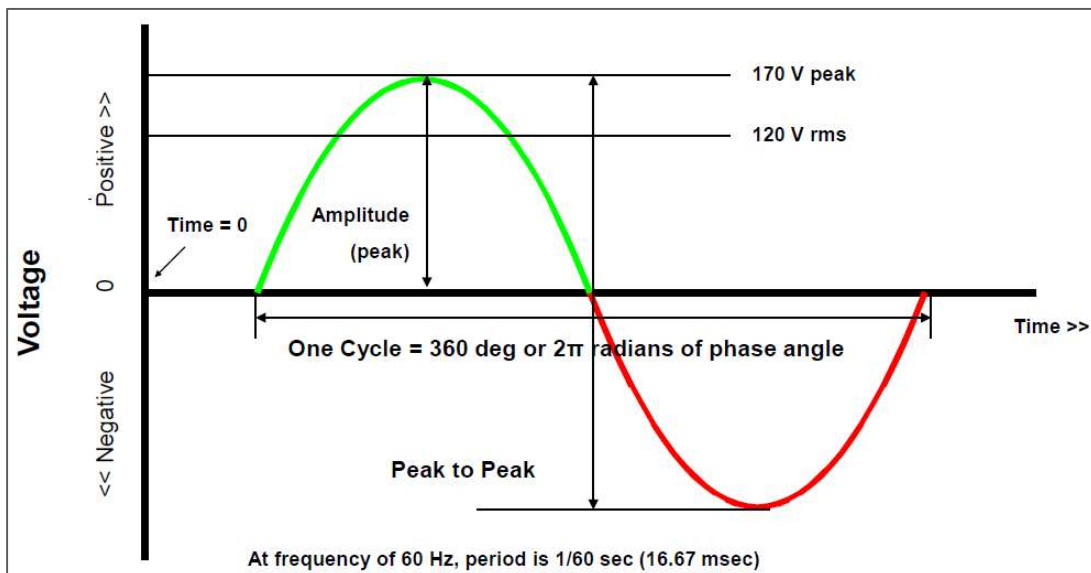
Figure 2.7. AC Waveform properties

For a true square wave, V_{AVG}, V_{RMS} and V_{PEAK} have the same value (Dunlop, 2012b).

True RMS devices are used to measure AC current and voltage, sinusoidal and non-sinusoidal waveforms (Fluke Corporation, 2018)

Figure 2.8. True RMS Meters, from right to left: Fluke 117, Fluke 325, Fluke 87V

The characteristics of a nominal waveform can be altered from prescribed limits by a series of that impact the operation of electrical loads, the power quality. These include: the power factor, voltage regulation (drop and surges) and imbalance, frequency regulation, phase imbalance and harmonic distortion. Inverters used in PVPS must produce AC output waveforms within acceptable limits of power quality (Dunlop, 2012c).

An oscilloscope measures the magnitude variation of a waveform signal over time, and displays this information in graphical form. These instruments can measure peak, RMS and average values fr waveform signals, and some can also measure power quality parameters, such as harmonic distorsion, power factor, inrush currents, and other data (Fluke, 2018).

Figure 2.9. Oscilloscope Fluke 190-204 ScopeMeter and Fluke 43B Power Quality Analyzer

2.1.3. PV inverter technologies and configurations

PV inverter technology and design are two characteristics that impact its conversion efficiency. An understanding of the compatibility between different types of electrical services and the inverter output specifications is important for designing and installing grid-connected PV systems. Transformers in PV inverters convert AC voltage from one level to another, isolating the DC input from the AC output and acting as an interface between the AC output and different utility services or distribution voltages.
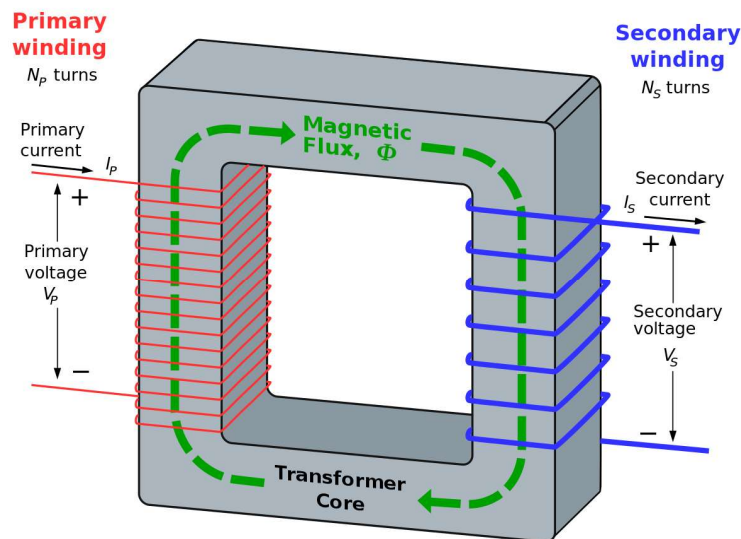
Figure 2.10. Transformer of a PV inverter

The transformer, an integral part of most inverters, transfers AC power from one circuit to another by means of magnetic coupling. Its basic design consists of two or more windings coupled around a magnetic core. AC current in one winding creates a time-varying magnetic flux in the core, this induces a voltage in the other windings. Several high-speed switching inverters use lighter weight and more compact high frequency transformers. A three-phase transformer is made of three sets of primary and secondary windings wrapped around an iron core. Transformers cannot convert DC to AC or vice versa nor can they modify the voltage or current of a true DC signal or the frequency of an AC supply (Dunlop, 2012d).

a) *Single-phase systems:*

They are characterized by a single AC source, only have one voltage waveform. One example are split-phase systems; they have multiple in-phase AC voltage sources connected in series, delivering multiple load voltages. They are commonly used to distribute electrical services to residential and small commercial customers.
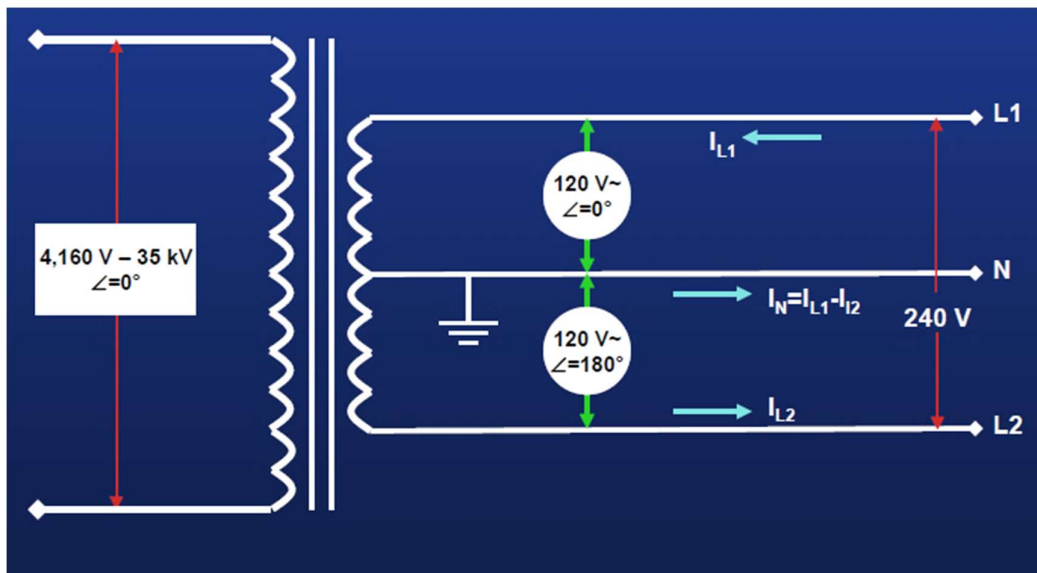
Figure 2.11. Single-phase/split-phase system

Small interactive inverters under 10 kW are often connected to these systems, or they may be connected in groups of three across each phase of a three-phase system.

b) *Three-phase systems:*

They can be designed in two configurations.

- In the Wye "Y" or "star" configuration, the phase and line currents are always equal. The line voltage between any two phases is equal to the phase voltage $\times \sqrt{3}$
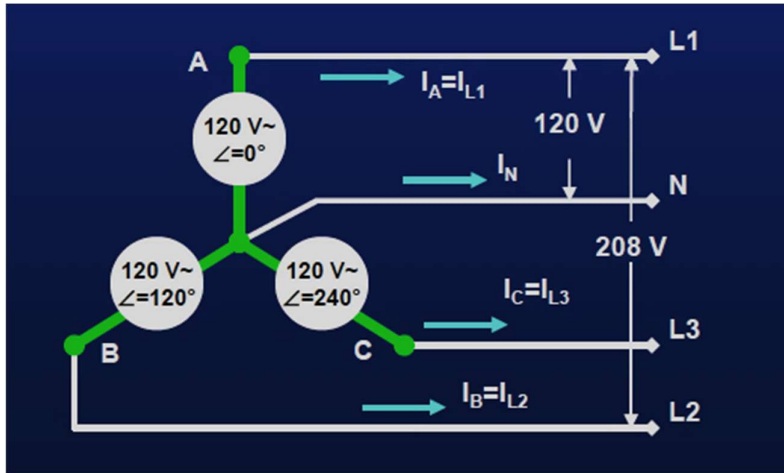
Figure 2.12. 4-Wire, 120/208 V - Wye "Y" configuration

Three-phase power is characterized by three separate voltage waveforms occurring simultaneously each cycle. Large inverters are designed to produce three-phase AC outputs (Dunlop, 2012c).

- In the Delta "Δ" configuration, the line voltage and phase voltages have the same value whereas the line current is equal to the phase current $\times \sqrt{3}$.
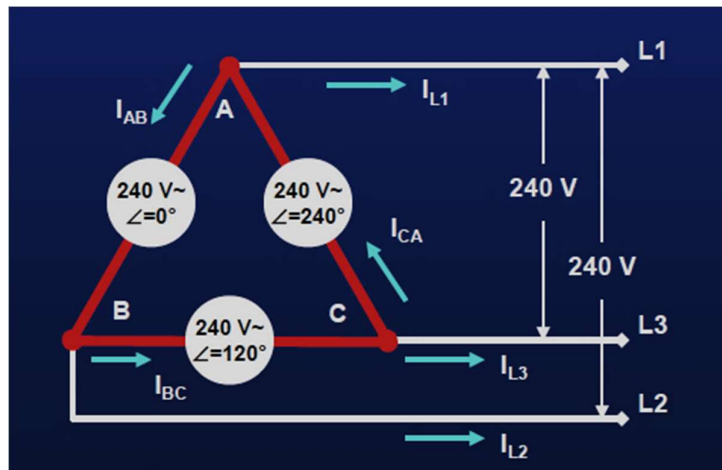
Figure 2.13. 3-Wire, 240 V - Delta "Δ" configuration

Larger inverters 30-50 kW and higher are interconnected to delta or wye configured three-phase power systems.

Inverters use different circuit designs and components. Transistors with high-switching speed convert DC to AC power. For high-power applications (up to several Megawatts), large thyristors are used to transmit HVDC power at grid-interties. Most inverters use metal-oxide semiconductor field-effect transistors (MOSFETs) or insulated gate bi-polar transistors (IGBTs). Switching at very high speeds (up to 800 kHz), MOSFETs operate at

lower voltage and resistance but higher efficiency than IGBTs; they are usually used for low-power applications (1-10 kW). IGBTs can withstand high current and voltage but switch at lower speeds (up to 20 kHz); they are suited for large-power applications (reaching 100 kW and over). Often the current and power capacity are increased by connecting switching components in parallel (Dunlop, 2012e).

c) *Grid-connected, utility-interactive or line-commutated inverters:*

An external source, for instance utility power triggers the switching device and synchronize their output. This type of inverter cannot operate in standalone mode, independently of the grid; drawing from PV arrays, they supply power in parallel with an electrical production and AC distribution network. The commutation (switching DC to make AC) is triggered by the AC source. Therefore, they do not supply power to loads during loss of grid voltage and energy storage is required. Local AC loads may be served by the inverter output, the utility or both. The excess power flows to the grid.

Interactive PV inverters are available from numerous manufacturers with AC power ratings ranging from around 200 watts for small module-level micro-inverters, to 500 kW - 1 MW for large commercial and utility scale inverters (Dunlop, 2012f).

Interactive inverters typically connect to the grid at the site's distribution panel or electrical service entrance. The AC output, independently of the AC loads, only requires an energy grid to operate. Utility-interactive inverters range from module-based microinverters with rated AC power output of the order of 200 W up to single units with outputs from 500 kW to 1 MW and larger.
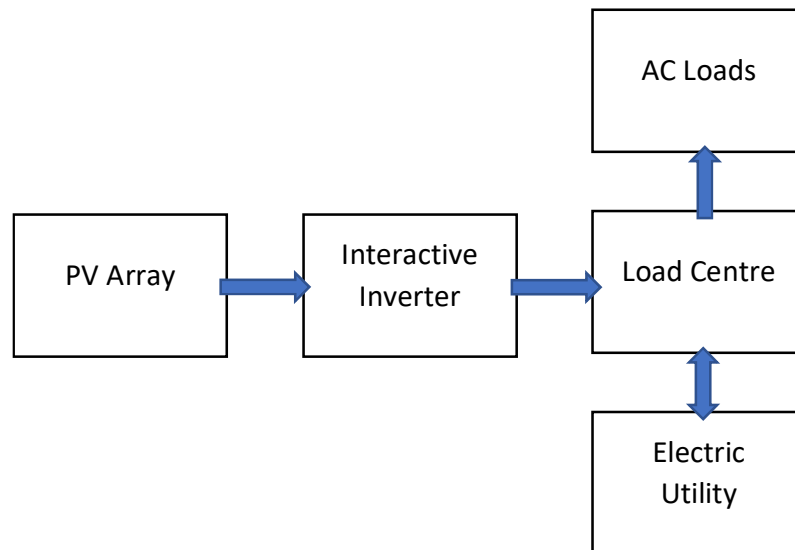
Types of interactive inverters include:

- *Module-level inverters* are rated 200-300 W for maximum AC power output – consistent with standard PV module sizes. They include AC modules (factory-integrated PV modules with interactive inverters) and micro inverters fitted at PV module level, similar in concept but as separate equipment. They achieve greater energy yield from partially shaded and multi-directional arrays. They have the advantage of individual module MPPT, minimizing the DC wiring and issues in source circuit design (Dunlop, 2012g)

- *String inverters* (1 to 12 kW) use one to six PV array source circuits connected in parallel, called "strings". A string consists of one or more PV modules connected in series, defining the system's DC bus voltage. They are connected in parallel at PV inverters and combiner boxes to build up higher array outputs. In large systems, multiple string inverters are distributed at subarray locations, avoiding a unique DC run. They provide redundancy in the event of failure of an individual inverter or the subarray, but also MPPT and monitoring at subarray level. This makes it easier to detect faults and optimizes the output of individual subarrays of various size, type, orientation or partially shaded. The AC output of multiple string inverters can be distributed equally across the three phases in groups of three, preventing phase imbalance (Dunlop, 2012h).

- *Central inverters,* rated from 30-50 kW up to 500 kW, interconnect to 3-phase grids and are designed for homogenous arrays (same modules and source circuit configurations, aligned and oriented in the same direction without shading).

- *Utility-scale inverters:* (500 kW-1 MW) for solar farms, PV power plant installations interconnected to the grid at distribution voltages (in kilovolts or kV). Most commercial grid-connected PV inverters with a rated up to 500 kW and that are mounted for public and private facilities operate at voltage less than 600 VAC. These inverters use higher DC input and AC output voltages to reduce losses, and the size and cost of the conductors and switchgear required. Packaged systems include inverters, transformers, switchgear, climate-controlled enclosure and a pre-designed mounting platform.

- *Bimodal inverters:* (2-10 kW) are battery-based interactive inverters that provide grid backup to critical loads. They can operate either in interactive or stand-alone mode, but not simultaneously. Using batteries for DC power input, they act as diversionary charge controllers. In interactive mode, the inverter supplies AC power output

proportionally to PV array generation, while maintaining a prescribed maximum battery voltage. When grid voltage is lost, the inverter automatically transfers to stand-alone mode, and transfer back-up loads off-grid. Controlling the load, charging the battery and starting the generator can also be included among their functions (Dunlop, 2012i).

- *Bipolar inverters:* use two monopole PV subarrays for DC input, with a positive and negative pole, and a centre tap ground. The maximum voltage to the inverter bus is 1200 VDC. +600 VDC and -600 VDC PV output circuits are referenced to ground and each monopole arrays are run in separate circuits.

d) *Stand-alone, battery-based, interactive or self-commutated inverters:*

- *Stand-alone inverters* operate from batteries and supply power, independently of the utility grid, to AC loads isolated from the grid. These inverters may also include a battery charger to operate from an independent AC source, such as a generator or a grid. They cannot synchronize with and feed power back into the grid. Their AC output regulation depends on input voltage. It is required that the output power rating for stand-alone be at least equal to the single largest connected load. Available on the market from as little as 50 watts but generally in the range of 4 to 6 kW, their common DC input voltage is 12 V, 24 V and 48 V for residential applications, and up to 480 V for industrial applications.
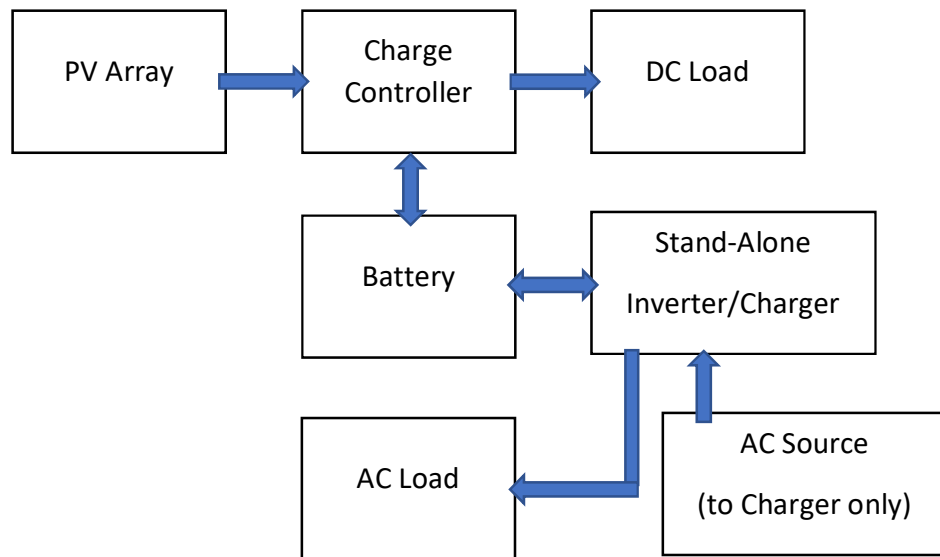
- *Self-commutated inverters*, operating on or off-grid, use an internal switching device, software and controls that can monitor the output AC current and voltage waveforms.

Most currently used PV inverters are interactive. They can use DC input as a voltage or current source to produce AC output voltage or current at constant amplitude with variable width. Most grid-connected inverters designed to operate directly from the PV are current source types (Dunlop, 2012j).

Due to exceedingly large battery banks, higher current operation, and large conductor sizes required generally limits battery-based inverters to around 25 kW to 50 kW for large remote power installations. Stand-alone and interactive PV inverters both generate AC power from DC power, however they have different applications and functions (Dunlop, 2012f).

```
┌──────────┐      ┌──────────────┐      ┌──────────┐
│ Battery  │ ───▶ │ Stand-Alone  │ ───▶ │ AC Load  │
│          │      │   Inverter   │      │          │
└──────────┘      └──────────────┘      └──────────┘
```

Stand-alone operation with battery as DC power source:
AC load is limited by inverter power rating

```
┌──────────┐      ┌──────────────┐      ┌──────────────┐
│ PV Array │ ───▶ │ Interactive  │ ───▶ │ Utility grid │
│          │      │   Inverter   │      │              │
└──────────┘      └──────────────┘      └──────────────┘
```

Interactive operation with PV array as DC power source:
PV array size is limited by inverter power rating
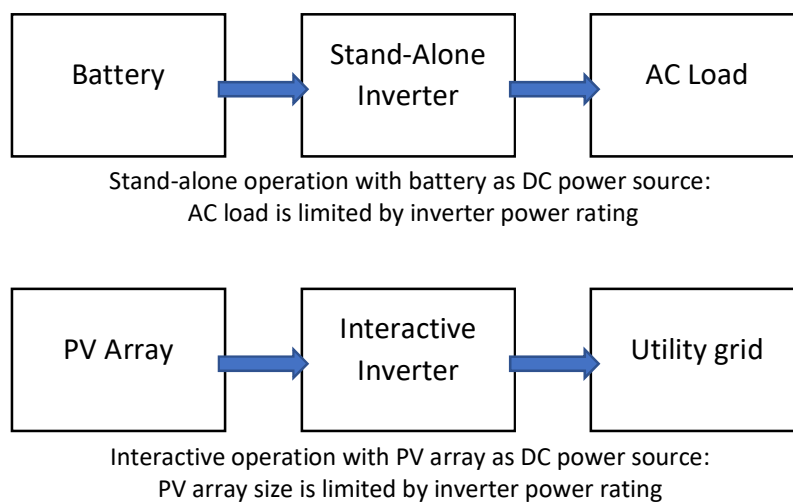
e) H-Bridge inverters:

They convert 12 VDC to a 120 VAC square wave using a 10:1 turn ratio transformer. The DC input current will be slightly greater than 10 times the AC output current.

f) Push-pull inverters:
They generate a square wave from bi-polar DC source using a centre-tap transformer (Dunlop, 2012k).

g) Low-frequency inverters:

Because of their design (H-bridge or push-pull inverter circuits), the resulting AC output is stepped up to higher voltage through a transformer. *Pulse-width-modulation (PWM)* controls the RMS voltage output via switching devices to regulate the AC output waveform of inverters. PWM control is also used to construct a true sine wave (Dunlop, 2012k). *Multistage low-frequency inverter* designs use parallel circuits to synthetize true sine waves.

PWM sine wave Inverters, use PWM control to simulate multi-stage AC waves by superimposing square waves of variable amplitude and width.

h) High-frequency inverters:

They use DC-DC converters and smaller transformers to step up DC input voltage all the way to higher levels or use higher voltage PV array, resulting in highly efficient and lightweight designs. The DC power is then inverter to AC power at high frequency without the need of a large 50 or 60 Hz transformer. PWM control can be used on the inverter output as a final switching stage to reduce frequency to produce 50 or 60 Hz AC power (Dunlop, 2012k).

2.2. Background

2.2.1. PV inverter selection

To identify and select the best inverter for a given application, PV system design and installation requirements must be considered (Dunlop, 2012l). For this, inverter manufacturers sheets are critical. Inverter selection is often the first consideration and is based on:

- The type of electrical service and voltage.
- Anticipated size and location of the arrays.

Since it won't operate at 100% conversion efficiency, an inverter may require a power input that exceeds its output, in order to harvest its rated power. For example, a 5000 W inverter operating at full power at 95% efficiency will require an input of 5,263 W (rated power divided by efficiency).

For interactive inverters, optimal DC ratings for the PV array can be 110-130% of the inverter maximum continuous AC power output rating. But the efficiency specified by manufacturers is obtain using a formula calculated under site-specific conditions, which means calculations based on them might not provide an accurate representation of the actual yield.

2.2.2. PV inverter specifications

Stand-alone and interactive inverters have comparable but different specifications due to their different applications.

Standard specifications for all types of inverters include:

- AC output power ratings
- DC input voltage
- AC output voltage
- Power conversion efficiency (Euro or CEC)

PV system inverters have several specifications and features that establish their performance capabilities, intended operating parameters and limits (Dunlop, 2012m).

a) *Interactive inverter specifications*
- *DC INPUT:*
  - Maximum array voltage V_{OC}
  - Start voltage and operating range
  - Maximum usable input current
  - Ground fault and arc fault detection
  - Recommended maximum array power
  - MPPT voltage range
  - Maximum array and source circuit current
- *AC OUTPUT:*
  - Maximum continuous output power
  - Power quality
  - Anti-islanding protection
  - Maximum continuous output current
  - Maximum output overcurrent device rating
- *PERFORMANCE:*
  - Nominal and weighted efficiencies
  - Stand-by losses (night-time)
  - Monitoring and communication interface
- *PHYSICAL SPECIFICATIONS:*
  - Operating temperature range
  - Mounting location, enclosure type
  - Size and weight
  - Conductor termination sizes and torques specifications
  - Conduit knockout stages and configurations

- *Other features:*
- Integral DC or AC disconnects
- Number of source circuit combiner boxes and fuse or circuit ratings
- Standard and extended warranties

Inverter AC power ratings are limited by the temperature of their switching elements. They operate over a certain temperature range and large ones use cooling fans.

Stand-alone inverters limit power output by disconnecting AC loads when their maximum DC input current is exceeded while interactive inverters do it by tracking PV arrays for maximum power points. Interactive inverters are rated for their maximum DC input

current, and their maximum continuous AC output current rating is used to size conductors and overcurrent protection between the inverter and point of utility interconnection (Dunlop, 2012m).

The AC output voltage for all inverters is defined by common electrical system configurations and utility voltage standards. Some inverters allow configuration for a variety of output voltages (Dunlop, 2012m).

b) *Inverter applicable standards*

The following standards apply PV inverters and include requirements for product listing, installation and interconnection to the grid. An overview of international and South African standards and guidelines for high quality PV installations and best practices.

- *UL 1741* standard for Inverters, Converters, Controllers, and Interconnection System Equipment for Use with Distributed Energy Resources: It concerns both stand-alone and interactive inverters.
- *IEEE 1547* standard for Interconnecting Distributed Resources with Electrical Power Systems: For interactive inverter systems (Dunlop, 2012m).
- *IEC 61683* & *EN 505 30* standards for energy efficiency specifications for inverters.
- *IEC 60255-26* standard for measuring relays and protection equipment – Part 26 is for requirements about electromagnetic compatibility.
- *IEC 603-7-712* standard for low voltage electrical installations – Part 7-712 is about the requirements for special installations or locations and solar PV power supply systems.
- *IEC 62109-1* & 62109-2 *standards* for the degree of protection provided by the enclosures of the electrical equipment. Part 1 describes general safety requirements for inverters and power converters (BSW Solar, 2016).
- South African Grid Code Requirements for Renewable Power Plants

The emergence of grid-connected PV systems is part of government plans all over the world to integrate solar power generation into electric grids and microgrids. Japan, Germany, the Netherlands, Switzerland and Austria have developed such programmes to implement residential PV installations. And South Africa is determined not to fall behind. Countries like Israel have been focuses on adapting PV to their specific climates and France envisions stand-alone PVPS set in rural areas, a less expensive option than extending the grid (IEA, 2000).

The more data are available on the localized integration of these technologies, the better scientists can grasp its benefits and achieve significant breakthroughs. This is the importance of scientific enquiry and research. South Africa has a rapidly increasing

electricity demand but also vast solar resources. The National Energy Act (2008) preconized a diversification of energy sources to include renewables into the energy mix but also improvements in energy efficiency (GoS, 2008)

c) *Inverter monitoring*

Monitoring functions are available for all interactive inverters. Data viewing points, inverter panels and communications interfaces record and display important information about the way interactive inverters operate and perform:

- DC input operating parameters (array voltage, current and power)
- AC output parameters (grid voltage, current and power)
- Energy production and error codes (indications for several fault scenarios that can trigger a failure)
- MPPT status

Sensors for temperatures and solar radiation can be added to the device after acquiring the inverter. Many interactive inverters measure and record energy production on a daily and overall basis. This enables the operator to analyse the performance of the system (Dunlop, 2012n).

d) *International and SA manufacturers and suppliers of PV inverters*

Leading manufacturers of commercial and utility-scale inverters 100 kW and higher include: Advanced Energy, Fronius, Ingeteam, KACO new energy, Power-One, PV Powered, Satcon Technology, Schneider Electric, Siemens Industry, SMA Solar Technology, Solectria Renewables, etc.

The city of Cape Town has a list of approved grid-tied PV inverters (Cape Town Gov, 2018). In South Africa, the inverter market is an emerging industry but still dominated by imported products. This is because inverters manufactured locally (35%-75% depending on the manufacturer) tend to be more expensive.

Local Market Leaders	Other International Suppliers
- AEG - TUB (setting facility to manufacture JEMA inverters) - MLT Drives	- SMA - CACO - Victron - Outback

• Microcare	
• SMA	

Table 2.1. PV inverter technology providers and market leaders in SA
source: (Maphelele, et al., 2013)

Climate conditions being a crucial parameters, studies have proposed different formulas for weighted efficiency in North America (California, United States) (Newmiller, et al., 2014), in Europe - Germany, Italy, Switzerland (Allet, et al., 2011a) & Turkey (Ongun & Özdemir, 2013) -, in Asia (India) (Panwar, et al., 2017) and Turkey. In South Africa, researchers should seize this opportunity to increase the reliability of local PV systems energy contribution to SA's grid.

2.3.   Conclusions & summary

- PV inverters have two main functions: They convert DC power input to AC power suitable for AC loads and keep the PV generator at the MPP.

- Different components and types of circuitry are used in a variety of designs.

- Stand-alone inverters extract DC power from batteries and supply AC power to AC loads off-grid whereas interactive inverters operate from PV arrays, producing AC power and interacting with the power grid. Both categories are rated for their DC input and AC output voltages. There are various types of interactive inverters available: module-level, string, central, utility-scale and bimodal inverters.

- Most inverters use monitoring and communications functions to record and display parameters of system operation, fault conditions and performance data (Dunlop, 2012o).

- In South Africa, international and national standards apply to PV inverters. The IEC 61683 standard deals with PV inverter efficiency.

- Inverters operate within a temperature range that limits their AC power ratings.

- Because temperature and irradiation influences DC input, climate conditions have an effect on PV inverter efficiency. Subsequently, the Euro and CEC efficiency would not be as accurate under SA's weather patterns.

3. LITERATURE REVIEW

The literature review investigates the origin of the research problem (Nallaperumal, 2014), understands what is already known about the simulation of PV inverter performance, the formulation and validation of weighted efficiency under dissimilar climate conditions.

This chapter explores important literature on PV inverters, the Euro & CEC efficiency formulas for estimates of annual PV systems energy output. It shows what can be summarized from various studies that have adapted those models to specific locations and papers that have proposed alternative weighted efficiencies more descriptive of particular sites.

3.1. Standard formulation of PV inverter efficiency

3.1.1. η_{DCAC} and $\eta_{DCAC\_WEIGHTED}$

Inverters are rated by the amount of AC power they can supply continuously. Their efficiency curve is shaped by the DC inputs they receive from PV modules. This input is determined by factors like PV module temperature T_{PV} and irradiance. The weighted efficiency used on the manufacturer's datasheets therefore reasons that they will not always operate at 100% of the nominal power (Mertens, 2014f). This suggests that over the year, and indeed over different hours of the day, η_{DCAC} will have different values. Accordingly, the use of maximum rated efficiency to predict how much energy will be produced by the PV system will return inaccurate estimations which do not weigh up those changes.

The weighted efficiency $\eta_{DCAC\_WEIGHTED}$ incorporates those variations, averaged for a number of DC input intervals and weighted by their contribution to the total energy production. The DC inputs are expressed as MPP power portions which represents the ratio P_{MPP}/P_{STC}. Their contribution to the annual energy yield does not just depend on how large their values are but also on their frequency of occurrence at the site. This occurrence is related to the irradiation and temperature characteristic of the location which influences voltage V_{MPP} and current I_{MPP} and therefore P_{MPP}. Thus, the link between climate conditions, $\eta_{DCAC\_WEIGHTED}$ and annual PV energy yield is established. Most interactive PV inverters have weighted efficiencies of 95% and higher (Dunlop, 2012m).
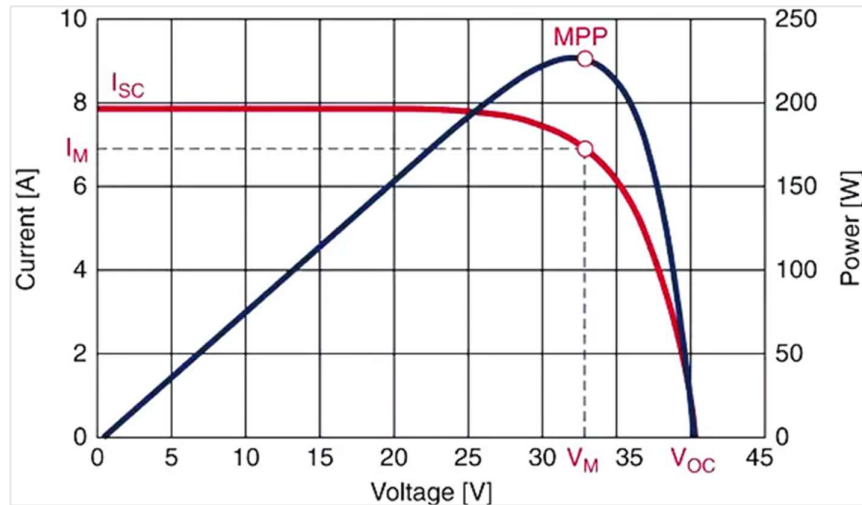
Figure 3.1. Maximum Power Point (MPP): I-V curve of Current vs Voltage (in red) and Power curve of Power vs Voltage (in blue)

The International Energy Agency report on the standard PV database makes the ensuing considerations (IEA, 2000):

General Information	Meteorology	System energies	Performance indices	Utility grid
Plant name				
Country			Reference yield	
Nominal power		Inverter energy output	Final yield	
Type of plant	Irradiation horizontal	Useful energy	Array capture losses	Energy to utility grid
Mounting structure	Irradiation in array plane	PV array fraction	System losses	Energy from utility grid
Array area	Ambient air temperature	Energy consumption	Performance ratio	
Availability of data			Array efficiency	
Calculated month				

Table 3.1. Available parameters in the IEA standard PV database report

An analytical and statistical study of failures related to grid-connected residential PV systems from 1 to 5 kWp, installed in Germany in the 1990's (Jahn, 2004) found a probability of one failure every 4.5 years for each plant. 63% of the total number of failures were attributed to PV inverters, 15% of them to PV modules and 22% to the other components.

Despite DC to AC conversion losses, modern inverters commonly used in residential PV systems can demonstrate peak efficiencies of up to 98% according to their manufacturers (Wyote, et al., 2013). If the PV generator is oversized, inverter inefficiencies can be observed at high input P_{DC} (Allet, et al., 2011a). But this thesis looks at weather-related causes that would explain a discrepancy between actual performance and rated datasheet performance.

PV inverter performance (η_{DCAC}) is described very differently by each manufacturer. Some only provide information about a weighted efficiency under predefined conditions ($\eta_{DCAC\_WEIGHTED}$) while others display data concerning voltage and output power dependency at different levels of detail (Allet, et al., 2011a).

It is then evident that predicting the energetic output of a PV plant at a given site is a crucial requirement for the choice of components, suggesting an economic benefit. Nevertheless, it cannot be done without a comprehensive analysis of PV inverter performance under conditions specific to that location. This is what drove the development of η_{EURO} and η_{CEC}, in the first place.

3.1.2. η_{EURO}

The European efficiency, introduced in 1991, calculates the performance of PV inverters (Burger, et al., 2009), considering the effect of irradiation profile. The averaged operating efficiency over a yearly power distribution corresponds to Central Europe climate conditions and uses data from Trier (Hotopp, 1990), a site located in north-western Germany (Photon Energy Group, 2004).

Formula:

$$\eta_{EURO} = 0.03\eta_{5\%} + 0.06\eta_{10\%} + 0.13\eta_{20\%} + 0.10\eta_{30\%} + 0.48\eta_{50\%} + 0.20\eta_{100\%}$$

To obtain the value of η_{EURO}, the formula assigns percentages of the time the inverter functions at given operating ranges. It is assumed that the inverter will spend 20% of its operating time functioning at nominal power ($\eta_{100\%}$; $P_{DC} = P_{DC\_NOM}$); 48% of the time, the inverter will be working at 50% of its nominal power ($\eta_{50\%}$), etc. (Mertens, 2014g)

The formula resulting from Hotopp's research, became a reference for expressing (grid-connected) PV inverter efficiency. But the label "European efficiency" is not entirely accurate for the fact that weather data used to calculate its weighting factors did not account for the entire European continent – for example, Southern regions (Italy). Great emphasis was put on variations at lower irradiation levels, which consequently makes it less suitable for sites with higher insolation (Ongun & Özdemir, 2013). The weighted efficiency was proposed by the EU Joint Research Center (JRC), based on climate conditions in Ispra (Italy) and it is now referenced by manufacturers on almost any inverter datasheet.

The European efficiency η_{EURO}, given by the EN 50524 standard (CENELEC, 2008), weighs specific part-load efficiencies (P_{MPP}/P_{STC}) based on how frequently they occur in Central Europe. (Valentini, et al., 2008).

The formulation of η_{EURO} is grounded on two characteristics: the inverter's built-in DC-AC transfer characteristic and the irradiation distribution standardised by the European model, always based on the measurements made by Rolf Hotopp in the late 1980s (Hotopp, 1990).

The percentage of six pre-defined irradiance ranges (Table.2) from 0 W/m^2 upwards were calculated by Hotopp and used as weighting factors to determine η_{EURO} given on inverters' datasheets. Each value is then correlated to a point expressing the P_{AC} level where the efficiency is read from the DC-AC transfer characteristic. η_{EU} is calculated as the sum of the products of the efficiency at each point of support and its respective weighting factor. (Allet, et al., 2011a)

$$\eta_{\text{EURO}} = \sum_{\text{ranges}} \chi_i \cdot \eta_i$$

η_{EURO}						
Weighting factor	0.03	0.06	0.13	0.10	0.48	0.20
Partial MPP power P_{MPP}/P_{STC}(%)	5%	10%	20%	30%	50%	100%
P_{MPP}/P_{STC}(%) Evaluation class	$0-5\%$	$5-10\%$	$10-20\%$	$20-30\%$	$30-50\%$	$50-100\%$

Table 3.2. Weighted efficiency formula coefficients for η_{EURO} (Allet, et al., 2011b)

Hotopp's method of calculating the weighting factors is based on irradiance measurements leading to an irradiation distribution.

Because the largest amount of energy, under the Central European climate, is generated in the middle range of a PV module's nominal power rating, manufacturers optimized the inverter efficiency for operation under partial loads. This is what η_{EURO} describes: six different loads scenarios taken into account and certain parameters used for weighing energy contributions.

3.1.3. η_{CEC}

For climates with higher insolation like US south-west regions, the California Energy Commission (CEC) proposed another weighting efficiency η_{CEC}, now specified for some inverters used in the United States.

Formula:

$$\eta_{CEC} = 0.04\eta_{10\%} + 0.05\eta_{20\%} + 0.12\eta_{30\%} + 0.21\eta_{50\%} + 0.53\eta_{75\%} + 0.05\eta_{100\%}$$

In the CEC protocol (Bower, et al., 2004) for measuring the overall efficiency of PV inverters, under time-varying climate conditions, the more characteristic operating conditions are weighted more heavily (Forrest & Jacobson, 2014).

η_{CEC}, introduced in 2004, is justified by the fact that η_{EURO} was not suitable for the type of irradiation profile in Sacramento, California (South-western United States). The EN 50530 energy standard, approved by CENELEC by 2010, recognizes the Euro efficiency (Hotopp, 1990) and the CEC efficiency (Brooks & Whitaker, 2005) formulas as reference for inverter efficiency calculations.

η_{CEC}						
Weighting factor	0.04	0.05	0.12	0.21	0.53	0.05
Partial MPP power $P_{MPP}/P_{STC}(\%)$	10%	20%	30%	50%	75%	100%
$P_{MPP}/P_{STC}(\%)$ Evaluation class	0 – 10%	10 – 20%	20 – 30%	30 – 50%	50 – 75%	75 – 100%

Table 3.3. Weighted efficiency formula coefficients for η_{CEC} (Ongun & Özdemir, 2013)

Since 1995, the State of California has promoted and provided monetary incentives for the use of single point inverter efficiency and test conditions (PTC), recognized as a more realistic measure of PV output than the manufacturer's estimate under STC or Standard Test Conditions. This more realistic approach is a better representation of actual solar and climatic conditions. Calculations made by the Energy Commission's about module performance under PTC generated momentous financial benefits. The actual PV output could be higher or lower depending on site-specific conditions such as tilt, azimuth, soiling, shading, geographic location, mounting technique, and season. (Truitt, et al., 2003)

Distributed AC products such as micro-inverters have their weighted DC-AC conversion efficiency measured according to the CEC performance test protocol (Bower, et al., 2004) or the European standard EN50530 (CENELEC, 2008) inverter efficiency method.

The methodology used by the CEC to rate the PV inverters on its list consists of measurements of the weighted efficiency of the devices at various loads points; η_{CEC} is then determined by the weighting factors as displayed in Table 3.3. (CEC, 2006)

3.2. Validation of inverter efficiency

PV inverters, rather than constantly operating at maximum or peak efficiency, instead perform according to an efficiency profile as function of the input power based on irradiation and temperature occurrence. Inverter efficiency testing is conducted over a range of operating voltages and power levels (Figure 3.2.)

		Power Level (%; kW)						
		10%	20%	30%	50%	75%	100%	
Input Voltage (Vdc)		0.67	1.35	2.02	3.37	5.05	6.73	Wtd
Vmin	210	94.88	96.21	96.37	96.30	95.90	95.23	95.98
Vnom	400	94.25	96.38	96.66	96.84	96.67	96.35	96.58
Vmax	480	94.73	96.10	96.44	96.75	96.70	96.35	96.55

CEC Efficiency = 96.5%
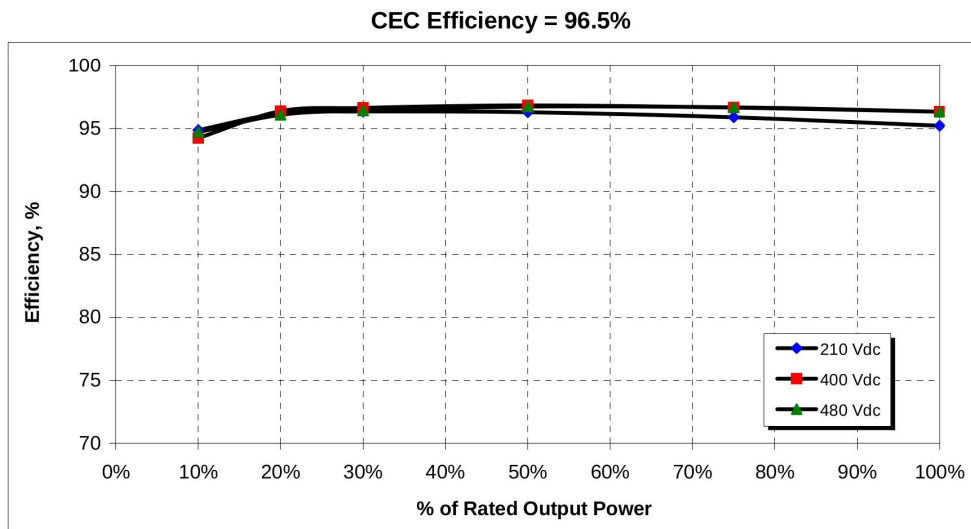
Figure 3.2. CEC weighted inverter efficiency per % of rated output power (source: California Energy Commission)

The relatively recent introduction of a marking system to compare the performance of inverters is one of the most contemporary issues in the field of PVPS integration into power grids around the world. The current definitions of the European and Californian efficiency cannot just be assumed to reflect every distribution of annual yield as function

of P_{MPP}, voltage and weather patterns with predefined weighting factors based on foreign climate conditions.

This suitability of the standard Euro efficiency has been questioned in scientific papers (Bletterie, et al., 2008). Comparing manufacturer data about conversion efficiency at different output power levels with actual measurements under steady conditions has sometimes shown great difference. Discrepancy have also been noted between laboratory and field measurements. Other than measurement uncertainty, differences of over 2% in overall efficiency under steady conditions can be reported leading to proportional energetic losses. Under unsteady conditions, further losses occur. A bigger mismatch between the generator and the inverter can worsen these additional losses (Allet, et al., 2011a).

Initially, in definition of η_{EURO}, the input energy is distributed for a system supposed to be located in central Europe (Hotopp, 1990). When under specific field conditions, equating the weighted conversion efficiency of an inverter $\eta_{DCAC\_WEIGHTED}$ to η_{EURO} implies a similar and optimal system design with PV generator and inverter ideally matched.

Given enough information on conversion efficiency, a site and system specific, weighted efficiency (η_{SITE_EURO}) can be calculated from either irradiance or generator output power (P_{DC}), describing the expected overall DC-AC conversion efficiency under steady conditions. Different weights do not necessarily mean an equally different weighted efficiency. Weighting factors very different from those used to calculate η_{EURO} can be determined, with the resulting η_{SITE_EURO} still very close to η_{EURO}. The data is evidently influenced by seasonal distribution (winter and summer) and the temperature dependence of η_{DCAC} can be observed through monitoring the system and highlight the profitability of cooling PV inverters which behave as thermodynamic systems (Allet, et al., 2011a).

The efficiency test for inverter is performed at minimum, maximum and nominal DC operating voltages, over the entire power range of the inverter. Inverter efficiency increases rapidly at low power levels. In fact, most inverters reach at least 90% efficiency at just 10% of their maximum continuous output power rating (California Energy Comission, 2018).

Inverters advertised for their high efficiency use the standard Euro and CEC weighting systems. One example is the RECon-line inverter which reaches very high absolute efficiency values: η_{MAX} = 99.7% at 90% of the nominal power P_{STC} or P_{DC_NOM}. Its η_{EURO}

also remains high – at over 98% – from the time the input reaches 20% of the DC load
Source: (FRIEM, 2016)
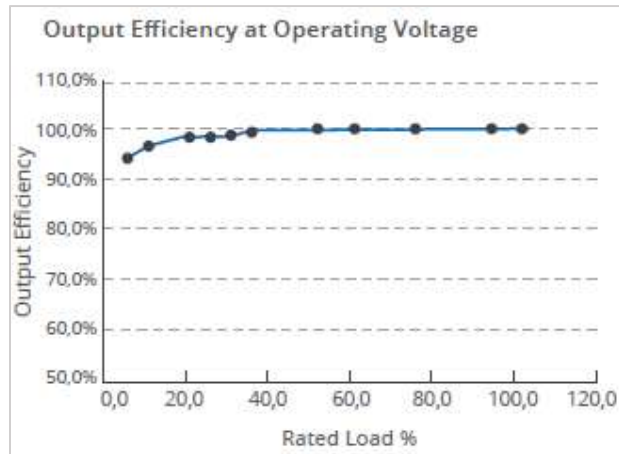
Figure 3.3. η_{EURO} efficiency curve RECon-line inverters under various DC load inputs
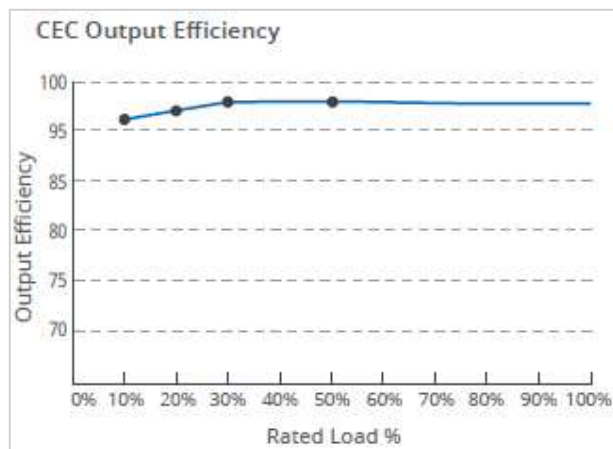
Figure 3.4. η_{CEC} efficiency curve RECon-line inverters under various DC load inputs

The manufacturer provides the following specifications:

- Maximum output efficiency: 99.3%
- Euro output efficiency: 98.8%
- CEC output efficiency: 99%

The California Energy Commission has set requirements for independent inverter efficiency testing. Incentive programs in other US states also require the use of PV inverters on the CEC list. A comprehensive list of eligible inverters and test results is available online (California Energy Comission, 2018).

3.3. Comparative literature on alternative weighted efficiency models

Several studies have been inspired by the challenge of performing a comprehensive analysis of PV inverter performance under field conditions outside of the ones used in η_{EURO} and η_{CEC}. In those surveys, irradiation distribution in places like Zurich (Switzerland), Izmir (Turkey), the cities of Indaial, Florianopolis and Itajai (Brazil), Aguascalientes (Central Mexico), Northern and Southern India, have been shown, as expected, to differ from the assumptions of the initial η_{EURO} and η_{CEC}. The objective is to understand the impact that different irradiation profiles can have on the energy yield of a PV inverter. The outcome of localized weighting factors for adjusting the MPPT behaviours of inverters is to produce a geography-specific efficiency description which can be customized for certain climatic geographies and optimize the design of power converters (Kellermann, et al., 2015).

Stemming from numerous proposals made in literature for redefining η_{EURO} (Baumgartner, et al., 2007; Burger, et al., 2009), a joint study by the solar utility EKZ[5], Zurich University of Applied Sciences (or ZHAW) and Oerlikon Solar[6] has looked at the effects that contribute to power losses for a better understanding of their impact on PV systems energy output. For a comprehensive analysis of PV inverter performance under specific field conditions, an outdoor test PV power plant can be used to analyse the performance of a PV inverter at a specific site and compared it to manufacturer data (Allet, et al., 2011a).

3.3.1. Weather data collection

To develop an accurate equation for MPPT efficiency of PV inverters under the site's climate, an evaluation model for a weighted conversion efficiency η_{SITE} is derived from the local irradiation profile (Ongun & Özdemir, 2013). The survey starts with the evaluation of the local irradiation data statistically (Figure 3.5.) to be able to get a PV simulation sequence.

Ongun & Özdemir (2013) collect weather data from the Turkish city of Izmir, using measurements by the State Meterorolology Directorate and Ege University Solar Energy Institute. Figures for key parameters come from DMI Menemen Observation Station no 17789 at minute-resolution (very accurate).

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[5] Utility of the Canton Zurich, Switzerland, www.ekz.ch/solarlab
[6] A firm that provides thin film silicon technology for PV systems
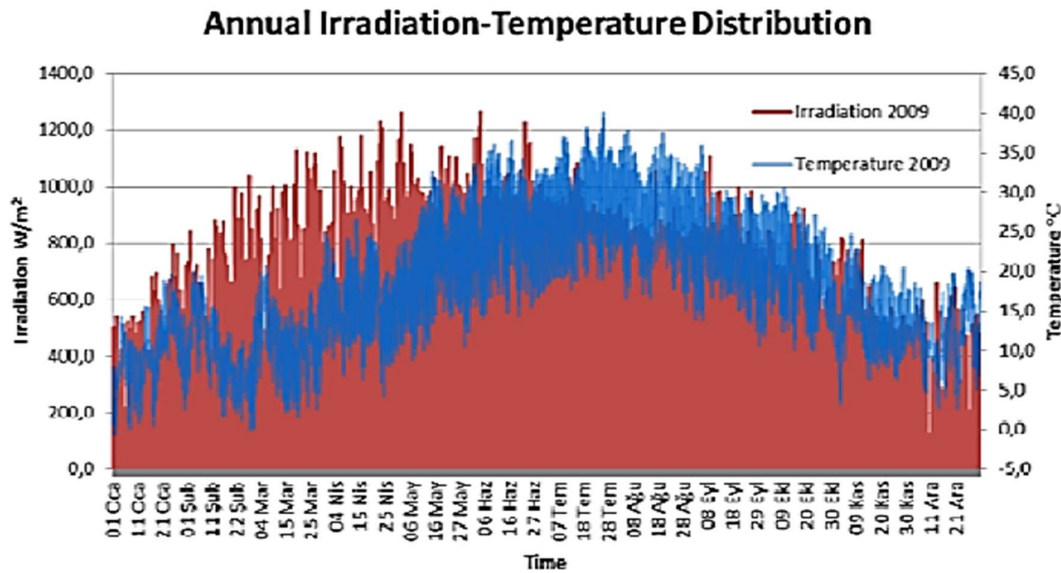
Figure 3.5. Annual irradiation-temperature distribution in Izmir (Turkey), using 2009 data from DMI Menemen observation station (Ongun & Özdemir, 2013)

The purpose is to determine the necessity to use the different points of support set by η_{EURO} & η_{CEC} (Table 3.2. & Table 3.3.). These points represent partial MPP power ranges, in other words ratios between the maximum power P_{MPP} that is obtainable from PV modules and the rated power P_{STC} stated for standard test conditions (STCs).

Drawing inspiration from Zhu, et al. (2011) study on the impact of DC input voltage on η_{DCAC} for high-latitude maritime climates, Rodrigo, et al. (2016) use solar irradiance and temperature measurements over 10 years in the low-latitude semi-desertic climate of Aguascalientes, central México as a basis for analysing the effect of climatic characteristics on η_{DCAC}. The decade-long data are compiled to generate a year of typical conditions.

The underlying concept is that DC input varies throughout the day at the site, but the annual distribution of those fluctuations is also not equal from one climate profile to another. Latitude, longitude and altitude are factors that determine geographic location and climatic characteristics. And research done in the field signifies the importance of representative and robust climate data spanning over a long enough period and synthesized into an average year.

These datasets prove crucial when making statistical representations of how different meteorological parameters occur at the site and are usually distributed over the typical year. A small number of variations can be observed from one year to another, making this approach more considerate towards those differences.
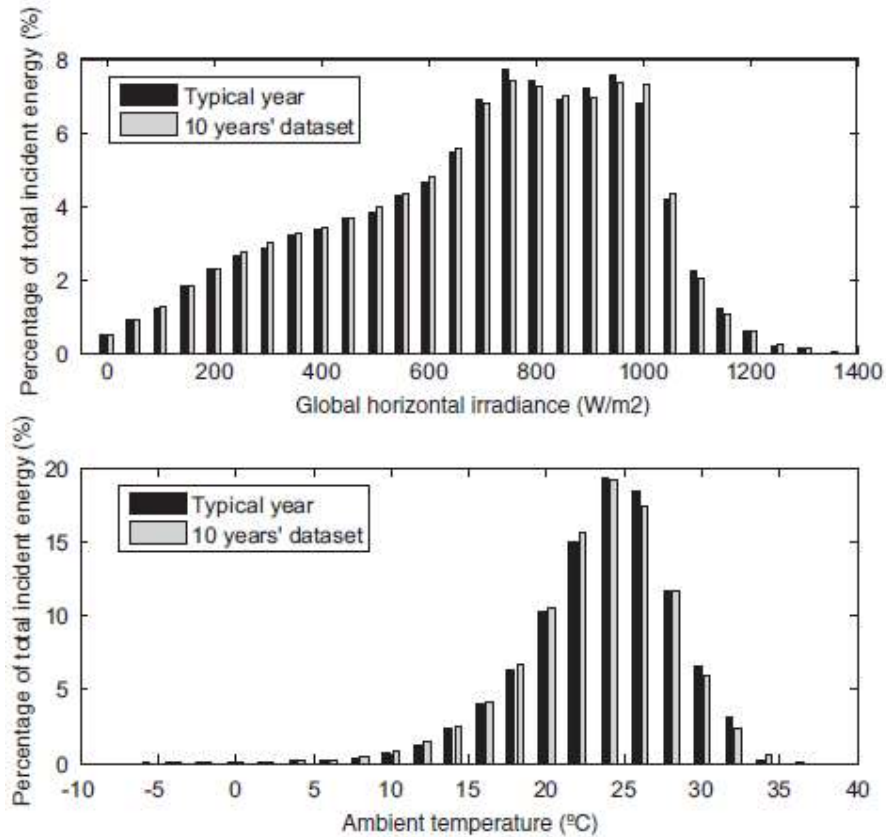
Figure 3.6. Percentage of total incident energy by GHI and temperature ranges: a comparison between the typical mean year and the 10 year's dataset in Aguascalientes, Mexico. (Rodrigo, et al., 2016).

In India, which is a vast country, the North and the South display contrasting irradiation profiles and Panwar, et al. (2017) calculate two separate weighted efficiencies representative of each region with ranges highlighted for various weight factors. This is done by applying the irradiation distribution over the whole annual sunny time and integrating the impact of temperature. Panwar, et al. (2017) obtained data from Meteonorm irradiance dataset (MN72, 2018). Suitable and realistic results are obtained through minute-wise figures of solar irradiation and ambient temperature, from a 10-year historical database (1990-2000) specific to the locations.
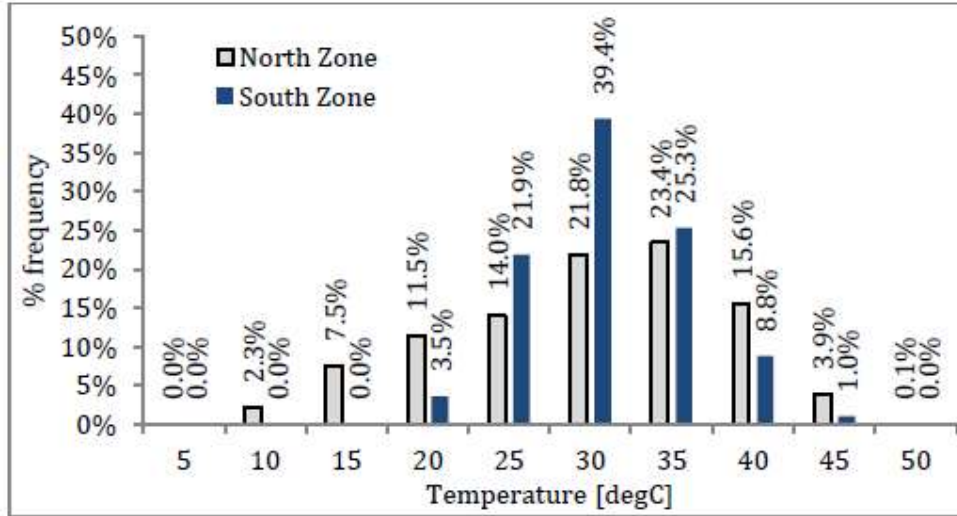
Figure 3.7. Histogram of ambient temperature profile for Indian north and south zone over a year
(Meteonorm-7)

Kellermann et al. (2015) get their data (values for climatic parameters) from the Brazilian INMET (National Institute of Meteorology).

3.3.2. Annual energy contribution of various irradiation classes

An evaluation of the irradiation data at specific sites, for annual energy distribution against irradiation classes reveals that yield estimations of η_{EURO} & η_{CEC} would not be valid for alternative sites. This is done by comparing the data for the frequency at which each irradiation classes (100 Wh/m^2 intervals) will occur at the chosen sites and their respective contribution to the overall energy output, for locations like:

- Northern and Southern Indian cities.

Panwar et al. (2017) highlights the fact that for India's North zone, nearly 45% of solar power is harvested above 800 W/m^2, which is poles apart from what was observed in Europe or California. For energy calculations, the input power to the inverter is the PV module output and not the irradiation data itself. This is a more realistic approach since the effect of the temperature is also incorporated:

$$T_{CELL} = T_{AMB} . (NOCT - 20) . \frac{GHI}{800}$$

The PV cell temperature T_{CELL} and the GHI help determine the short circuit current I_{SC} and the open circuit voltage V_{OC}:

$$I_{SC} = I_{STC} . \frac{GHI}{G_{STC}} . \left(1 + \alpha . (T_{CELL} - T_{AMB})\right)$$

$$V_{OC} = V_{STC} \cdot \left(1 + \beta \cdot (T_{CELL} - T_{AMB})\right)$$

Also the ambient temperature T_{AMB}, the Nominal Operating Cell Temperature $NOCT$, the temperature coefficients of current α and voltage β. These are the parameters behind the determination of the Maximum Power Point MPP for a given percentage of loading (fill factor, P_{MPP}/P_{STC}, V_{MPP}/V_{STC}, I_{MPP}/I_{STC}) (Bründlinger, et al., 2014).

$NOCT$, however useful, does not take into account specifications about the mounting systems of the PV panel, such as fully ventilated or insulated mounting; these are known to have a sensible influence on T_{CELL}. Consequently, alternative methods for calculation of T_{CELL} are now often used in a number of PV simulation programmes like PVSYST (Mermoud & Wittmer, 2017).

The power is calculated as a function of the two and the fill factor FF: $P = V_{OC} * I_{SC} * FF$; the ratio between the available power (at X time) and the rated power P_{MPP}/P_{STC} is accounted for.
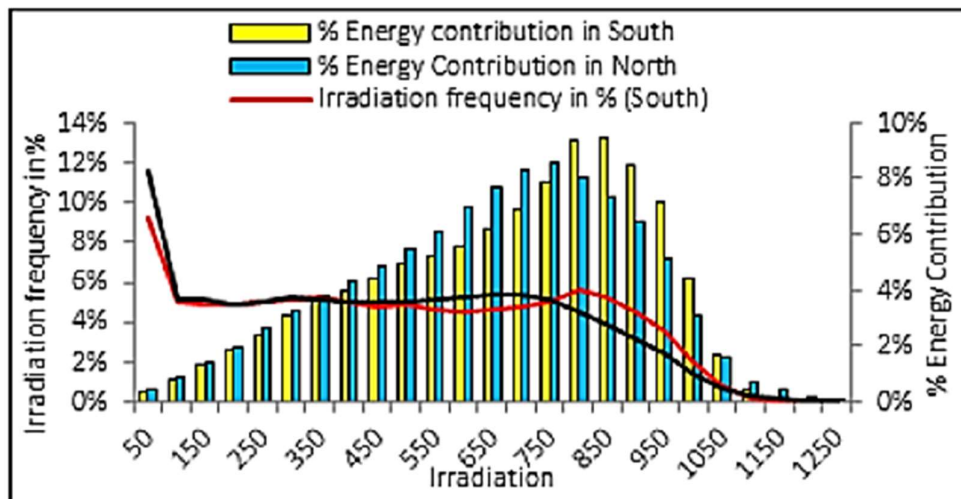
Figure 3.8. Histogram of one-year irradiation profile for north and south zone (Meteonorm-7)

- Izmir in Turkey (PV array = 1000 W, V_{OC} = 100 V, I_{SC} = 10 A)

Ongun & Özdemir (2013) make energy calculations for crystalline silicon (c-Si) modules as prescribed by the EN50530 standard. Maximum energy outputs P_{MPP} are derived from open circuit voltages V_{OC} and short circuit currents I_{SC} being both dependent on irradiance and temperature at a given time of the day:

$$V_{OC} = V_{OC\_STC} \cdot \left(1 + \beta \cdot (T_{PV} - T_{STC})\right) \cdot \left(\ln\left(\frac{G}{C_G} + 1\right) \cdot C_V - C_R \cdot G\right)$$

$$I_{SC} = I_{SC\_STC} \cdot \frac{G}{G_{STC}} \cdot (1 + \alpha \cdot (T_{PV} - T_{STC}))$$

Influencing factors are: the PV module's temperature T_{PV}, the standard test condition temperature T_{STC}, the solar irradiation G, the temperature coefficient of current α, the temperature coefficient of the voltage β and other technology dependent factors.

By assessing the irradiation statistics for annual energy distribution against various classes of irradiance, calculations from the graph show a contrast with European and Californian efficiencies described in Section 3.1.

Irradiance levels of 500 W/m^2 and below, 500 - 750 W/m^2 and 750 W/m^2 and above each produce about one third of the yearly energy yield. Weighting factors for various power ranges are therefore distributed differently for Izmir's formula.
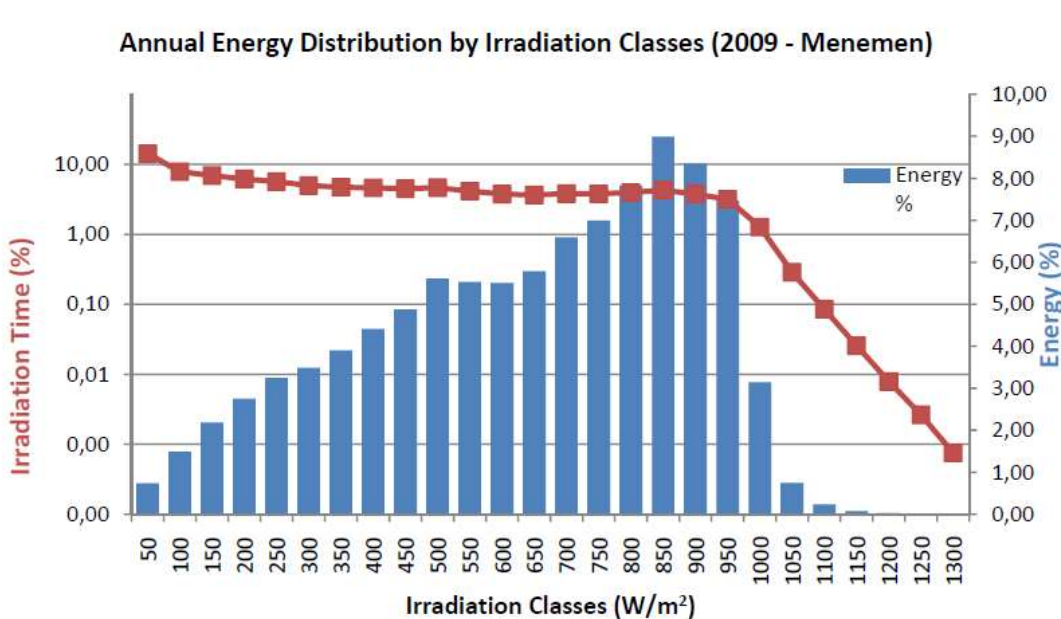
Figure 3.9. 2009 irradiation profile evaluation for annual energy yield distribution in Izmir (Turkey)

The discrepancy between assumptions about energy contributions uncovered by the study can be summarized as below:

	η_{EU}	η_{CEC}	η_{IZM}
0 - 500	79%	42%	~ 30%
500 - 750		53%	~ 30%
0 - 750		95%	~ 60%
500 - ∞	~ 20%	58%	~ 60%
750 - ∞		5%	~ 30%

-   Indaial in Brazil's Santa Catarina state.

To determine how the variation of solar radiation, climatic conditions in Santa Caterina impact the PV system performance, Kellermann et al. (2015) uses the IEC 61683 standard to calculate the weighted average efficiency. Daily data recordings were done from July 2010 to June 2014 with measurements in 5-second intervals.

The maximum power of the PV module is determined; 7 classes of yearly generated energy are matched with their respective weighting factors according to their annual frequency of occurrence.
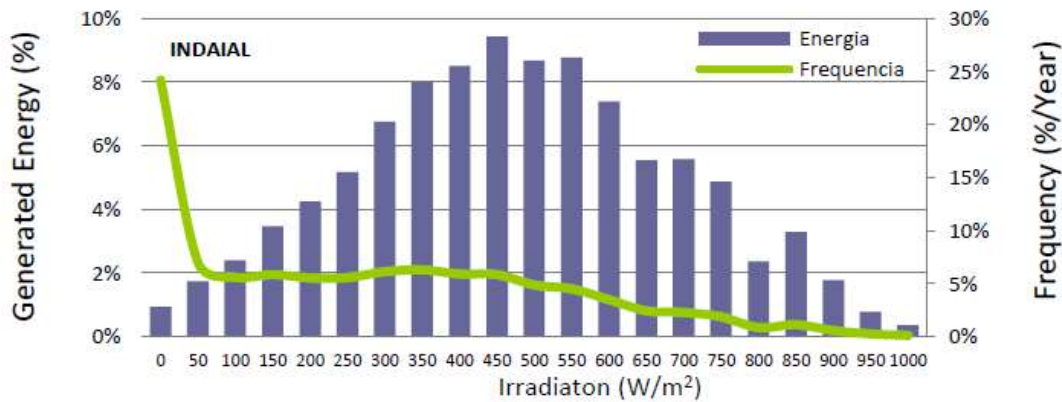
Figure 3.10. Energy available per year for each band of radiation and frequency of occurrence at Indaial (Brazil)

3.3.3. Calculation of weighting factors

After the energy contributions are compared with the yields, the determination of the weighting coefficients helps assess the weighted efficiency that can be expected from inverters and the DC-AC unit's output power. These factors are recalculated from η_{EURO} & η_{CEC} and adjusted to localized conditions.

Allet, et al. (2011) use an outdoor PV power generator for a comprehensive experiment including an array of several modules of various technologies, connected to the grid, monitored and logged on both the DC and AC sides of the inverter. The test measures the I-V characteristics of a reference module for each technology once every minute and, in that interval, tracks it at V_{MPP}.

Panwar, et al. (2017) examine the irradiation data as well as the energy yield for each irradiation class, their frequency of occurrence and percentage of loading (available power divided by the rated power or P_{MPP}/P_{STC}). This is to calculate weighting factors and the total energy yield. The methods used consider pattern of solar irradiation

distribution over the whole annual sunny time, the impact of temperature; the energy analysis assigns weight factors to their respective ranges of powers.

After the weighted conversion efficiency equation is determined, some commercial inverters can be measured for their efficiencies according to the EN 50530 standard and the respective yields can be calculated and simulated (Rodrigo, et al., 2016).

The datasheets of PV inverters do not all contain data about the dependency of P_{AC} and V_{DC} – although some give a graphic as an illustration – but all list the η_{EURO} or η_{CEC} standard for the calculated efficiency value representative of their projected operating efficiency. Some inverters give η_{EURO} as function of V_{DC} and provide enough data to recalculate η_{EURO}. Overall conversion efficiency is derived from the calculation of $\eta_{\text{DCAC\_WEIGHTED}}$ (weighted by the input power) from P_{DC} and P_{AC} measurements (Allet, et al., 2011b).

The inverter's MPP-tracking affects inverter's input therefore the measurement of the generator's I_{MPP} & V_{MPP} (Häberlin, et al., 2005). Since P_{MPP} cannot be measured while the inverter's tracking is in process, a monitoring system can be setup for a separate analysis of η_{MPPT} and actual η_{DCAC}. Consequently, a reference module can be used to derive maximum output power and approximate tracking efficiency. Minutely I-V scans and the maximum power of the PV module P_{MPP_MODULE} can be used to estimate $P_{MPP\_GENERATOR}$, the maximum power of the PV generator.

$$P_{MPP\_GENERATOR} = P_{MODULE} \cdot \frac{P_{NOM\_GENERATO}}{P_{NOM\_MODULE}}$$

Cable losses (cable resistance) from the PV array or generator to the PV inverter are of course taken into account for the purpose of accuracy, given the effect of the rising generator current (Allet, et al., 2011b).

$$\Delta P_{MPP\_GENERATOR} = I_{DC\_GENERATOR}{}^{2} \cdot R_{CABLE}$$

The total efficiency of the inverter can be calculated by multiplying η_{MPPT} and η_{DCAC} (Ongun & Özdemir, 2013):

$$\eta_{\text{tot}} = \eta_{\text{MPPT}} \cdot \eta_{\text{DCAC}} = \frac{P_{DC}}{P_{MPP}} \cdot \frac{P_{AC}}{P_{DC}} = \frac{\int_0^{T_M} P_{AC}\,(t)\,dt}{\int_0^{T_M} P_{MPP}\,(t)\,dt} = \frac{P_{AC}}{P_{MPP}}$$

Performance factors are weighted by the input power corresponding to them (P_{DC}; $P_{MPP\_GENERATOR}$ for η_{MPPT} and η_{TOT} and P_{DC} for η_{DCAC}), the true relevance of those values can then be determined (Allet, et al., 2011b).

$$\eta_{\text{DCAC\_WEIGHTED}} = \frac{\sum \eta \cdot P_{DC} \cdot \varDelta t}{\sum P_{DC} \cdot \varDelta t}$$

Besides, data under steady conditions (Allet, et al., 2011b) can be included to compare η_{DCAC} and η_{EURO} Label which describes inverter weighted efficiency under steady conditions, at different output power levels under defined voltage.

To achieve realistic weighting factors, the frequency at which inverters operate at various input power level ranges used in η_{EURO} can be analysed or recalculated from local irradiance distribution extended by the nominal power proportion of the system ($P_{DC\_NOM\_GENERATOR}$ compared to $P_{AC\_NOM\_MAX}$), but this ignores temperature and generator's lowlight dependency (Allet, et al., 2011b).

When the conditions are assumed to be steady, differences can appear in dynamic environment with fluctuations of the electric load as well as with differences in sensors used for DC measurement (Allet, et al., 2011b).

Allet, et al. (2011) determined a tracking efficiency of 98% under stable weather conditions (i.e. little variation in irradiation and module temperature). The comparison between conversion efficiency and the η_{EURO} reveals that the measured efficiency is overall lower than predicted on the inverter's datasheet. Thus, the need to recalculate weighting factors used for η_{EURO} calculations. And the same goes for η_{CEC}.

As a result, two alternative and simplified efficiency formulas are proposed for Izmir (Ongun & Özdemir, 2013):

$\eta_{\text{IZM1}} = 0.02\eta_{10\%} + 0.13\eta_{30\%} + 0.22\eta_{50\%} + 0.28\eta_{70\%} + 0.35\eta_{90\%}$

$\eta_{\text{IZM2}} = 0.04\eta_{10\%} + 0.12\eta_{30\%} + 0.21\eta_{50\%} + 0.53\eta_{70\%}$

This shows that ranges that are important for one location are not necessarily so on another site because their energy contribution is no longer as significant.

In India, (Panwar, et al., 2017) also proposes two novel weighted efficiencies for each region, the North and the South:

$\eta_{\text{IND\_NORTH}} = 0.01\eta_{10\%} + 0.04\eta_{20\%} + 0.07\eta_{30\%} + 0.22\eta_{50\%} + 0.66\eta_{100\%}$

$\eta_{\text{IND\_SOUTH}} = 0.01\eta_{10\%} + 0.03\eta_{20\%} + 0.06\eta_{30\%} + 0.20\eta_{50\%} + 0.69\eta_{100\%}$

Panwar et al. (2017) underline the importance of developing similar methods for alternative efficiency models for other countries with yet different solar zones like Australia or South Africa.

Kellermann, et al. (2015) introduce three efficiency formulas for the cities of Indaial, Florianopolis and Itajai in the Brazilian state of Santa Catarina:

$$\eta_{IDL} = 0.02\eta_{5\%} + 0.02\eta_{10\%} + 0.13\eta_{25\%} + 0.47\eta_{50\%} + 0.32\eta_{75\%} + 0.04\eta_{100\%}$$

$$\eta_{FNS} = 0.02\eta_{5\%} + 0.02\eta_{10\%} + 0.12\eta_{25\%} + 0.43\eta_{50\%} + 0.35\eta_{75\%} + 0.05\eta_{100\%}$$

$$\eta_{IAI} = 0.02\eta_{10\%} + 0.02\eta_{20\%} + 0.13\eta_{30\%} + 0.47\eta_{50\%} + 0.32\eta_{75\%} + 0.04\eta_{100\%}$$

Allet et al. (2011)'s anticipations about the conversion performance specific to the site and the system used shows a deviation from η_{EURO} of just 0.3%. The survey notes that conversion characteristics are very different under field conditions than under laboratory conditions, when directly comparing measured and expected conversion performances. This disparity results in more than 2% losses under steady weather conditions, with measurement uncertainty (1.1%) not factored in. When the PV generator is undersized relative to the respective inverter, the system never actually reaches levels of output power where DC-AC conversion would be maximised, commonly to be found around 50% of the inverter's maximal AC power.

By weighting the efficiency of each measurement by its respective input power, the relevance of each value is factored in. $\eta_{DCAC\_WEIGHTED}$ is computed by weighting each measurement by the input power $P_{DC\_GENERATOR}$ (Allet, et al., 2011a).

Systems	A	B	C	D	E	F
η_{DCAC}						
η_{EU} label	97.1%	94.6%	95.4%	94.5%	93.6%	91.8%
η_{EU} adapted based on GHI	96.9%	-	-	94.5%	-	-
η_{EU} adapted based on P_{DC}	96.8%	-	-	94.2%	-	-
η_{DCAC} weighted steady	94.7%	93.3%	94.6%	94.4%		90.8%
η_{DCAC} weighted unsteady	93.7%	92.4%	93.4%	93.9%	86.0%	89.3%

Table 3.4: Comparison between η_{EURO} label and alternative calculated values of η_{EURO} adapted based on the measured irradiation distribution (stretched depending on the system), the DC energy distribution and the actually measured, weighted performance $\eta_{DCAC\_WEIGHTED}$ overall (211'449 data points), and filtered for steady conditions (34'035 data points). (Allet, et al., 2011a)

Allet et al. (2011) could only calculate η_{SITE_EURO} where conversion efficiency at the six

needed points of support is given by the manufacturers' datasheet. $\eta_{DCAC\_WEIGHTED}$ (or the normalized average of those weighted values) represents the actual, measured conversion efficiency of energy for a selected timeframe (Table 3.4.). If measurements under unsteady conditions and irradiance levels below 10W/m^2 are removed, the dataset dwindles from over 210'000 to only 34'000 measurements. As a result, $\eta_{DCAC\_WEIGHTED}$ rises by 0.5% up to 3.8% throughout all PV systems, evidence of the negative effect of fluctuating input power. Despite this, the values for $\eta_{DCAC\_WEIGHTED}$ filtered still do not provide an adequate description of η_{EURO}, showing underperformance of up to almost 4% when compared to η_{EURO} Label.

Another reason for contrast is that a calculation of η_{EURO} Label based on an optimal system design not representative of irradiation distribution (Burger, et al., 2009). Using the same method as Hotopp (Hotopp, 1990), but by means of Zurich irradiation measurements, renders very different weighting factors. The difference shows that a lot more irradiation is measured at irradiance levels above 750W/m^2 than suggested by the weighting factors used for the calculation of η_{EURO} Label, which indicates that the most irradiation would be absorbed between 400W/m^2 and 750W/m^2. And this particularity becomes even more pronounced when the data of irradiation measurements are filtered for steady conditions, further increasing the relative amount of energy irradiated above 750W/m^2. Therefore, the factors for low irradiation become less relevant while the ones for high levels (above 750W/m^2) gain importance (Allet, et al., 2011).

PV power output is not just dependent on the installed capacity, but also on the ambient temperature on-site and most importantly the irradiance hitting the collector's surface.
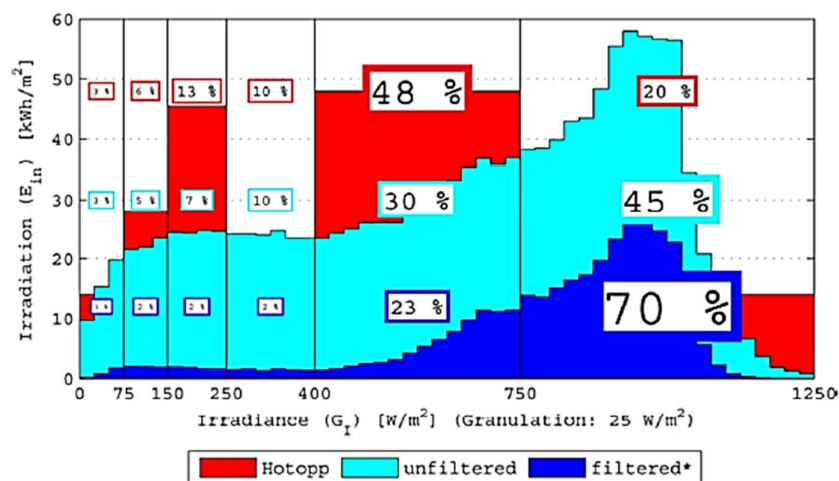
Figure 3.11.: Irradiation distribution displayed according to the total measured irradiation for the year 2011 (in Dietikon, Switzerland) from Hotopp's weighting factors (red) and on filtered (blue) and unfiltered (cyan) measurement data. Maximal allowed change between two sequences: GHI: max. $\pm 0.5\%$; T_{PV}: max. $\pm 1\%$; GHI > 10 W/m^2)

The use of irradiance measurements does not compensate for the generator's temperature and lowlight dependencies. Also, other system losses like cable resistance, soiling, shading, I-V imbalance and MPP-tracking are ignored. Therefore, the weighting factors should also be calculated according to the inverter's input power distribution. The values are expected to give the most accurate estimation of $\eta_{DCAC\_WEIGHTED}$, since they give compensation for both, power proportion and generator losses, and are representative of the systems actual operating behaviour (Allet, et al., 2011).

η_{SITE_EURO} is calculated with optimal matching between the generator and the inverters, considering either only the site-specific irradiation based on the weighting factors from irradiation distribution or the entire system based on the factors from the inverter's input energy distribution. These adapted efficiencies are expected to match better with the weighted DC-AC conversion efficiency ($\eta_{DCAC\_WEIGHTED}$ filtered) measured for a PV system under steady conditions (Allet, et al., 2011).

Calculating the adapted Euro efficiency requires knowing the expected conversion efficiencies (η_{DCAC} Label) at the points of support used for the calculation of η_{EURO}.

Unfortunately, those values are not always given in the inverters' datasheets. Small inaccuracies would arise from the fact that the supporting points are defined at normalised output (AC) energy levels, while the weighting factors have been calculated for energy input levels (irradiance or DC power). Calculating the weighting factors based on output energy would include DC-AC conversion efficiency in the weighting factors which is not desired. It is preferable to know the conversion efficiency for defined input, instead of output energy (Allet, et al., 2011).

There is a measurement uncertainty associated with the determination of η_{DCAC} , albeit under optimal laboratory conditions (Baumgartner, et al., 2007).

Allet, et al. (2011) uncovers differences of up to 2.2% of $\eta_{MPPT\_WEIGHTED}$ between data filtered for steady conditions and unfiltered data (unsteady conditions). However, the determination of η_{MPPT} under field conditions is a model-based problem. The manufacturer's information on performance under field conditions can ultimately be done by measuring η_{DCAC}.

3.4. PV simulation under specific weather data

PVPS can be simulated using software like PVSYST which provide the following aspects (Mermoud & Wittmer, 2017):

- Meteorological Data (GHI, DHI, ambient temperature, wind velocity, etc.)
- Design of grid-connected systems
- Reports, graphs and results about the system's behaviour
- Extensive database of PV modules & PV inverters with their characteristics and manufacturer's datasheets

The 'Project design' section of the software can be used for the complete study of a PV project. It involves the selection of meteorological data, the system's design, shading studies, losses calculations and economic evaluation. The simulation is performed over a full year in hourly steps, yielding customized reports and many useful results (Mermoud & Wittmer, 2017).

Perez, et al. (2008) however acknowledges, in their study, that the effect of cloudiness becomes significant at a sub hourly level when the performance of a localized site-specific PV system is considered.

The PVSYST 'Databases' section includes the management of climatic data, i.e. monthly and hourly data, and synthetic generation of hourly values. External data can also be imported (From NASA-SSE and Meteonorm 7.2 station) for new sites. This database contains definitions of all the components of PV installations like modules, inverters, batteries, etc. (Mermoud & Wittmer, 2017)

Performance ratio (PR), the ratio of actual and theoretical performance, is conceivably the most frequently used method for comparing PV projects, but it is a very approximate way of predicting yield of a PV system. (SMA, 2018). It is mostly independent of orientation and incident solar irradiation, which makes it most significant when comparing plants that supply energy to the grid at different locations.

PR gives an evaluation of the energy that can really be transferred to the grid after factoring in the power losses. This is usually between 77 and 82% if the plant is well-designed (Miller & Lumby, 2012). It is more effective for comparing average values over a specific time period (a year or a month) rather than at an hourly resolution, because of the amount of fluctuations due to cell temperature operating efficiency, dependent on ambient temperature and incident irradiation, which can vary a lot over the period of a few hours.

PVSYST is useful when simulating PV systems to get data on how a particular PV inverter can be expected to behave under certain climate conditions found at a selected geographic location (Mermoud & Wittmer, 2017).

Meteonorm is a software that delivers monthly meteorological data (GHI, DHI, wind speed and temperature) for any location on the earth, with a database encompassing 8325 weather stations on the ground and the possibility to retrieved satellite data for new sites and generate new data files (PVSYST 6).

Many international databases are also contained:

- GEBA (Global Energy Balance Archive) (Gilgen, et al., 1998) for GHI (1986–2005).
- The World Meteorological Organization Climatological Normals (WMO, 1998), the US National Climatic Data Centre (NCDC, 1995/2002).
- The National Renewable Energy Laboratory (NREL) database on temperature, humidity, wind data, sunshine duration and days with rain.
- The Swiss database (based on Swissmetnet of MeteoSwiss): for radiation (1986–2005); for temperature, wind and precipitation (2000–2009),
- Globalsod data (NCDC, 2002): Parameters for temperature, wind speed and precipitation (2000–2009 means).
- The Turkish State Meteorological Service: GHI (2004–2013).

The monthly average radiation values are calculated for periods of 10 years or more. For each continent, a harmonized period is utilized. Meteonorm 7 uses satellite data and information to interpolate radiation in remote areas, i.e. where there is no radiation measurement available nearer than 200 km (50 km for Europe) from the selected location. But if the nearest site is located at more than 30 km (10 km for Europe) away from the selected site, the software uses a blending of ground and satellite data.

Updates for Meteonorm version 7.2 includes updated meteorological and turbidity data, update of the time periods for temperature, humidity, precipitation and wind speed (1961–1990 and 2000–2009), for radiation parameters (1981–1990, 1991–2010 and1996–2015), update of the satellite database (enhanced maps, particularly for areas with high albedo), new turbidity climatology based on Gueymard (2012), and new models for calculation of one-minute radiation data.

NASA-SSE or Surface Meteorology and Solar Energy programme provides monthly data, averaged for the period of 1983-2005, collected via satellite measurements, for any cell within a 1°x1° grid over the world (1° latitude = 111 km) (NASA, 2018c). Daily values of irradiances and temperatures are also available in this database for any period in 1983-2005.

The difference between ground and satellite measurements is that the SSE dataset is a continuous and consistent 22-year global climatology of insolation and meteorology data.

It draws from a number of databases like "Goddard Earth Observing Systems (GEOS-1), the International Satellite Cloud Climatology Project (ISCCP D-1), from data of the Geostationary and Polar satellite for Environmental Observation (GOES and POES), the European Geostationary satellite Meteosat, Japanese satellites, etc.

Data provided by the SSE within a specific grid cell are not necessarily representative of a specific microclimate, or point, within the cell, but they are considered indicate the average over the entire area of the cell. Consequently, quality ground measurement data should not be substituted by the SSE dataset, which is only intended to compensate for there is a lack of ground measurements in some locations, and to stretch areas where ground measurements are available.

The Southern African Radiometric Network (SAURAN) was instituted in 2014 to address the lack of long-term high-quality solar data, measured within high-temporal resolution and accessible publicly in the region. This network was initiated by the Centre for Renewable and Sustainable Energy Studies (CRSES) at Stellenbosch University and the Group for Solar Energy Thermodynamics at the University of KwaZulu-Natal in Durban (Bekker, 2007).

3.5.   Summary & conclusions

The literature survey reveals scientific efforts to improve upon the traditional weighted efficiencies, Euro and CEC efficiencies in terms of accuracy and adapt them to locations with different weather data. It understands the opportunity of developing weighted efficiency models alternative to Euro and CEC (Panwar, et al., 2017) by evaluating them against localized irradiation profiles (Ongun & Özdemir, 2013).

Existing research in the scientific literature on weighted efficiency of PV inverter under a diversity of atmospheric and climatic conditions have yielded very interesting results, reshaped the understanding of PV systems operation and raised a number of issues.

- Despite being used as references to assess PV inverter performance, the European and Californian Energy Commission formulas for weighted efficiency, although respectively based on a southern and a northern climate, are not suitable to provide accurate yield estimations in different locations. Just like the CEC efficiency formula fixed inadequacies related to the Euro efficiency when applied to higher insolation patterns, by making use of the same approach by with different weighting system, the

same has been for both models in places like India, Turkey, and Brazil, resulting in alternative formulations.

- The Euro & CEC efficiencies formulas were designed to assess the efficiency of a PV inverter based on how often it will be operating at various percentage of its nominal DC power. The effect of irradiance influences the DC input, but the effect of the temperature effect is incorporate by expressing the power portions as function of P_{MPP} instead of irradiance.

- The importance of developing new weighted efficiency models, alternative to Euro and CEC (Panwar, et al., 2017) by evaluating them against different irradiation profiles (Ongun & Özdemir, 2013) calls for additional research for other regions like South Africa.

- The value of PV array power evidently affects both conversion η_{DCAC} and MPP tracking η_{MPPT} efficiencies of the PV inverter. Atmospheric effects on annual yield estimation of PV systems like grid connected power plants require to be studied accurately to provide realistic predictions of their economic revenue. Since the input power fluctuations can result from climatic conditions.

- Meteonorm provides an extensive meteorological database, for thousands of sites, that uses measurements over decades to generate the irradiation and temperature distribution over a typical mean year. PVSYST software is a tool of choice for researchers to simulate the behaviour of a PV system under weather conditions at almost any site on Earth. It generates numerical and graphical results and combines ground and satellite weather data from NASA-SSE and Meteonorm.

4. METHODOLOGY – WEATHER DATA, PV DESIGN & YIELD SIMULATION

The objective of this research is to determine which formula for PV inverter weighted efficiency would be valid in terms of weighting factors matching South African weather data. With the purpose of increasing the accuracy of PV yield estimates, a large array of methodologies, models, software and computer packages have been developed for researchers and engineers.

The literature review has shown that the behaviour of a PV system, and indeed of a PV inverter, cannot just be simulated under STC because, in reality, they operate under localised and time-fluctuating weather conditions.

The first part of the experiment to answer the main research question involves the collection of weather data and the design of the PV system to simulate its annual yield. Cape Town (South Africa) is the city selected for this case study. PVSYST software simulation provides precious climate data about the site, from Meteonorm 7.1 station, and a well-equipped platform to design a grid-connect PV system by selecting components from its vast catalogue of PV modules and inverters. High resolution hourly data provide information about the behaviour of the system and its energy yield distribution under climate conditions on-site is simulated over the whole typical mean year.

4.1. Site selection (survey area)

The site of Cape Town is used in this study as a reference for South African climate conditions. Its proximity to the national grid means PV systems installed could have a more direct and positive economic impact there. It is located in the Western Cape province and south-western tip of the country, latitude −33.97° S, longitude 18.60° and at an altitude of 46 meters. The city lies between the Indian and Atlantic Oceans and enjoys a Mediterranean climate with mild winters and pleasant summers. The temperatures during the summer - December to February - ranges from around 17 °C to 25 °C (daily averages), whereas in in the winter months of June to August, the daily average temperatures are between 9 °C and 18 °C (Meteonorm 7.1 station). Rainfall is moderate throughout the year, with refreshing sea breezes that can sometimes become slightly bracing during the winter.

4.2. Research design

This is purely a desktop study approach that uses software tools approved as industry standards and for engineering research: PVSYST software platform to design the PV

system by choosing its components and simulate its energy yield under meteorological data for Cape Town extracted from Meteonorm 7.1 and Microsoft Excel 2016 for calculations and analysis of the results.

In the context of this thesis the aim is to evaluate the validity of η_{EURO} & η_{CEC} at the selected site and use the results to reformulate their expressions. The performance calculation relies on the most accurate data available. Measurements are only rounded up after calculations and then it is within 2 decimals.

Solar PV modules and inverter specifications are picked from PVSYST extensive component database, providing manufacturer's datasheets and efficiency parameters. One major strength of this approach lies in its relatively simple and flexible design. It is also reinforced by high resolution hourly figures which provide great accuracy. Its weakness would be that, since it is designed to evaluate a single plant in detail and use the results to draw conclusions on a more general matter, it may need to be replicated for a greater variety of module and inverter technologies as well as system configurations.

As discussed in the literature review, there are various alternative methods and approaches to this problem, but the general concept is to investigate the performance of PV systems in depth based on site specific parameters. Thus, the approach chosen is adequate to answer the research question because all the necessary hourly data are available as accurate as possible. All the variables that can affect the outcome when evaluating Cape Town weighted efficiency η_{CPT}, like time resolution of data, the behaviour of the generator and the inverter are well controlled. Irradiation and temperature data at an hourly resolution were used to simulate the performance of the simulated PV system in this research experiment, which is well suited to determine weighting factors and energy portion and distribution.

Microsoft Excel 2016 was used as the computer platform to model the yield and the distribution of a number of time-varying parameters (efficiency, AC output, DC input, irradiance, etc.) with variables collected from both PVSYST 6.73 (Mermoud, 2013). and Meteonorm 7.1. (Meteotest, 2013) for PV energy analysis. The results of MS Excel calculations were then subject to comparison and interpretation.

The behaviour of a power generating system is often described stochastically using probability and cumulative distributions from chronological load data. The stochastic simulation approach uses data gathered from a detailed statistical analysis of the solar irradiation and temperature in Cape Town to simulate the energy production and distribution. This method and process is commonly used in modelling of systems that

incorporate random behaviour and inherently random variables like weather conditions (Kaplani & Kaplanis, 2012).

Meteonorm version-7.1. software provided the most realistic data for accurate results, hourly-data of irradiation and ambient temperature selected from the historical database across two decades to predict the weather profile for the site of Cape Town.

The main outcomes were calculated with the intent to graphically represent the correlation between PV yield distribution and weather conditions in the second part of the experiment.

The selected Si-monocrystalline PV modules are of 250 Wp capacity each, forming an array of 1kWp connected to an on-grid PV inverter of matching capacity operating under MPPT displaying its efficiency curve and values as a function of various DC inputs.

A detailed description of the system can be found in the Annex to this document.

4.3.   Sources of data: Cape Town weather profile

As evidenced in research literature, PV inverter estimations based on inaccurate solar irradiation data will negatively impact the ability to predict PV systems annual energy yield.

Data describing the solar resource at the site of Cape Town in South Africa is usually available from many sources, each having its advantages:

a) Meteonorm 7.1. & PVSYST 6.73

This is the database used in this research to import data for the geographic site of Cape Town (South Africa). The file contains meteorological data, and other key climatic parameters like albedo definition, etc.

The Meteonorm database, compiled by the private company METEOTEST (Meteotest,2013), uses data from the closest ground-based weather stations and combines them with satellite data to interpolate the data, thus generating a dataset for the specific project site, in this case Cape Town. Meteonorm synchronizes ground and satellite data harnessed from 1986 to 2005 from a database of around 1800 weather stations and establishes, for any site in the world, a Typical Year Mean or TMY of data (Meteotest, 2013). This is not representative of a real historical year, like 2018 for example. What it shows is a statistical representation of a typical year at the desired location (Meteotest, 2013). The margin of uncertainty, experience over more than 25 years of developing meteorological databases for energy functions, for Irradiation uncertainty is usually around 8% (Meteotest, 2013).

PVSYST allows the user to manage the meteorological data extracted from Meteonorm data files. For PVSYST 6.73, Cape Town coordinates (Latitude, Longitude, Altitude and Time zone) can also be located on an interactive map of the globe – within 20 km –, imported and saved in a file containing monthly meteorological data.

Months	GlobHor [kWh/m^2]	GlobInc [kWh/m^2]	GlobIAM [kWh/m^2]	GlobEff [kWh/m^2]	DiffEff [kWh/m^2]	TAmb [°C]	WindVel [m/s]
January	255.0	238.9	231.7	231.7	60.99	21.24	6.2
February	205.0	211.2	205.2	205.2	56.55	21.27	6.0
March	188.7	221.1	215.6	215.6	48.06	19.73	5.3
April	129.7	172.5	168.5	168.5	43.91	17.12	4.2
May	93.1	137.5	134.1	134.1	41.43	15.03	3.8
June	75.5	121.3	118.1	118.1	32.94	12.87	3.6
July	85.1	132.7	129.5	129.5	34.33	12.52	3.9
August	110.3	155.9	152.2	152.2	37.94	12.90	4.3
September	148.5	179.7	175.2	175.2	52.13	14.19	4.6
October	196.8	211.0	205.5	205.5	62.00	16.57	5.1
November	231.6	221.0	214.1	214.1	63.49	18.24	5.8
December	257.6	235.2	227.7	227.7	68.06	20.24	6.2
Year	1976.9	2238.0	2177.3	2177.3	601.82	16.80	4.9

Table 4.1. Effective incident solar energy at Cape Town (South Africa) (source: Meteonorm 7.1)

GlobHor: Global Horizontal Irradiation or GHI;
GlobInc: Global Incident irradiation in collector surface
GlobIAM: Global corrected for incidence (IAM, Incidence Angle Modifier)[7]
GlobEff: Effective Global irradiation, corrected for IAM and shadings
DiffEff: Effective Diffuse irradiation, corrected for IAM and shadings

The Meteorological data extracted from Meteonorm 7.1. that are primarily relevant to this research include the following variables:

- Hourly data
- Daily data
- Monthly data
- Global Horizontal Irradiation (GHI)
- Diffuse Horizontal Irradiation (DHI)
- Direct Normal Irradiation (DNI)
- Ambient Temperature

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[7] The IAM effect decreases the irradiance that actually reaches the surface of PV cells, compared to the irradiance under normal incidence. This decrease is mostly due to reflexions on the glass cover, which increases with the incidence angle (PVSYST 6.73).

There are also secondary data like wind velocity, relative atmospheric humidity and pressure that PVSYST includes in its calculations.

From the facts states above, it is evident that, when it comes to actual site measurements, Meteonorm 7.1. was the best tool available for this study, because it uses a rigorous method to provide data generated statistically for individual geographical sites. This allows for a in-depth case study and a simulative analysis which are significant in the context of this this research.

b) *The South African Weather Service (SAWS)* as the main source for ground measurements of irradiation data. Sun hour as well as high accuracy pyranometer measurements are available for Cape Town.

- *Ground station measurements using pyranometers*. The accuracy of the resulting global and diffuse irradiation data depends on the accuracy of the instrument, its calibration and its spectral sensitivity.

- *Ground station measurements of sunshine hours*. The proportion (%) of sunshine measured during an hour can provide an estimate of the overall irradiation at the site in Cape Town. For diffuse radiation, additional estimations are required, for instance sky clearness indices, but with less accuracy.

The above sources provide irradiation data with a resolution that varies from 5-minute tom monthly averages.

Because of these variations in accuracy and resolution among irradiation data sources, (Bekker, 2007) proposed a classification system based on accuracy and resolution for South African solar irradiation data.

Grading	Accuracy	Resolution
A	Regularly calibrated ground measurement stations, pyranometer accuracy < 1%, data accuracy < 10%	Daily measurements, 5- or 10-minute intervals
B	Estimates from hourly sunshine hour measurements	Daily measurements, 1-hour intervals
C	Satellite measurements	Monthly average, 1-hour intervals
D	Non-calibrated pyranometers or silicon-based irradiance meters	Daily or monthly average only

Table 4.2. Accuracy and resolution classification system for South African irradiation data (Bekker, 2007)

For Cape Town, available data have the accuracy-resolution grades of A-C; A-D; D-A (Bekker, 2007)

This study, however, does not rely on *NASA'S Surface Meteorology and Solar Energy (SSE)*, or satellite-based data, because the SSE program only uses satellite observations made every 3 hours over a 10-year period with a resolution of 1° by 1°, despite its measurement accuracy above 85% (NASA, 2006). Satellite irradiation measurements and observations are not capable of incorporating the effect of the microclimate at the measurement location, despite being helpful for locations where no ground measurements are available, which is not the case for Cape Town.
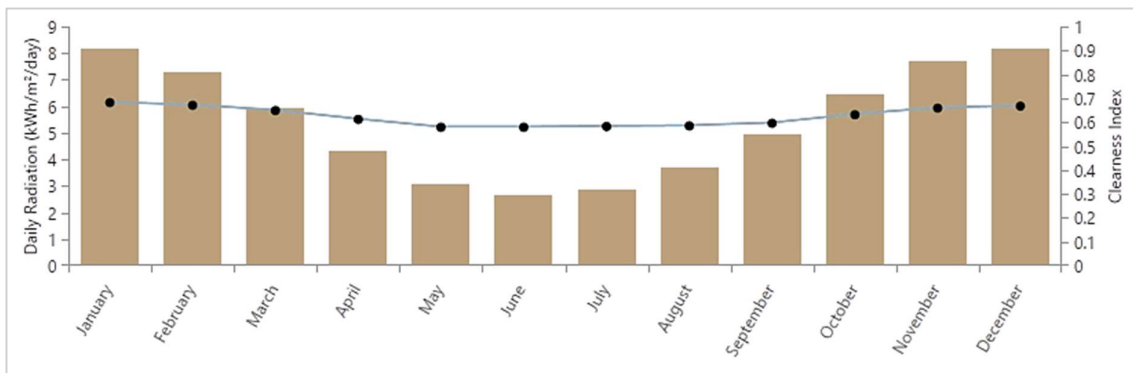
Month	Clearness Index	Daily Radiation (kWh/m²/day)
January	0.682	8.170
February	0.670	7.300
March	0.648	5.910
April	0.611	4.300
May	0.578	3.090
June	0.578	2.640
July	0.581	2.850
August	0.584	3.670
September	0.595	4.920
October	0.631	6.460
November	0.659	7.680
December	0.667	8.180

Figure 4.1. Monthly Average Solar Irradiation Solar Global Horizontal Irradiance (GHI) Data

source: Homer Pro, Homer Energy, LLC, 2016
NASA Surface meteorology and Solar Energy database.
Global horizontal radiation, monthly averaged values over a 22-year period (July 1983 – June 2005)

Annual Average (kWh/m²/day): 5.43

The low resolution of the NASA-SSE data makes them more appropriate for approximations of solar potential and feasibility studies rather than performance of PV plants.

4.4. System Design

A grid-connected system was used for the simulation and yield calculations. The system was designed as follows:

a) *Project:*
- Site: Cape Town
- Country: South Africa
- Geographic localisation: Latitude -33.97° S, Longitude 18.60° E, Altitude 50 m
- Time zone: UT+2
- Weather data: Synthetic from Cape Town Meteonorm 7.1 station
- Albedo: 0.20

b) *PV array specifications:*
- Tilt angle of collector plane: 30°
- Orientation/azimuth of collector plane: 0°
- Nominal power under STC: P_{STC} = 1000 Wp
- I_{MPP} = 108 V; V_{MPP} = 8.2 A
- 4 Generic Si-monocrystalline 250 Wp 60 cells modules (See Appendix A for more details)

c) *PV inverter specifications:*
- Manufacturer AEG Industrial Solar GmbH
- Model: AS-IR01-1000 inverter (See Appendix A for more details)
- Operating voltage: 80-400V
- Nominal power: 1 kWac
- Grid-connected, equipped with MPPT function
- η_{MAX} = 96.9%; η_{EURO} = 96.0%; η_{CEC} = 96.0%

In the initial stage of the South African REIPPPP (The Renewable Energy Independent Power Producer Programme), the fixed tilt system was the most prevalent, like the representative design in this study, given the latitude of the location (Bekker, 2007).

4.5. Assumptions

In designing a performance model for PV inverters based on a purely theoretical design, a number of assumptions that have been made to run the simulations. The most

noteworthy would be the loss assumptions from PVSYST standard values (PVSYST SA,2012)

Category	Loss description	Assumption
Shading and Spectral	Incidence IAM loss [IAMLoss]	59.394 kWh/m^2
	Incidence beam loss [IAMBLss]	33.536 kWh/m^2
	Incidence diffuse loss [IAMDLss]	23.789 kWh/m^2
	Incidence albedo loss [IAMALss]	2.067 kWh/m^2
PV Modules	PV loss due to irradiance level [GIncLss]	7.466 kWh
	PV loss due to temperature [TempLss]	234.65 kWh
	Module quality loss [ModQual]	14.507 kWh
	Module array mismatch loss [MisLoss]	21.436 kWh
	DC Ohmic wiring loss [OhmLoss]	23.368 kWh
AC electrical components	Global inverter losses [InvLoss]	70.888 kWh
	Inverter efficiency loss – during operation [IL Oper]	66.168 kWh
	Inverter Loss due to power threshold [IL Pmin]	4.72 kWh

Table 4.3. PVSYST system's loss assumptions

4.6.   Limitations

Though a reliable and rigorous source of data, the use of a typical mean year of solar irradiation was among the key limitations in the first segment of the research, because a sample spanning over multiple years (For example: 3 years) collected directly from the site, would provide a better perspective and yield even more robust data. This can be explored in more depth in future research in the context of a DTech thesis, to measure how it will affect the results presented in this study. The next segment discusses the method used to analyse the performance of the PV inverter used for the simulated PV system under Cape Town irradiation and temperature distribution and determine the

appropriate and valid formulation of its weighted efficiency; the more robust the data pool, the more effective and accurate this analysis will be.

Another limitation of this research lies in the system design, because only one type of system is analysed. In reality, however, there exist various PV design and MPP-Tracking possibilities, that could have an impact on certain parameters like energy yields at different hours.

Ground measured meteorological data for real PV sites in Cape Town can be of great importance since South Africa's renewable energy sector and market are not quite as advanced as those of Germany or the United States. This reinforces the need for further and more thorough research in this very important field. In fact, access to this type of data, along with actual recorded performance data for the site would greatly increase the validity of the results of this research.

4.7. Summary

The first part of the thesis served the purpose of collecting synthetic weather data representative of the climate conditions at the site and accurately simulating the energy yield distribution of PVSYST-design grid-connected PV system as it would be operating under Cape Town climate conditions.

The overall research design is based on a stochastic simulation using hourly irradiation and temperature data for the site of Cape Town. The 1kWp grid-connected system operates in MPPT mode and the PV inverter displays an efficiency curve with values in correlation with a number of DC inputs for both η_{EURO} & η_{CEC}.

The main strength of this method is that it simple and well defined, making it possible to assess the data and scenario analysis for a variety of temperature, irradiation and DC inputs. The typical mean year averaged by Meteonorm 7.1 is as accurate as possible, but one limitation of this research methodology would be in its system's homogeneity and the absence of field experiments over 1 or more years.

Nevertheless, part 2 of the research methodology tackles the formulation and validation of Cape-Town based weighted efficiency model.

5. METHODOLOGY – FORMULATION & VALIDATION

$\left(\eta_{CPT\_EURO}, \eta_{CPT\_CEC}, \eta_{CPT}\right)$

Simulation results obtained with the process described in part 1 of the experiment, the energy yield annual distribution and the system behaviour under site conditions were subsequently expressed as a function of irradiation classes, DC input power and PV inverter efficiency. Part 2 assess the validity of assumptions made by η_{EURO} & η_{CEC} compared to actual temperature and irradiation distribution in Cape Town in relation to energy yield from the selected PV inverter, in order to determine η_{CPT}, a formula with weighting factors representative of the site's weather data.

The purpose of this chapter is to discuss and analyse (1) the overall research design, (2) describe the modelling methodology for temperature and irradiation distribution, (3) energy output distribution per class of irradiance, (4) discuss and assess the validity of η_{EURO} & η_{CEC} and the parameters used to evaluate them under Cape Town weather profile, and (5) discuss the method to calculate η_{CPT_EURO}, η_{CPT_CEC} & η_{CPT}.

The proposed values can be quantified by weighting the standard Euro & CEC efficiency against the local solar irradiation profile, which indicates how much power per unit the site receives from sunlight over a month or a year.

This is done to represent and express the impact of the location on the standard formulations of η_{EURO} & η_{CEC}.

5.1. Research Design

This segment of the research is designed to evaluate η_{EURO} & η_{CEC} which make assumptions based on Trier (Germany), Ispra (Italy) and Sacramento (California) weather profiles. The thesis statement suggested that, PV inverters based in Cape Town will not operate as often under the predefined conditions because now in a different climate. Weather patterns specific to Cape Town were classified in the same manner as η_{EURO} & η_{CEC} evaluation classes, and calculations in MS Excel were used to reveal the correspondence with power portions and energy contributions.

The DC power produced fluctuates between 0 and P_{MPP}, which, unlike P_{DC_NOM} or P_{STC}, can vary over a relatively short time period. The PV inverter therefore operates at variable DC input according to how Cape Town data curves oscillate over time. The values associated with these parameters were therefore integrated and averaged over a period of time (an hour, a day or a month), using cumulative distributions from chronological

load data. The hourly distribution was obviously used for accuracy as previously stated. Site-specific results were obtained.

For the analysis of the energy contribution of various evaluations classes, the DC input was considered instead of the irradiation data itself. This provides more realistic results as it involves the effect of temperature too.

Using the same method as the Euro & CEC efficiencies, specific weighting factors were attributed to the various power portions for their contributions to the previously calculated energy yield. These weights were then compared for evaluations classes analogous to η_{EURO} & η_{CEC}.

η_{CPT_EURO} & η_{CPT_CEC} represent the formulas and efficiency values calculated by applying weights for Cape Town to Euro & CEC evaluation classes (efficiencies at various intervals of portions η_{MPPn}).

η_{CPT_1} & η_{CPT_1} are the two values or weighted efficiencies obtained by assigning weighting factors as calculated for Cape Town to the corresponding η_{CPT} evaluation classes.

5.2. Temperature and irradiation distribution – modelling methodology

The purpose of modelling temperature and solar irradiation distribution over a typical year is to plot a graphical representation of Cape Town weather profile, using hourly average data over the whole typical mean year.

This corresponds to 8760 measurements for both ambient temperature and solar irradiance – under which the PV cells and modules are operating – that were used to simulate the annual distribution in this research.

The hourly data from January 1st 00h00' to December 31st 23h00' were exported from PVSYST 6.73 Meteonorm 7.1. database and compiled for this research using MS Excel 2016 to produce the annual irradiation and temperature distribution chart. The more generous clear sky model – based solely on the site latitude, longitude and altitude – primarily describes the irradiation absorbed by the atmosphere in absence of clouds. Although, it may slightly be influenced by the Linke trouble coefficient (JRC, 2018), describing the amount of water vaper and aerosols contained in the atmosphere, such a file would obviously not be suitable for the yearly evaluation of a PV system yield with such unrealistic assumptions (PVSYST 6.73, 2017a).
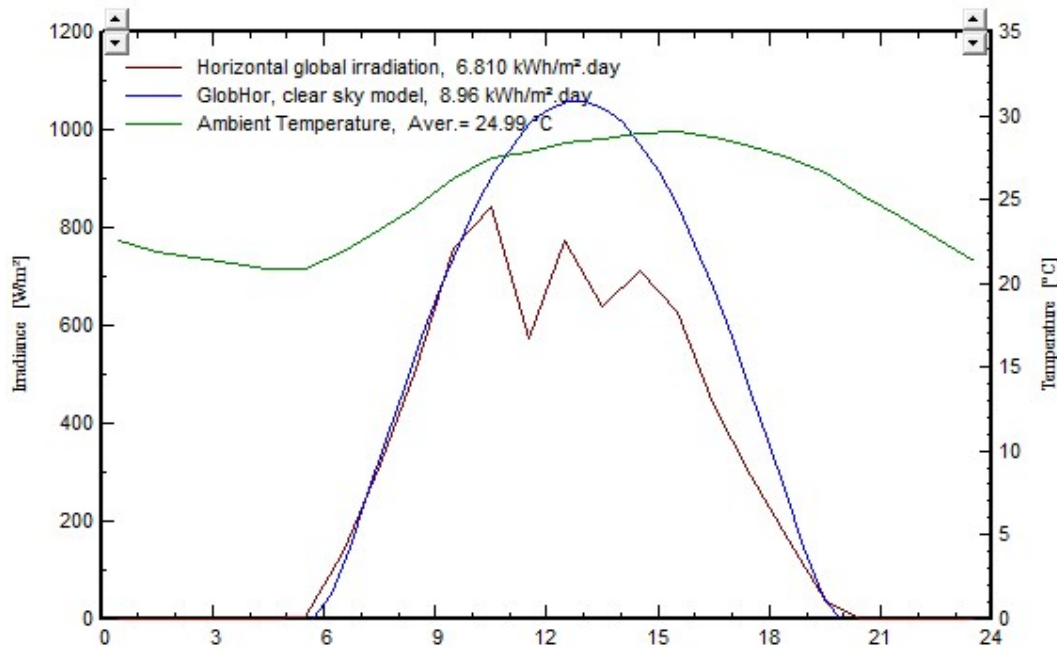
Figure 5.1. Hourly irradiation & temperature measurements (00h – 24h) on January 1st in Cape Town
(source: PVSYST 6.73; Meteonorm 7.1)

For each day of the typical mean year, 24 measurements of hourly averages are available, exported and compiled in MS Excel.

5.3.   Energy output per class of irradiance

Modelling the PV system's energy yield linked to various bands of irradiance occurring over a typical mean year aims to evaluate the contribution that each class of irradiance makes to the overall energy output the system, based on how often they occur at the specified location, in this case Cape Town. In other words, how much weight can be assigned to a particular portion of the irradiated energy compared to the overall inverter output?

This will result in a graphic representation of the energy output of the PV inverter – i.e. the PV inverter output or the energy injected into the grid (after AC wiring losses are factored in) – as a function of the weather profile at the site.

The frequency of occurrence is for the following classes of irradiance:

- $0 - 50$ W/m^2
- $50 - 100$ W/m^2
- $100 - 150$ W/m^2
- $150 - 200$ W/m^2

- $200 - 250$ W/m^2
- Etc.

In this research, formulas were created in MS Excel to assess the data and determine the number of occurrences of hours during which the average irradiance is within each 50/Wm^2 interval. This was then calculated as a percentage of the total number of hours within the typical mean year (8760).

Using this same method and data hourly resolution, it was also determined how much each irradiation class contribute to the energy output. Although PVSYST provide simulations of important parameters like annual hourly irradiation and energy injected into the grid, what is most important for this study is to recombine those data to be able to describe in details how much time the PV inverter will be operating in very specific intervals of irradiance and show, not only how much they contribute to the generated energy but also what values of P_{MPP}/P_{STC} they correspond to. This is important to assess the validity η_{EURO} & η_{CEC} and for the formulation of the weighted efficiency of the inverter under the site's conditions η_{CPT}.

5.4. Data analysis – validity of η_{EURO} & η_{CEC}

The prime goal of this thesis is to assess η_{EURO} & η_{CEC} in the SA climate system for a simulate PV system and its grid-connected inverter's efficiency in PVSYST, under different scenarios of irradiation and temperature over a typical mean year, using hourly measurements from Meteonorm 7. The secondary goal is to propose a corrected formula η_{CPT} based on the discrepancy between assumptions and realistic data. The reason for this case study and scenario analysis is to test the effect that weather patterns have on $\eta_{DCAC-WEIGHTE}$.

5.4.1. Efficiency characteristics of the grid inverter

The manufacturer's datasheet of the PV inverter used for the simulation part of this thesis displays the following technical data (PVSYST 6.73, 2017b)

- Manufacturer, model: AEG Industrial Solar GmbH, AS-IR01-1000, 2017
- Available since: 2017
- Nominal DC power: 1 kW
- Nominal AC power: 1 kWac
- Operating mode: MPPT
- Maximum efficiency: 96.9%

- Euro efficiency: 96.0%
- CEC efficiency: 96.0%

The Euro & CEC efficiency profiles are given by the manufacturer as a function of the DC input power V_{DC}. This is important because it provides enough data to recalculate η_{EURO} & η_{CEC} (Allet, et al., 2011b).
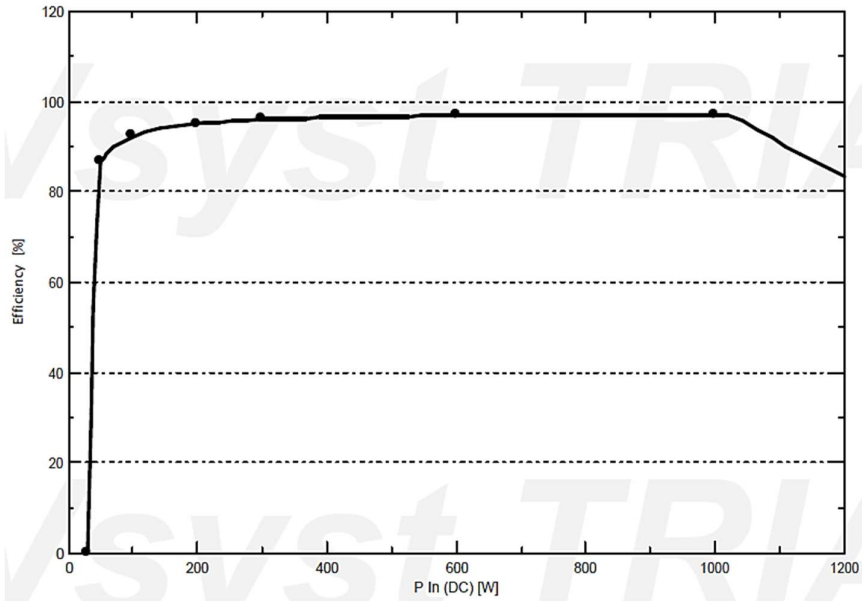
Figure 5.2. Euro efficiency curve: Inverter's η_{EURO} efficiency profile vs DC input power
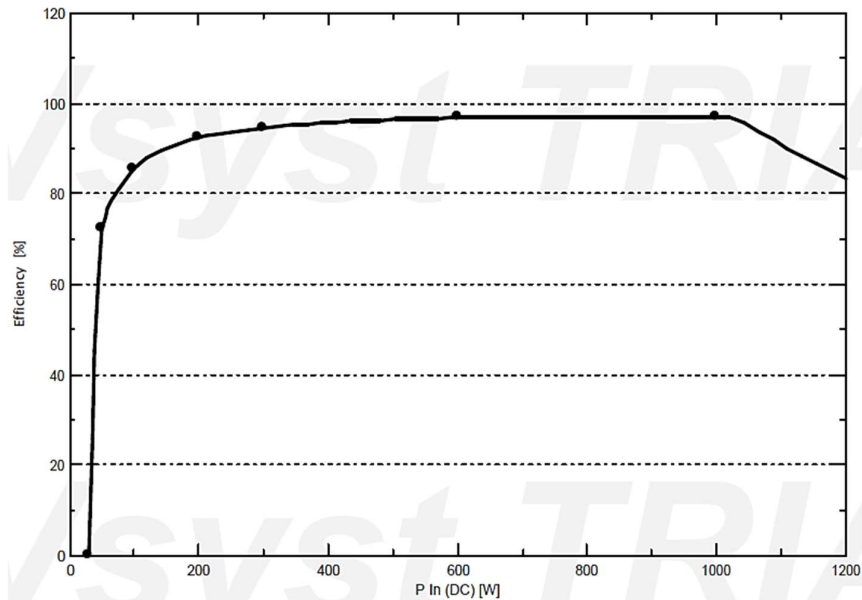
Figure 5.3. CEC efficiency curve: Inverter's η_{CEC} efficiency profile vs DC input power

	DC input P_{DC} [kW]	Euro efficiency [%]	CEC efficiency [%]

Power threshold	0.03	00.00	00.00
	0.05	86.71	72.15
	0.10	92.27	85.65
	0.20	95.05	92.40
	0.30	95.97	94.65
	0.60	96.90	96.90
	1.00	96.90	96.90

Table 5.1. Values for Euro & CEC as a function of the DC input power

The DC input is used to determine the efficiency since it corresponds to the PV array energy output, allowing for the DC wiring (cable) losses. Irradiation certainly influences PV inverter efficiency as it determines the energy that the solar panels will receive to produce the DC output that is in turn supplied to the converter. But if this is applied to determine P_{MPP}/P_{STC} and calculate the weighted efficiency, the temperature effect is ignored. Since the PV cells that produce the DC power have a temperature coefficient for both the voltage and the current, it is more accurate to use the DC input – instead of irradiance - because it incorporates all the losses associated with the DC side of the system.

As seen in Chapter 2, PV inverters rarely operate at maximum efficiency. Fluctuating climate conditions are constantly altering the DC input, and these meteorological characteristics vary differently from one location to another. The occurrence of the DC inputs (Table 3.4.) would not be the same in Cape Town as in Trier, Ispra or Sacramento used for the Euro & CEC efficiencies. In other words, η_{EURO} & η_{CEC} would not make accurate predictions of the PV system's annual energy yield.

5.4.2. Relationship between irradiation distribution, P_{MPP}/P_{STC} & η_{MPP}

One of the parameters that are crucial for the formulation of PV inverter weighted efficiency is the ratio between the maximum available power P_{MPP} from PV modules and the nominal power under STC given by the manufacturer P_{STC}, depending on the temperature and irradiation at a given time of the day. The inverter simulated for this research operates in MPPT mode. Data retrieved from the PVSYST PV system simulation provided no less than 8760 hourly measurements, over the entire year, for both the energy output of the PV array and the PV inverter. These data were compiled in MS Excel to calculate the corresponding 8760 P_{MPP}/P_{STC} and 8760 P_{AC}/P_{DC} values for each hour of the year.

Using this method, the pattern was determined between the various classes of irradiation and the respective portions of nominal power with the related inverter efficiencies η_{MPPn}.

For example, at 5% of P_{MPP}/P_{STC}, the corresponding efficiency or η_{MPP1} is noted $\eta_{5\%}$.

In the same way as it was for irradiance, for each 5% interval of P_{MPP}/P_{STC}, the frequency of occurrence over the year was calculated, along with the contribution of each portion to the overall energy yield.

In this way the irradiance distribution and classes for Cape Town can be correlated with the distribution of P_{MPP}/P_{STC} & η_{MPPn}.

5.4.3. Determination of η_{CPT_EURO} & η_{CPT_CEC}, η_{CPT1} & η_{CPT2}

To establish the validity of η_{EURO} & η_{CEC} for Cape Town weather profile, the weights assigned for each η_{MPP}, based on how often the PV inverter operates under the various DC inputs, conditioned by on-site irradiation and temperature occurrence and distribution (Ongun & Özdemir, 2013), were compared for the EU, US & SA locations.

- η_{CPT_EURO}: Weights for Cape Town data calculated for Euro irradiance classes
- η_{CPT_CEC}: Weights for Cape Town data calculated for CEC classes
- η_{CPT1}: Weights and classes adjusted from η_{EURO} for Cape Town efficiency formula
- η_{CPT2}: Weights and classes adjusted from η_{CEC} for Cape Town efficiency formula

The determination of η_{CPT_EURO} & η_{CPT_CEC} allows to compare the distribution of the energy generated in Cape Town for each the various intervals of P_{MPP}/P_{STC} [%] to Trier or Sacramento. This gives an assessment of how accurate η_{EURO} & η_{CEC} are for the SA climate. Based on this, a number of alternative weights were proposed for the Cape Town efficiency formula and evaluation classes were adapted, using a model matching the local profile.

5.5. Summary

Simulation were carried out in PVSYST & MS Excel to produce a graphic illustration of the distribution of ambient temperature and incoming irradiation at the site, assess the validity of estimates made by the η_{EURO} and η_{CEC} equations, and subsequently adjust the weighting factors and power portions to make them more representative of a Cape Town-based scenario. The formulas obtained for a Cape Town weighted efficiency were then compared with η_{EURO} & η_{CEC} to measure the impact on their ability to systematically predict the system's annual energy yield.

6. RESULTS, RESEARCH FINDINGS & INTERPRETATIONS

The effect of climate conditions, weather profile on PV inverter efficiency η_{DCAC} were tested, calculated and simulated for a 1 kWp grid-connected PV system. The simulations were carried out using PVSYST 6.73 software package as well as formulas created and compiled in Microsoft Excel 2016. The η_{EURO} & η_{CEC} PV inverter efficiency formulations were assessed as η_{CPT_EURO} & η_{CPT_CEC} under Cape Town climate irradiance, temperature and generated energy distribution, and η_{CPT1} & η_{CPT2} were calculated using the methodology for calculating new weights assigned within the adequate resolution of evaluation classes (Ongun & Özdemir, 2013).

Subsequently, the following results will be discussed:

1) Cape Town annual irradiation-temperature distribution

    a) Simulation using hourly average data from Meteonorm 7

    b) Contrast between Cape Town profile and η_{EURO} & η_{CEC} sites: Trier (Germany), Ispra (Italy) and Sacramento (California) using monthly data

2) PV energy yield distribution per evaluation classes

    a) Energy available annually for each irradiation classes

    b) Comparison with energy contributions of η_{EURO} & η_{CEC} classes

    c) Energy contribution per portions of P_{MPP}/P_{STC} & cumulative energy yield

    d) Impact of data resolution: hourly data vs monthly data

3) η_{CPT_EURO} & η_{CPT_CEC} results

4) η_{CPT1} & η_{CPT2}

6.1. Cape Town annual irradiation-temperature distribution

a) Simulations using Meteonorm 7.1 hourly average data

Here, two of the objectives of this research were achieved: simulate Cape Town climate conditions and offer a comparison with those in Trier and Sacramento.

The charts below show the annual distribution of solar irradiation and temperature in Cape Town (Figure.), from 8760 measurements over then entire typical mean year for each parameter (irradiance and temperature).

The highest value of irradiance, 1157.9 W/m^2, is measured on January 22nd at around midday. The constant fluctuations are better represented using this type of resolution, showing a sensible amount of variations during both summer and winter days and months.
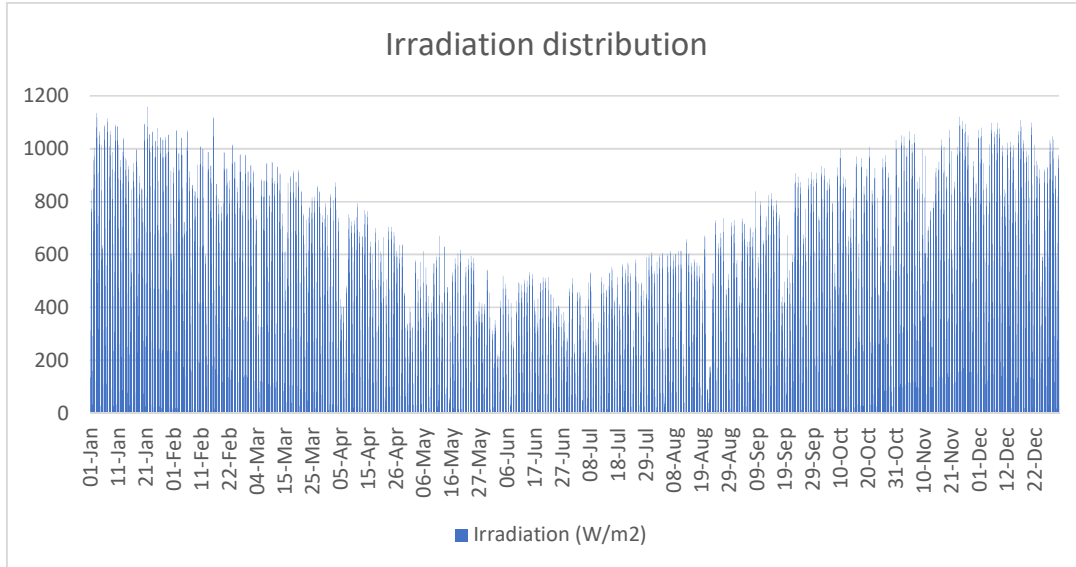
Figure 6.1.: Cape Town annual irradiation distribution (using hourly irradiation and temperature data from MeteoNorm 7.1 station)

The highest value of temperature is measured on February 21st at 31.9°C and the lowest registers at 3.3°C, on the 16th of July at 06:00. Although the overall temperature trends show, as expected, a decline during winter months, significant fluctuations can be observed throughout the year.
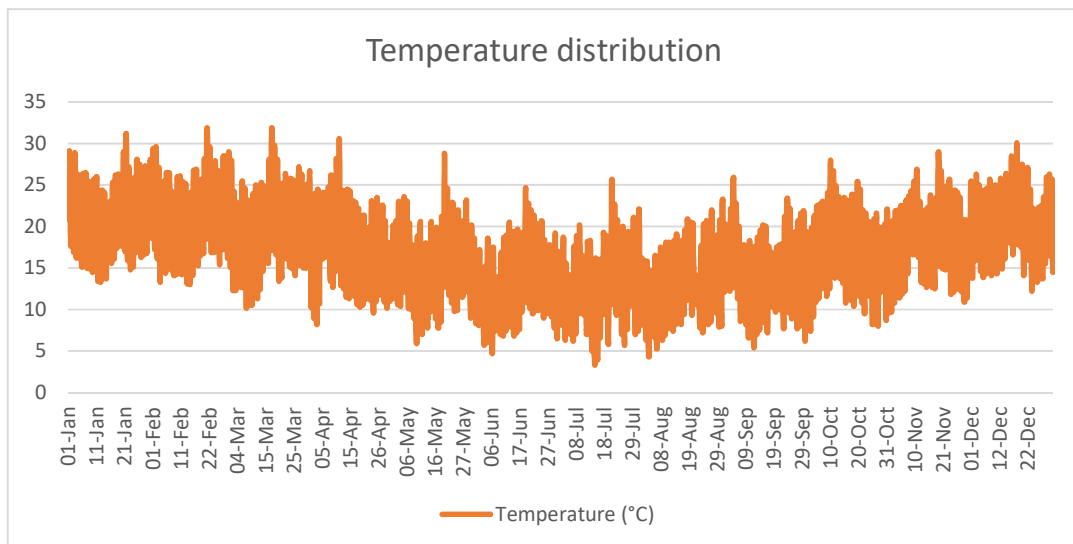
Figure 6.2.: Cape Town ambient temperature distribution (using hourly irradiation and temperature data from MeteoNorm 7.1 station)

By overlapping the irradiation and temperature distribution charts, a picture of high-resolution weather pattern trends emerges and reveals, beyond seasonal trends, important variations within smaller timeframes.
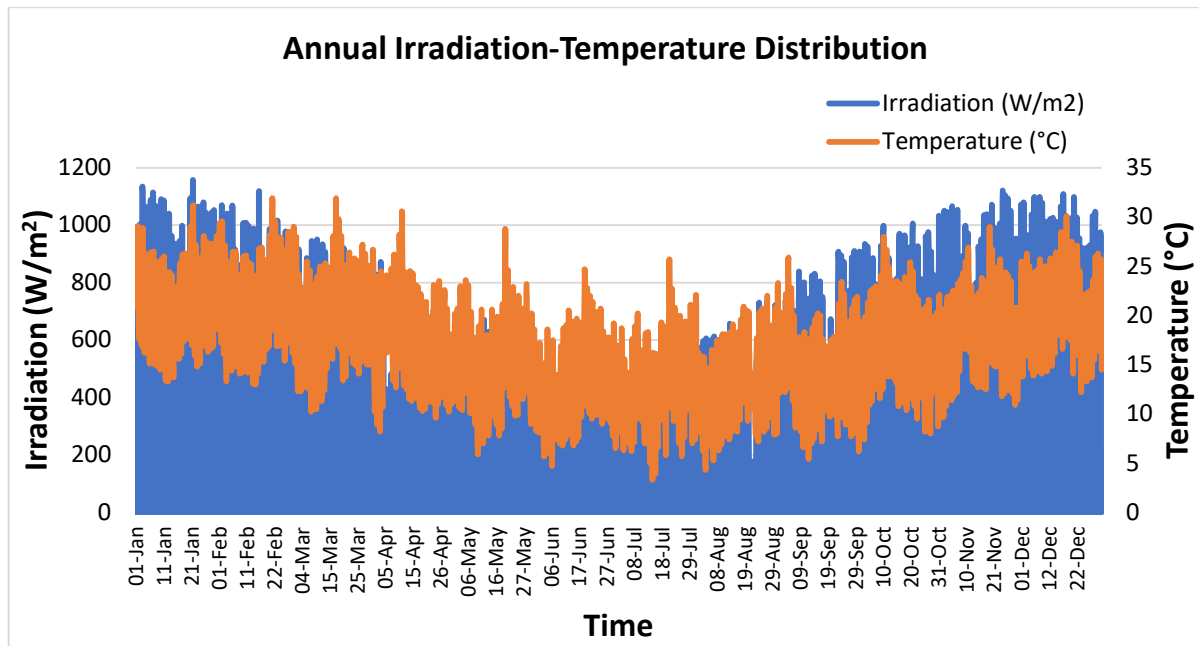
Figure 6.3.: Superposition of Cape Town annual irradiation & temperature distribution (using hourly irradiation and temperature data from MeteoNorm 7.1 station)

The amount of details provided by hourly resolution highlights the fact that even in the case of two weather profiles with similar seasonal trends (located in the same region), more detailed measurements would be needed to compare their more localized variations.

However, a simple monthly resolution of the results above was needed to display the contrast between Cape Town, Trier, Ispra and Sacramento weather profiles from PVSYST 6 & Meteonorm 7 data, commonly used in research and industry today.

b) *Comparison between Cape Town profile and η_{EURO} & η_{CEC} sites*

The distribution of annual irradiation and temperature using monthly data, although less detailed, still display the same curve trend than the chart based on hourly figures, However, when compared with results for the locations used by η_{EURO} & η_{CEC} (Trier, Ispra and Sacramento), there is a clear contrast in weather data scattering over a year. For Cape Town, peaks occur towards the beginning and the end of the year from November to February - monthly average of 257.6 W/m^2 in December and 21.3°C in February (Figure 2.)
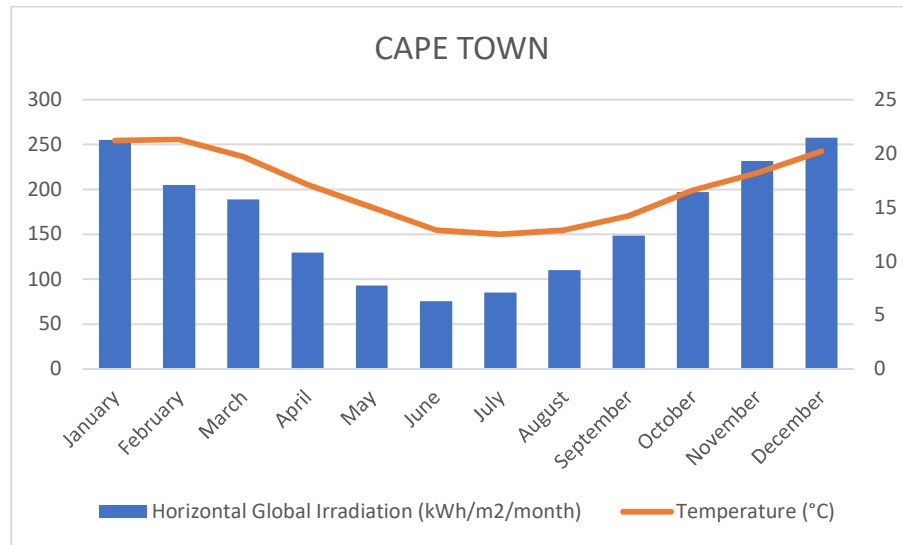
Figure 6.4. Annual temperature and irradiation profile at Cape Town (South Africa), using monthly resolution and data from Meteonorm 7

For the sites of Trier, Ispra and Sacramento, peaks tend to be in the middle of the year (June – July). The 3 sites' irradiation and temperature curves do not display the same seasonal trend as Cape Town, whose climate characteristics are more representative of the South Hemisphere.
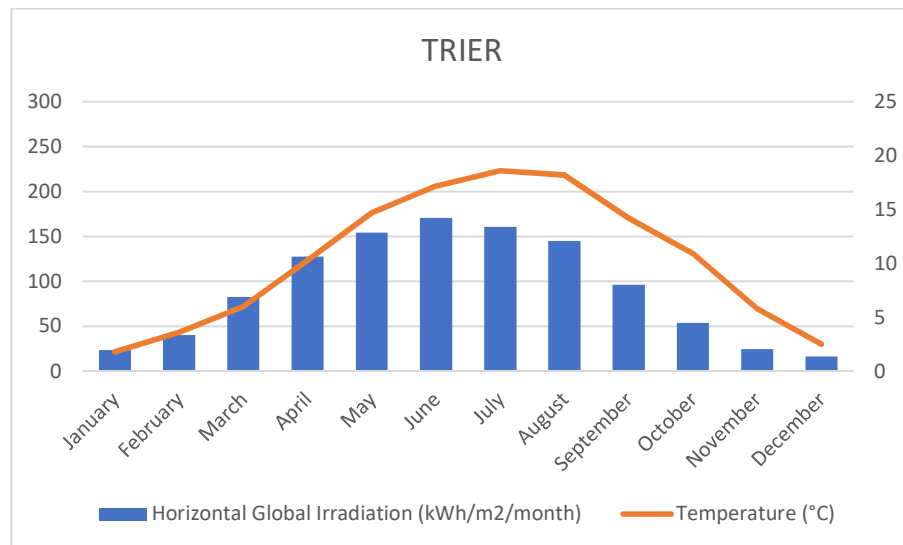
Figure 6.5. Annual temperature and irradiation profile at Trier (Germany), using monthly resolution and data from Meteonorm 7

In Trier peak monthly averages occur at 170.7 W/m^2 in June and 18.6 °C in July.
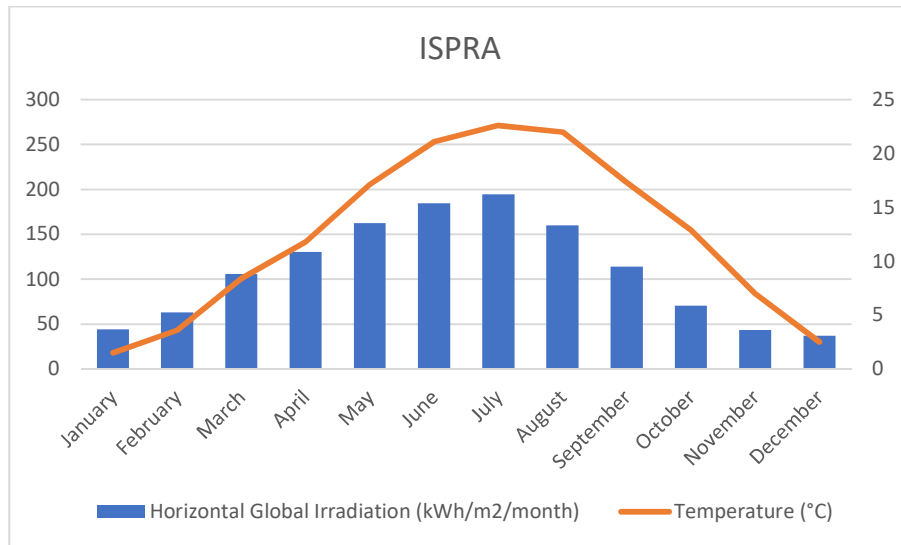
Figure 6.6. Annual temperature and irradiation profile at Ispra (Italy), using monthly resolution and data from Meteonorm 7

In Ispra monthly averages top at 194.7 W/m^2 and 22.6 °C both in July.
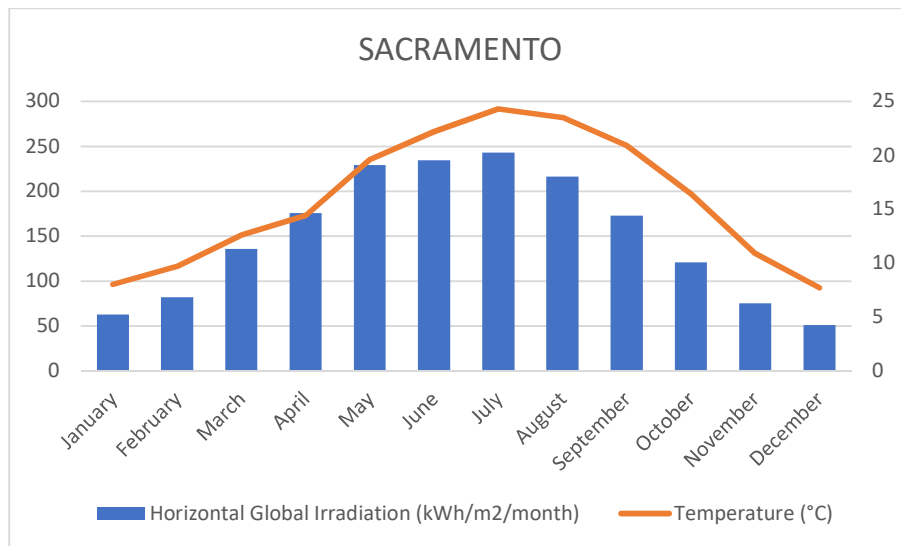
Figure 6.7. Temperature and irradiation profile at Sacramento (California, USA), using monthly resolution and data from Meteonorm 7

In Sacramento, the highest monthly averages are calculated in July at 242.8 W/m^2 and 24.3 °C.

The results show that climate conditions are different in Cape Town in comparison to η_{EURO} & η_{CEC} sites, therefore PV inverter energy yield and efficiency have to be expressed differently.

Although monthly resolution, seasonal trends, regional proximity can help reveal differences between two weather profiles, they do not provide enough data to accurately portray resulting differences in PV inverter efficiency formulation. Having gathered hourly data on weather pattern distribution, the PV system's energy yield distribution per evaluation classes were simulated.

6.2. PV energy yield distribution per evaluation classes

a) PV generation and energy yield

The yield results were very similar for η_{EURO} (1833 kWh/year) and η_{CEC} (1819 kWh/year) and the performance ratios respectively 0.819 and 0.815.

The energy output of the system considered for the purpose of this research, simulated using hourly values obtained from PVSYST calculations, shows that, despite $P_{NOM\_GENERATOR}$, the nominal power of 1kW, there is actually no instance of AC power output P_{AC} above 900 W (0.9 kW, the highest instance), even with the inverter operating in MPP-Tracking mode.

$$P_{MPP\_GENERATOR} = P_{MPP\_MODULE} \cdot \frac{P_{NOM\_GENERATOR}}{P_{NOM\_MODULE}} = \frac{1000\ W}{250\ W} = 4 \times P_{MPP\_MODULE}$$

$$P_{AC} = P_{MPP\_GENERATOR} \times \eta_{DCAC} = 4\ P_{MODULE} \times \eta_{DCAC}$$
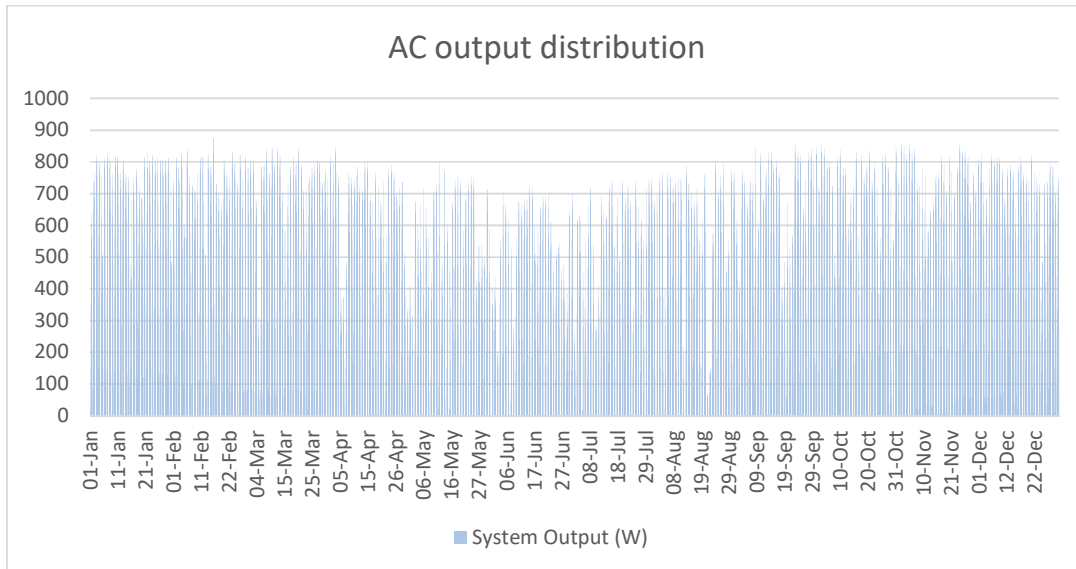
Figure 6.8. AC output distribution of the system, hourly measurements over the typical mean year

The above equation implies losses due to the amount of DC input from PV modules, P_{MODULE}, because the generator will not always operate under standard conditions of 25°C and 1000 W/m^2 as shown previously in the annual irradiation and temperature distribution charts, but also because to the inverter efficiency never reaches 100%. DC

Ohmic losses, cable or wiring losses between the DC and AC sides are also taken into consideration (Allet, et al., 2011a):

$$\Delta P_{MPP\_GENERATOR} = I_{DC\_GENERATOR}{}^2 \cdot R_{CABLE}$$

The highest value for the DC input of the simulated plant is measured at 904 W, on February the 15th at 11 a.m. when an irradiance of 1114.5 W/m^2 and temperature of 24.4 °C. The next hour, at 12 a.m., although irradiance increase slightly to 1119.3 W/m^2, so does temperature to 25.6°C, so the DC input registers a tad lower, 902 W. The effect of climate conditions is evident in that PV modules current and voltage inherently have a temperature coefficient of variation and electric wires cause power losses according to the intensity of the temperature-dependent current that passes through them as well as their own electrical resistance (Allet, et al., 2011a).
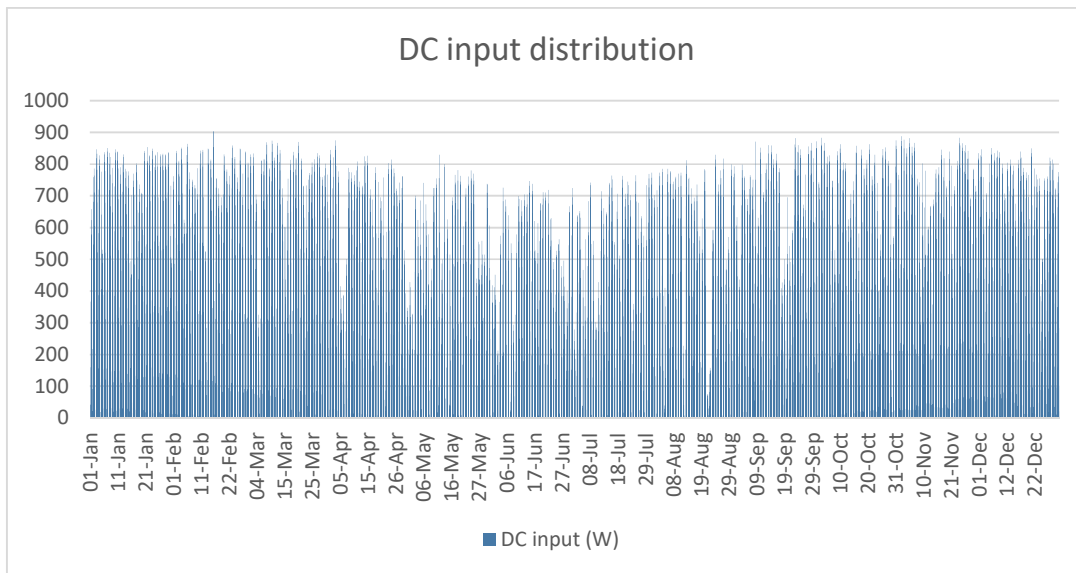
Figure 6.9. DC input distribution of the system, hourly measurements over the typical mean year

By overlapping irradiation, DC input and AC output distributions, it can be observed that the biggest loss of power between irradiance and DC input occur during summer from December to February when the overall temperature also rises (refer to Table 6.). Meanwhile, during the winter, despite less amounts of irradiance, the temperature also falls, resulting in relatively high DC inputs & AC outputs.

Some observations can be made about the effect of ambient temperature and incident radiation on which depend, among others, PV module temperature and the power generated from current and voltage:

- At 12:00 on July 15th, under 551.1 W/m^2 and 14.2°C, the system's DC input is 764 W and the AC output, 740 W (η_{DCAC} = 96.86%).

- On August 6th at 12:00, under similar conditions (553.9 W/m^2 and 14.2°C), the DC input is lower, at 645 W and the AC output at 625 W (η_{DCAC} = 96.90%).

- At 13:00 on August 5nd, under similar irradiance (551.5 W/m^2) but at lower temperature (13.8°C), the DC input is at 744 W, but inverter efficiency rises to its maximum rated value of 96.90% (AC output = 721 W).

- On January 22th at 12:00, when irradiance reaches its annual peak at 1157.9 W/m^2, with an ambient temperature of 31.2°C, the DC input is 854 W and the AC output 828 W, the inverter slightly surpasses its maximum efficiency (η_{DCAC} = 96.95%).
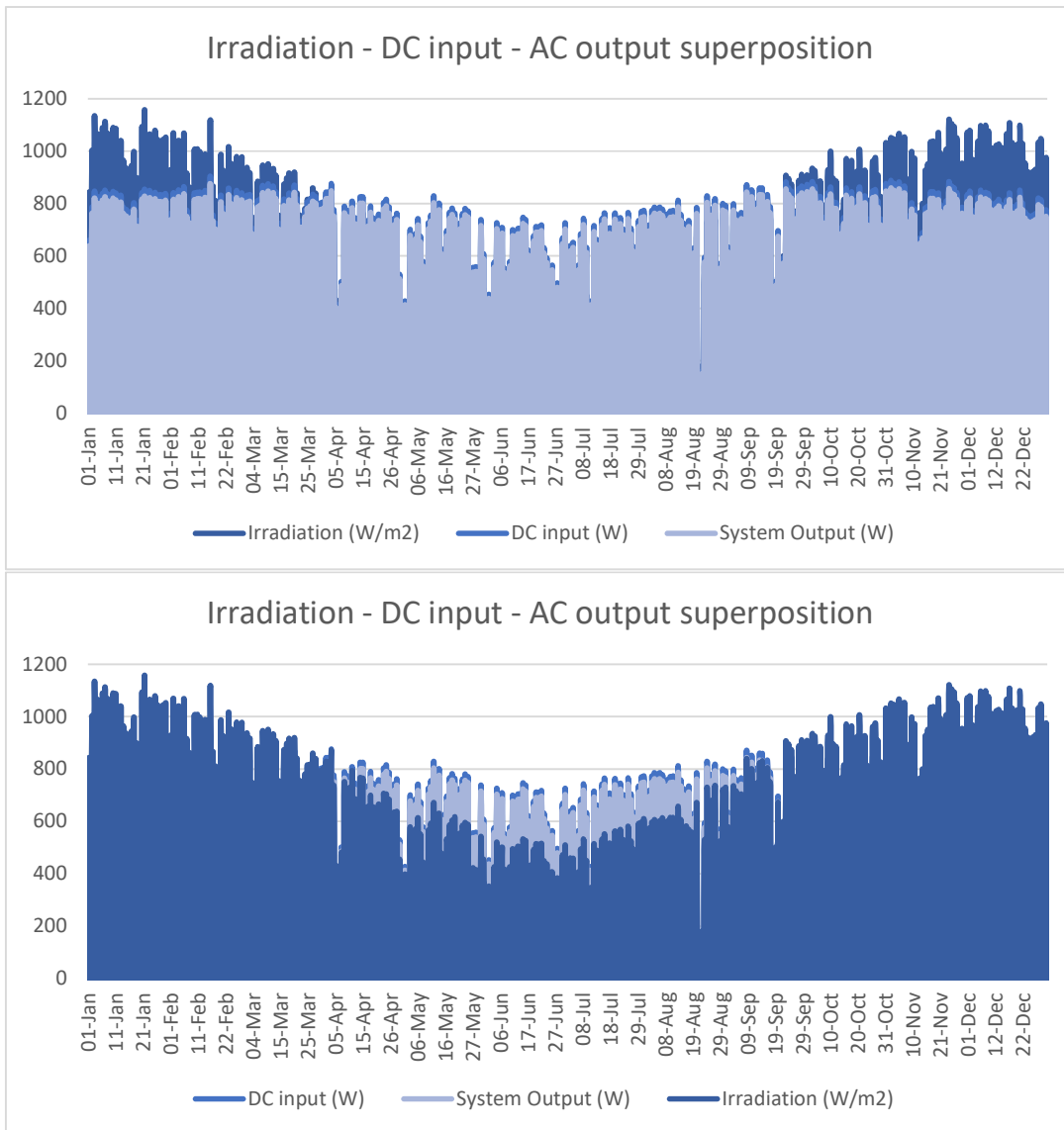
Figure 6.10.: Superposition of annual irradiation, DC input & AC output distributions (using hourly data from PVSYST 6.73 and Meteonorm 7.1 station)

b) *Energy available annually for each irradiation classes*

The results of the evaluation of irradiation data for annual energy distribution against irradiation classes – using hourly data – are presented below.

The frequency curve using hourly data displays how often each irradiation classes occur each year in Cape Town. Each irradiation band is represented by its lowest value. For example, band 0 represent the class 0 – 50 W/m^2 (Fig.2)
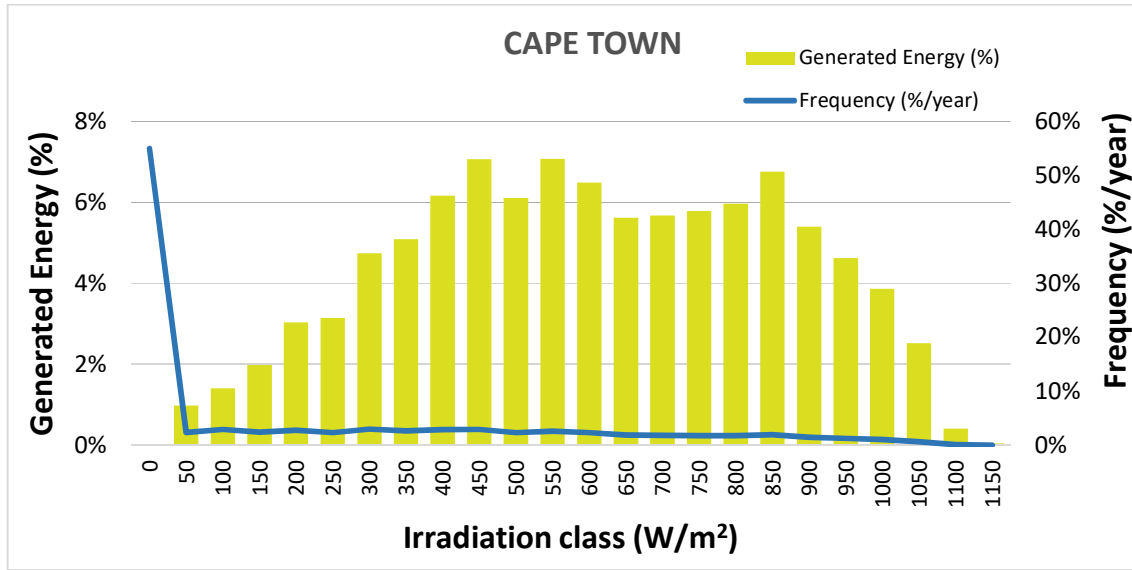
Figure 6.11. Energy available per year for each band of radiation and frequency of occurrence, from Meteonorm 7 hourly data and using the PV inverter operating according to η_{EURO}

Irradiation class (W/m^2)	Frequency (&/year)	Generated energy (%)
0 – 50	54.99%	0.02%
50 – 100	2.37%	0.98%
100 – 150	2.91%	1.41%
150 – 200	2.40%	1.98%
200 – 250	2.76%	3.04%
250 – 300	2.29%	3.15%
300 – 350	2.98%	4.74%
350 – 400	2.63%	5.09%
400 – 450	2.84%	6.17%
450 – 500	2.95%	7.07%
500 – 550	2.32%	6.12%
550 – 600	2.57%	7.07%
600 – 650	2.32%	6.49%
650 – 700	1.88%	5.62%
700 – 750	1.80%	5.68%
750 – 800	1.78%	5.78%
800 – 850	1.77%	5.97%
850 – 900	1.92%	6.76%
900 – 950	1.48%	5.40%
950 – 1000	1.26%	4.63%
1000 – 1050	1.02%	3.86%

1050 - 1100	0.65%	2.52%
1100 – 1150	0.10%	0.41%
1150 – 1200	0.01%	0.05%

Table 6.1. Frequency of occurrence of each irradiance class and the associated percentage of generated energy over the entire typical mean year, using Meteonorm 7 hourly data

From data analysis, calculations show that one third (33.63%) of annual energy yield would be harvested at and below 500 W/m^2 irradiation levels. A quick inspection of the graph can reveal this too. The other thirds would be harvested between 500 and 750 W/m^2 (30.99%) and above 750 W/m^2 (35.38%) irradiation classes respectively.

This evidently demonstrates that yield estimations based on European efficiency would not be valid for Cape Town irradiation since it assumes 79% of annual yield would be harvested at and below 500 W/m^2 irradiation levels (see Table 3.2.).

CEC efficiency on the other hand, displays a closer match with Cape Town irradiation profile at lower levels (<500 W/m^2) since it assumes 42% energy yield for that range (see Table 3.3.). But even this model does not represent a proper match for medium and high irradiation levels because it assumes 95% of annual yield would be harvested below 750 W/m^2 irradiation levels, which is not the case with Cape Town data.

c) Energy yield per portions of P_{MPP}/P_{STC} & cumulative energy yield

To achieve the main goal of this study, which is to determine a weighted efficiency formula for Cape Town describing the inverter's performance based on the average P_{MPP} contributions of the respective evaluation classes, given on how often they occur at the site during a typical mean year, a relationship was established between irradiation classes and portions of P_{MPP}/P_{STC}.

Irradiation class (W/m^2)	Occurrences over the year	Average P_{MPP}/P_{STC} (%)	Evaluation class (%)
0 - 50	4817	0.09484012	0 – 5%
50 - 100	208	9.758184135	5 – 10%
100 – 150	255	11.27330784	10 – 15%
150 – 200	210	18.25054052	15 – 20%
200 – 250	242	24.09709979	20 – 25%
250 – 300	201	29.91637159	25 – 30%
300 – 350	261	34.58849425	30 – 35%
350 – 400	230	42.04953178	40 – 45%
400 – 450	249	46.97755112	45 – 50%
450 – 500	258	51.89846481	50 – 55%
500 – 550	203	57.07087635	55 – 60%

550 – 600	225	59.49290862	55 – 60%
600 – 650	203	60.5586097	60 – 65%
650 – 700	165	64.49513061	60 – 65%
700 – 750	158	67.9968019	65 – 70%
750 – 800	156	70.12820064	70 – 75%
800 – 850	155	72.81159206	70 – 75%
850 – 900	168	76.09587393	75 – 80%
900 – 950	130	78.58767685	75 – 80%
950 – 1000	110	79.59545882	75 – 80%
1000 – 1050	89	82.05054753	80 – 85%
1050 – 1100	57	83.7945786	80 – 85%
1100 – 1150	9	86.28887667	85 – 90%
1150 – 1200	1	85.39962	85 – 90%

Table 6.2. Correlation between irradiation and averaged power portion evaluation classes correlated based on their frequency of occurrence per year at the site, compiled from hourly figures

A more detailed analysis and inspection of the Cape Town solar irradiation data and the simulated PV system's energy yield calculations gives the weights (Tables 6.3. & 6.4.) for 5% intervals representing the different irradiation classes. The energy contributions are assessed for both η_{EURO} & η_{CEC}.

P_{MPP}/P_{STC} (%)	0 - 5	5 - 10	10 - 15	15 - 20	20 - 25	25 - 30	30 - 35	35 - 40	40 - 45
CPT (EURO) (%)	0.07	0.74	1.02	1.96	2.40	2.73	3.39	3.57	4.91
Cumulative energy yield (%)	0.07	0.81	2.01	3.97	6.37	9.10	12.49	16.06	20.97

P_{MPP}/P_{STC} (%)	45 - 50	50 - 55	55 - 60	60 - 65	65- 70	70 - 75	75 - 80	80 - 85	85 - 90	90 - 95
CPT (EURO) (%)	5.85	6.86	6.95	8.91	10.13	12.10	13.77	11.67	2.69	0.09
Cumulative energy yield (%)	26.82	33.68	40.63	49.54	59.67	71.77	85.54	97.21	99.90	99.99

Table 6.3. Weighted efficiency formula coefficients for η_{EURO}

P$_{MPP}$/P$_{STC}$ (%)	0 - 5	5 - 10	10 - 15	15 - 20	20 - 25	25 - 30	30 - 35	35 - 40	40 - 45
CPT (CEC) (%)	0.06	0.65	1.15	1.88	2.31	2.65	3.33	3.51	4.85
Cumulative energy yield (%)	0.06	0.71	1.86	3.74	6.05	8.70	12.04	15.55	20.39

P$_{MPP}$/P$_{STC}$ (%)	45 - 50	50 - 55	55 - 60	60 - 65	65- 70	70 - 75	75 - 80	80 - 85	85 - 90	90 - 95
CPT (CEC) (%)	5.81	6.81	6.93	8.88	10.11	12.08	13.77	11.67	2.69	0.09
Cumulative energy yield (%)	26.21	33.02	39.95	48.83	58.95	71.03	84.80	96.47	99.16	99.26

Table 6.4. Weighted efficiency formula coefficients for η$_{CEC}$

One of the most important findings made from the calculations above is that there is barely any instances above 90% P$_{MPP}$/P$_{STC}$ ratio – just 2 out of 8760 measurements, contributing less than 0.1% to the overall energy yield – due to the diminishing effect of PV module temperature. This means that the 1000 Wp PV array would, by no means, produce the rated 1000 W power throughout the year, operating in Cape Town weather, unless it is cooled by some mechanism (temperature effect).

d) Comparison with energy contribution of η$_{EURO}$ classes

A comparison of calculations based on Cape Town data, for European and CEC efficiencies are presented in the Table 4. The values displayed for P$_{MPP}$/P$_{STC}$ represent the maximum values of the classes. For instance, 5% P$_{MPP}$/P$_{STC}$ corresponds to the class 0 – 5%.

P$_{MPP}$/P$_{STC}$ (%)	5%	10%	15%	20%	25%	30%	50%	75%	100%
Euro	3%	6%		13%		10%	48%		20%
CEC		4%		5%		12%	21%	53%	5%
CPT (Euro)	0.07%	0.74%		2.98%		5.13%	17.72%		73.18%
CPT (CEC)		0.71%		3.03%		4.96%	17.50%	44.82%	28.22%

Table 6.5. Weights for Cape Town data calculated for Euro and CEC classes:

Energy yield per evaluation classes (%)			
Evaluation class P_{MPP}/P_{STC} (%)	Euro efficiency	Evaluation class P_{MPP}/P_{STC} (%)	CEC efficiency
0 – 5%	3%	0 – 10%	-
5 – 10%	6%	10% – 20%	4%
10% – 20%	13%	20% – 30%	5%
20% – 30%	10%	30% – 50%	12%
30% – 50%	48%	50% – 75%	21%
75% – 100%	20%	75% – 100%	5%
Energy yield per evaluation classes (%)			
Evaluation class P_{MPP}/P_{STC} (%)	Cape Town Euro efficiency	Evaluation class P_{MPP}/P_{STC} (%)	Cape Town CEC efficiency
0 – 5%	0.07%	0 – 10%	0.71%
5 – 10%	0.74%	10% – 20%	3.03%
10% – 20%	2.98%	20% – 30%	4.96%
20% – 30%	5.13%	30% – 50%	17.50%
30% – 50%	17.72%	50% – 75%	44.82%
75% – 100%	73.18%	75% – 100%	28.22%

e) *Impact of data resolution on distribution profile: hourly vs daily vs monthly averages*

The use of hourly averages data resolution provided a detailed and the most accurate representation of the energy and frequency of occurrence distribution over the typical mean year, which is crucial to calculate the coefficients that will weigh the different P_{MPP}/P_{STC} portions.
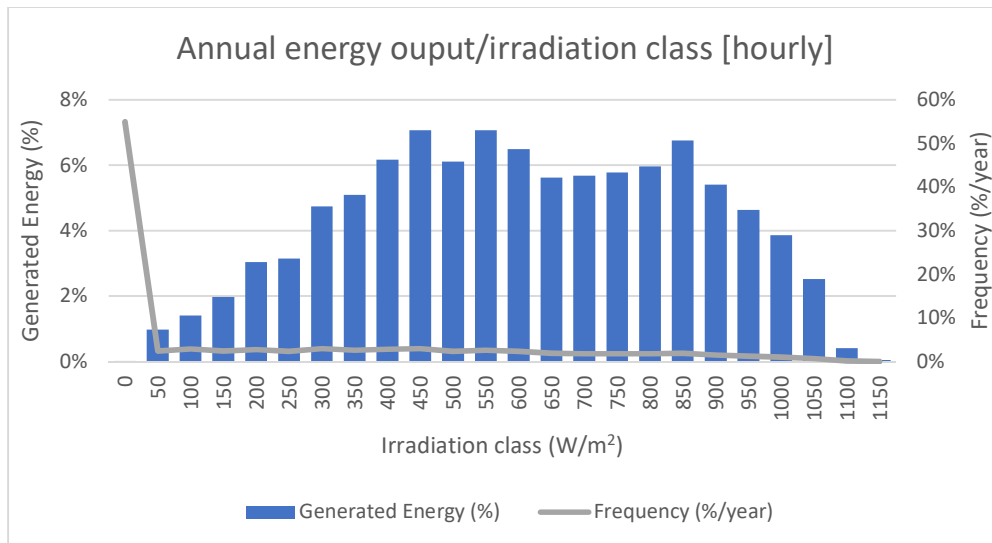
Figure 6.12. Annual energy output distribution per irradiation class using hourly averages

If the frequency of occurrence and the energy contribution are based on daily or on monthly averages however, it can be observed that the resulting graphs fail significantly to consider a large portion of irradiation classes and yield inaccurate profiles because these means do not account for the amount of variation of these parameters during the course of the day.
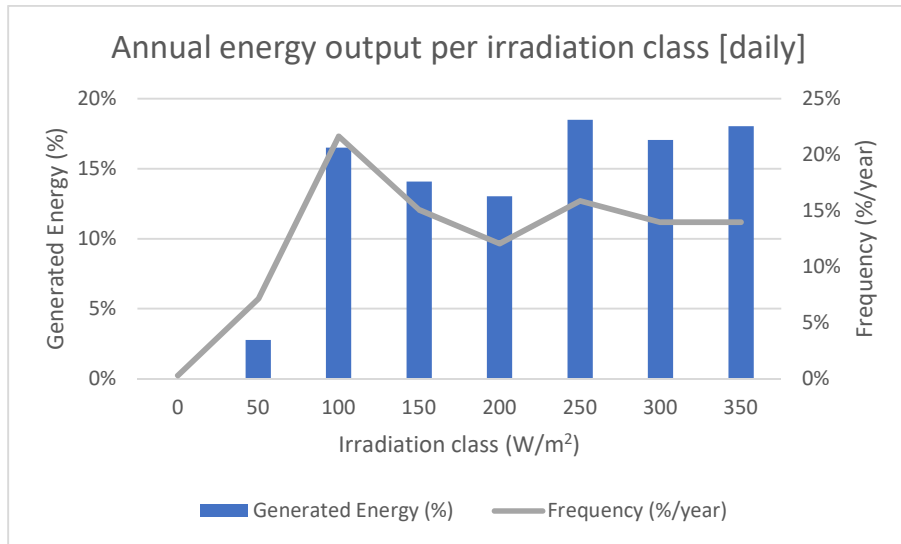
Figure 6.13. Annual energy output distribution per irradiation class using daily averages yields inaccurate and incomplete patterns

The use of a daily resolution assumes, for example, that the band of irradiation from 100 to 150 W/m^2 contributes to 21.64% of the generated energy and that is simply not the cases as the higher hourly resolution puts that number at 1.41%.

Moreover, daily averages imply that irradiations classes from 350 W/m^2 and higher neither occur nor contribute to the energy output of the PV system under Cape Town weather conditions which is false from the outset. The lower the resolution, the bigger the discrepancy as shown with monthly averages.
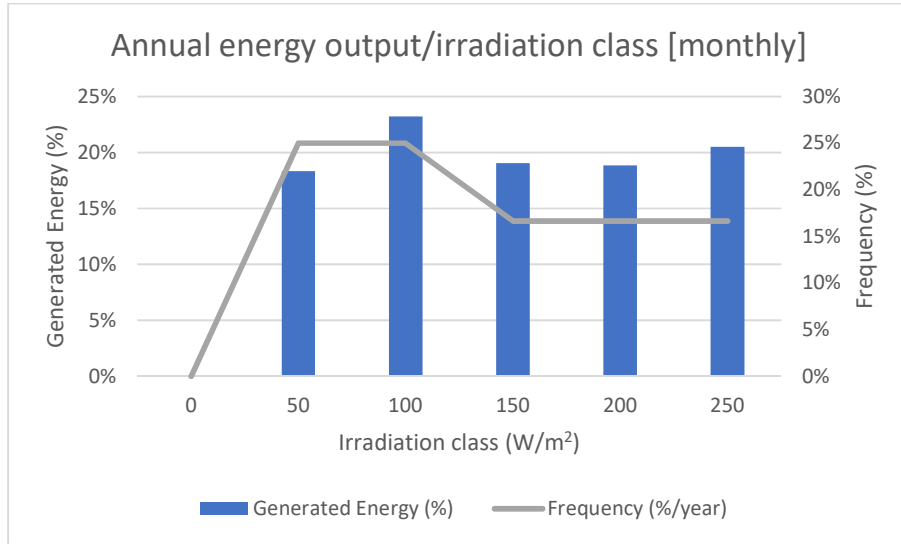
Figure 6.14. Annual energy output distribution per irradiation class using monthly averages yield inaccurate and incomplete patterns

The monthly or daily values of the energy output of the PV system that is injected into the grid can be useful to determine how much energy can be expected from a particular PV plant. But to make accurate predictions of this yield, irradiation classes, with their frequency of occurrence and energy contribution must be simulated using at least hourly resolutions to produce a reliable representation of Cape Town weather profile.

6.3. η_{CPT_EURO} & η_{CPT_CEC} results

Given the findings regarding the DC input power distribution for Cape Town weather patterns, it is clear that even the Euro efficiency profile given on the inverter's manufacturer's datasheet would incorporate hardly any DC input values over 900 W under Cape Town weather conditions.
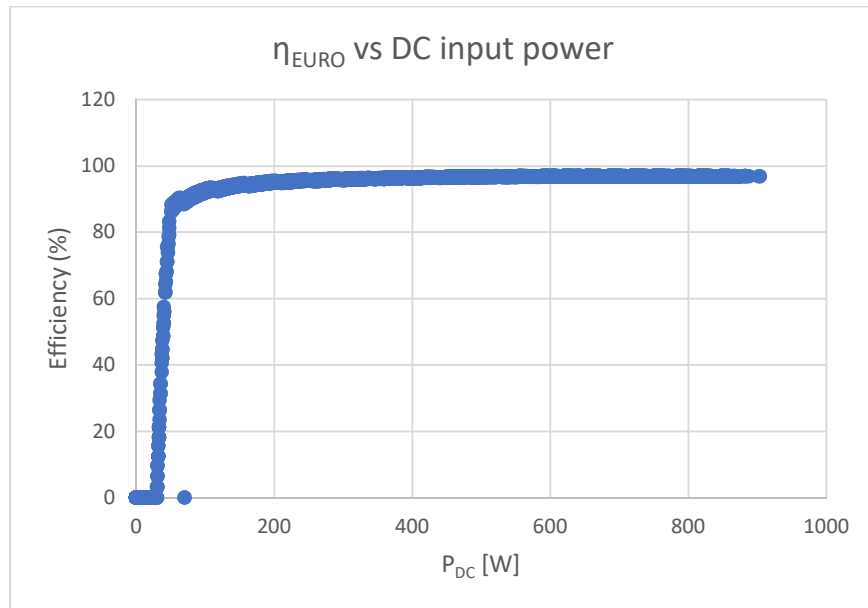
Figure 6.15. Euro efficiency profile vs DC input power simulation. Under Cape Town weather conditions at the site (Cape Town) there would be almost no values of DC input over 900 W
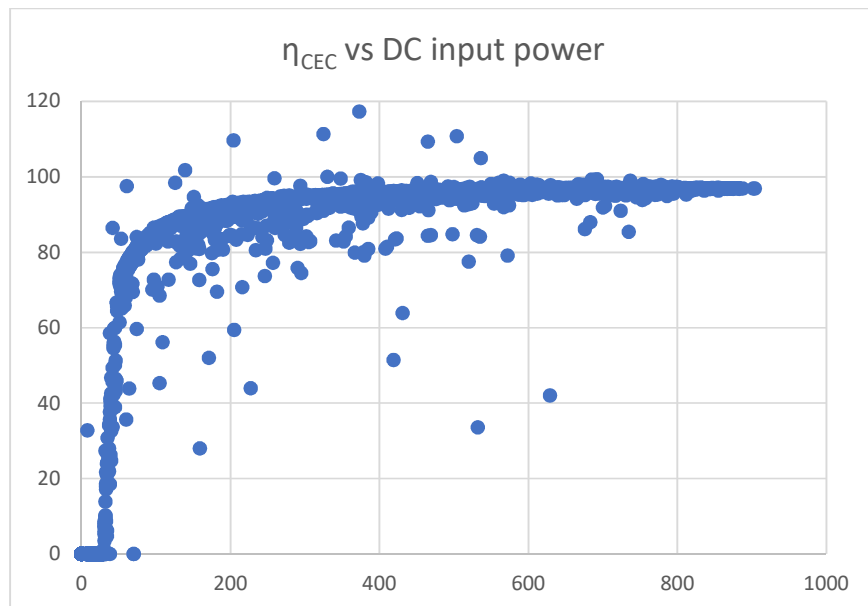
Figure 6.16. CEC efficiency profile simulation. Under Cape Town weather conditions, there would be almost no values of DC input over 900 W. The application of CEC efficiency yielded a few unrealistic points with efficiencies over 100% but the overall profile is characteristic of the efficiency described on the datasheets

Results show that when Euro & CEC efficiency weighting factors are applied to power portions and efficiencies under Cape Town weather profile, the predictions and assumptions do not match the observations.

η_{EURO} = 96.0% (manufacturer's assumption)

$\eta_{SITE\_EURO} = 0.03\eta_{5\%} + 0.06\eta_{10\%} + 0.13\eta_{20\%} + 0.10\eta_{30\%} + 0.48\eta_{50\%} + 0.20\eta_{100\%}$

= (0.03 × 0.09426675) + (0.06 × 0.894046596) + (0.13 × 0.940146185) + (0.10 × 0,955648449) + (0.48 × 0.964214856) + (0.20 × 0,96878767)

= 93.08%

η_{CEC} = 96.0% (manufacturer's assumption)

η_{SITE_CEC} = $0.04\eta_{10\%}$ + $0.05\eta_{20\%}$ + $0.12\eta_{30\%}$ + $0.21\eta_{50\%}$ + $0.53\eta_{75\%}$ + $0.05\eta_{100\%}$

= (0.04 × 0,334600036) + (0.05 × 0,899637071) + (0.12 × 0,922981631) + (0.21 × 0,95208976) + (0.53 × 0,965853847) + (0.05 × 0,968725509)

= 92.94%

η_{CPT_EURO} & η_{CPT_CEC} represent the efficiency formulas and values determine by applying weighting factors calculated for Euro and CEC classes – under Cape Town climate conditions – to average efficiencies at partial MPP powers (P_{MPP}/P_{STC}) as per DC inputs characteristic to the site.

η_{CPT_EURO} = $0.0007\eta_{5\%}$ + $0.0074\eta_{10\%}$ + $0.0298\eta_{20\%}$ + $0.0513\eta_{30\%}$ + $0.1772\eta_{50\%}$ + $0.7318\eta_{100\%}$

η_{CPT_CEC} = $0.0071\eta_{10\%}$ + $0.0303\eta_{20\%}$ + $0.0496\eta_{30\%}$ + $0.1750\eta_{50\%}$ + $0.4482\eta_{75\%}$ + $0.2822\eta_{100\%}$

This model offers a more accurate representation of the energy contribution made by each power portions to the overall energy yield based on irradiation class occurrence at the site and taking into account the effect of temperature on the DC input.

η_{CPT_EURO} = (0.0007 × 0,09426675) + (0.0074 × 0,894046596) + (0.0298 × 0,940146185) + (0.0513 × 0,955648449) + (0.1772 × 0,964214856) + (0.7318 × 0,96878767)

= 96.35%

η_{CPT_CEC} = (0.0071 × 0,334600036) + (0.0303 × 0,899637071) + (0.0496 × 0,922981631) + (0.1750 × 0,95208976) + (0.4482 × 0,965853847) + (0.2822 × 0,968725509)

= 94.83%

η_{DCAC}	η_{EURO}	$\eta_{SITE-EURO}$ calculated based on P_{DC}	η_{CPT_EURO}	η_{CEC}	$\eta_{SITE-CEC}$ calculated based on P_{DC}	η_{CPT_CEC}
	96.0%	93.08%	96.35%	96.0%	92.94%	94.83%

Table 6.6.: Comparison between η_{EURO} & η_{CEC} and actual on-site calculated values of η_{SITE_EURO} & η_{SITE_CEC} applying Euro and CEC weights and based on the site's DC energy distribution (dependent on the measured irradiation and temperature distribution), and the more realistic weighted efficiencies η_{CPT_EURO} & η_{CPT_CPT} (8760 data points each)

An analysis of the results reveals a discrepancy of 2.92% between the value of η_{EURO} assumed by the manufacturer and the value calculated for the site's characteristic DC input distribution. A similar inconsistency of 3.06% can be observed between the assumption made for η_{CEC} and the value computed under Cape Town conditions. This is solved used values taking into account weighting factors specific to the sites and applying them to Euro and CEC classing to yield more realistic formulas.

6.4. Weighting factors for η_{CPT} : η_{CPT_1} & η_{CPT_2}

The values obtained for η_{CPT_EURO} demonstrate that the energy contribution of the power portions corresponding to lower Euro evaluation classes (0-5% and 5-10% P_{MPP}/P_{STC}) are very small at the site of Cape Town (0.07% for $\eta_{5\%}$ and 0.74% for $\eta_{10\%}$) whereas for the most energy is concentrated towards higher classes (17.72% for $\eta_{50\%}$ and 0.7318%. Moreover, the simulations and calculations show no occurrences of power portions over 95% or $\eta_{95\%}$. η_{CPT_EURO} is therefore reformulated as follows:

η_{CPT_EURO} = $0.0007\eta_{5\%}$ + $0.0074\eta_{10\%}$ + $0.0298\eta_{20\%}$ + $0.0513\eta_{30\%}$ + $0.1772\eta_{50\%}$ + $0.7318\eta_{95\%}$

= η_{CPT_1} = $0.01\eta_{10\%}$ + $0.03\eta_{20\%}$ + $0.05\eta_{30\%}$ + $0.18\eta_{50\%}$ + $0.73\eta_{95\%}$

A look at the expression of η_{CPT_CEC} highlight a similar phenomenon which is minimal energy input for lower power portions of CEC evaluation classes (5-10% P_{MPP}/P_{STC}) and this is imposed by the distribution of weather parameters at the site. The majority of the energy comes from upper classes (17.50% for $\eta_{50\%}$, 44.82% for $\eta_{75\%}$ and 28.22% for $\eta_{100\%}$). η_{CEC} shows closer parallels with Cape Town but with no occurrences over $\eta_{95\%}$, the data still does not match well enough to reflect Cape Town climate conditions. η_{CPT_CEC} is therefore reformulated as follows:

η_{CPT_CEC} = $0.0071\eta_{10\%}$ + $0.0303\eta_{20\%}$ + $0.0496\eta_{30\%}$ + $0.1750\eta_{50\%}$ + $0.4482\eta_{75\%}$ + $0.2822\eta_{95\%}$

η_{CPT_2} = $0.04\eta_{20\%}$ + $0.05\eta_{30\%}$ + $0.17\eta_{50\%}$ + $0.45\eta_{75\%}$ + $0.28\eta_{95\%}$

Using a compromise between accuracy – detailed description of various evaluation classes – and simplicity – merging coefficients with less significant energy contributions –, η_{CPT_1} & η_{CPT_2} can be combined in a formula that better expresses the weighted efficiency of the PV inverter operating under Cape Town climate conditions.

η_{CPT} = $0.04\eta_{20\%}$ + $0.05\eta_{30\%}$ + $0.18\eta_{50\%}$ + $0.45\eta_{75\%}$ + $0.28\eta_{95\%}$

7. CONCLUSIONS & RECOMMENDATIONS

Photovoltaic power systems or PVPS are emerging as a major means of generating electricity for grid and off-grid usage. Improved awareness of global warming, climate change, CO_2 and GHG pollution are one motive behind this trend, the other behind the increase of conventional and fossil fuels at risk of being depleted by the unrelenting energy demand. Solar PV is seen as a favourable option because of its environmental and socio-economic benefits. To produce the AC power used by appliances and loads, grid-connected PVPS utilize PV inverters which convert the DC power generated by the PV modules or solar panels. But these systems are fundamentally dependent to meteorological conditions which vary not only around the world but even at a fixed location depending on the time and the seasons. For PV systems to be a reliable and economic alternative for investors and users, it essential to predict their annual energy yield. This energy harvest depends on the performance of the PV inverter which is in turn influenced by the climate parameters like temperature and irradiation. These fluctuations mean that the maximum efficiency of these devices will seldom be reached.

Two standard methods tackle this problem and are considered as references to compare PV inverters: The Euro efficiency, based on Central European climate and designed for low insolation sites, and the CEC efficiency, developed for higher insolation, as measured in California (USA). Both use different weighting factors according to the energy contributions of various classes of irradiations to the maximum power generated by PV modules and the annual energy yield.

But literature shows that these models would be less valid for different locations with different climatic patterns. For this reason, this thesis used hourly meteorological data for the site of Cape Town to evaluate the Euro and CEC formulations under South African conditions. In the research experiment, PVSYST photovoltaic software was used to simulate a grid-connected PV plant and its annual energy yield. Energy, temperature and irradiation distribution were then used to study how local meteorology would influence the expression of inverter weighted efficiency.

The resulting energy yield data was then compiled in MS Excel 2016 to determine weighting factors representative of the site and compare them with the assumptions made in the European and Californian context. This was expressed by calculating the new weighting factors for Euro and CEC classes which represent the actual energy contribution of various irradiation and power classes based on how often they operate at the site.

7.1. Summary of findings

As set by the chief objective of this thesis, results of simulations and data analyses where presented to evaluate the Euro and CEC efficiency under South African weather conditions, using climate data from Cape Town (Western Cape).

- The methodology to express and the PV inverter weighted efficiency models mentioned on the manufacturer's technical sheet, compiled from the literature and combined with a stochastic simulation approach produced weighting factors unique to site:

  - $\eta_{EURO} = 0.03\eta_{5\%} + 0.06\eta_{10\%} + 0.13\eta_{20\%} + 0.10\eta_{30\%} + 0.48\eta_{50\%} + 0.20\eta_{100\%}$

  - $\eta_{CEC} = 0.04\eta_{10\%} + 0.05\eta_{20\%} + 0.12\eta_{30\%} + 0.21\eta_{50\%} + 0.53\eta_{75\%} + 0.05\eta_{100\%}$

  - $\eta_{CPT} = 0.04\eta_{20\%} + 0.05\eta_{30\%} + 0.18\eta_{50\%} + 0.45\eta_{75\%} + 0.28\eta_{95\%}$

- This discrepancy originated in the contrasts between weather conditions on the site and those used by η_{EURO} & η_{CEC} based on foreign sites (Trier, Ispra and Sacramento). As a matter of fact, the irradiation and temperature distribution for Cape Town showed that different energy contributions could be expected for the various power portions of the DC input.

- There is a discrepancy of 2.94% between the manufacturer's and the site's η_{EURO}. For η_{CEC} the difference is 3.06%. This would lead in sizeable losses over the year.

- η_{EURO} & η_{CEC} assumptions, when compared with η_{CPT} calculated for a 1kWp operating with a grid-connected inverter mentioning η_{EURO} & η_{CEC}, would not be valid in Cape Town because they weigh various inputs in a way that does not match the local weather. η_{CPT} is not just a simpler but also a more accurate formula. There are no instances of power portions P_{MPP}/P_{STC} over 95%; lower evaluations classes do not contribute as significantly in Cape Town as they do in η_{EURO} & η_{CEC}.

- The simulation of the annual energy output distribution of the PV plant used for this research reveals that irradiation classes between 0-500 W/m^2 contribute 33.63% or 1/3 of the overall energy output and roughly the same portions were observed between 500 W/m^2-750 W/m^2 (30.99%) and 750 W/m^2 and upwards (35.38%). It was found that η_{CEC} is closer to matching Cape Town profile because both weigh higher insolation with more detail and significance than η_{EURO}.

- The use of hourly irradiation, temperature, energy input & output and efficiency figures in this study is justified by their accuracy and detailed depiction of the

fluctuations and changes in these parameters. It is therefore adapted for calculating weighted efficiencies.

- Because the CEC efficiency η_{CEC} and the Euro efficiency η_{EURO} make different assumptions for the temperature and irradiation distribution, for the contribution of each class of irradiation and P_{MPP}/P_{STC} power portions to the generated energy and overall energy production, they would not be valid for the site surveyed and therefore would not provide accuracy in predicting annual energy yield.

- η_{CPT} is the best reformulation and adaption of η_{EURO} & η_{CEC} to Cape Town local irradiation profile because it is calculated by incorporating both the effects of temperature and insolation as they occur at the site and the distribution of weather patterns is reflected in its weighting factors.

7.2. Conclusion

The results demonstrate that the ideal formulation of PV inverter efficiency for a site located in South Africa would be different from η_{EURO} & η_{CEC} energy assumptions and weighting factors. These findings are concluded from PVSYST simulation and MS Excel calculations using Meteonorm 7 hourly data files, and they are as accurate as possible for this kind of approach to the research problem. The energy yields of the system under η_{EURO} & η_{CEC} are consistently high, daily and overall but still follow the seasonal trends. But, beyond the trend, the use of different weights under η_{CPT} appear to question the accuracy of those predictions. The total PV generation that can be expected for a system would be affected since the findings for η_{SITE_EURO} & η_{SITE_CEC}, site tested efficiencies do not match the manufacturer's assumptions, with respective discrepancies of 2.92% and 3.06%.

From the findings of this thesis research, we can conclude that the current definition of weighted efficiency should therefore be reformulate and incorporated in PV inverters designed to operate at various sites in South Africa.

This study has provided a more accurate estimate, labelled η_{CPT} from the name of the site it is based upon. This model can be a valuable input into further research into alternative South African efficiency models and approaches to increase the scientific knowledge on the effects of South African climate on inverter performance. This can enable industrials and utility companies to make more accurate predictions of annual energy yield in the context of PVPS integration to the national electricity grid.

This formula can be used to measure the performance of PV systems operating in similar temperature and irradiation distributions throughout the country. This will hopefully

influence and spark future research initiatives in the field of solar power, the most promising form of renewable energy. The notions explored, and the issues raised in this case study can be a very helpful tool for local and international manufacturers to adapt their products to the South African solar inverter market. It can enable them to better assess the reliability and accuracy of their devices, which represents an environmental, social and economic asset.

7.3. Future research

The aim of any academic research is not limited to increasing the body of knowledge in a particular field but to become an inspiration for further investigation into the subject. Science progresses by using the conclusions from previous work to spark further research and interest. The theoretical model developed in this dissertation can be the focus of further adaptations into different settings and conditions. A number of proposals can be put forward to further develop the research completed in the experiment previously detailed, for more breakthrough in this field.

- In this research experiment, the use of hourly data from the historical Meteonorm database did not take measurement uncertainty into consideration. As seen in the literature, results collected in the laboratory and those measured on the field for a wider diversity of solar plants, over a period of several years can be different to a certain point. It would therefore be interesting to assess how that would affect the Cape Town weighted efficiency model.

- The data extracted from PVSYST 6.73 and subsequently compiled in Microsoft Excel yielded precious and very accurate information and graphical representations over a typical mean year. However, it can be suggested to use a different platform like Matlab to make a parallel analysis of the data, considered of multiple years and produce even more representative figures.

- The weighted efficiency formulated in this work was used based on data from the city of Cape Town, which although located in South Africa and rich in meteorological records, does not necessarily represent every micro-climate around the vast country. As a result, this model should be reproduced and confirmed for other locations within the country to either reinforce or contextualize the results of this research.

- The effect of geographic dispersion and local climates should be tested for different and optimal PV array tilt angles and brands of PV inverters.

These improvements could greatly enhance the understanding of how weather patterns impact the performance of PV inverters and serve as the solid basis for innovative energy and industrial planning. Manufacturers could use this as an inspiration to develop new PV devices adapted to localized demands and climate conditions.

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APPENDICES

APPENDIX A – PV SYSTEM CHARACTERISTICS

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Characteristics of a grid inverter

Manufacturer, model :	**AEG Industrial Solar GmbH, AS-IR01-1000 (1kw)**
Availability :	Prod. from 2017
Data source :	Manufacturer 2017

80

Operating mode		**MPPT**	Nominal PV Power	Pnom DC	1.0 kW
Minimum MPP Voltage	**Vmin**	**N/A V**	Maximum PV Power	Pmax DC	N/A kW
Maximum MPP Voltage	**Vmax**	**400 V**	Maximum PV Current	Imax DC	N/A A
Absolute max. PV Voltage	Vmax array	450 V			
Min. Voltage for PNom	Vmin PNom	N/A V	Power Threshold	Pthresh.	30 W
Behaviour at Vmin/Vmax		Limitation	Behaviour at Pnom		Limitation

Output characteristics (AC grid side)

Grid Voltage	Unom	240 V	**Nominal AC Power**	**Pnom AC**	**1.0 kWac**
Grid frequency	Freq	50/60 Hz	Maximum AC Power	Pmax AC	1.1 kWac
	Monophased		Nominal AC current	Inom AC	4.2 A
Maximum efficiency	Max Eff.	96.9 %	Maximum AC current	Imax AC	N/A A
European average efficiency	Euro Eff.	96.0 %			

Remarks and Technical features

Internal DC switch, Output Voltage disconnect adjustement,

Technology: Transformerless
Protection: -25 - +60°C, IP 65: outdoor installation
Control: LED (standard)
www.aeg-industrialsolar.de

Sizes: Width 300 mm
Height 280 mm
Depth 138 mm
Weight 9.50 kg

Figure A.1. Technical specifications of the grid connected inverter (PVSYST 6.73)

Grid-Connected System: Simulation parameters

Project : **Cape Town Solar PV**

Geographical Site	**Cape Town**		Country	**South Africa**

Situation		Latitude	-33.97° S	Longitude	18.60° E
Time defined as		Legal Time	Time zone UT+2	Altitude	50 m
		Albedo	0.20		
Meteo data:		**Cape Town**	Meteonorm 7.1 - Synthetic		

Simulation variant :	**New simulation variant**	
	Simulation date	15/07/18 09h14

Simulation parameters	System type	**No 3D scene defined**		
Collector Plane Orientation	Tilt	30°	Azimuth	0°
Models used	Transposition	Perez	Diffuse	Perez, Meteonorm
Horizon	Free Horizon			
Near Shadings	No Shadings			

PV Array Characteristics

PV module	Si-mono	Model	**Mono 250 Wp 60 cells**		
Original PVsyst database		Manufacturer	Generic		
Number of PV modules		In series	4 modules	In parallel	1 strings
Total number of PV modules		Nb. modules	4	Unit Nom. Power	250 Wp
Array global power		Nominal (STC)	**1000 Wp**	At operating cond.	887 Wp (50°C)
Array operating characteristics (50°C)		U mpp	108 V	I mpp	8.2 A
Total area		Module area	**6.5 m²**	Cell area	5.7 m²

Inverter		Model	**AS-IR01-1000 (1kw)**		
Original PVsyst database		Manufacturer	AEG Industrial Solar GmbH		
Characteristics		Operating Voltage	80-400 V	Unit Nom. Power	1.00 kWac
Inverter pack		Nb. of inverters	1 units	Total Power	1.0 kWac
				Pnom ratio	1.00

PV Array loss factors

Thermal Loss factor	Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
Wiring Ohmic Loss	Global array res.	226 mOhm	Loss Fraction	1.5 % at STC
Module Quality Loss			Loss Fraction	-0.8 %
Module Mismatch Losses			Loss Fraction	1.0 % at MPP
Strings Mismatch loss			Loss Fraction	0.10 %
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Param.	0.05

User's needs : Unlimited load (grid)

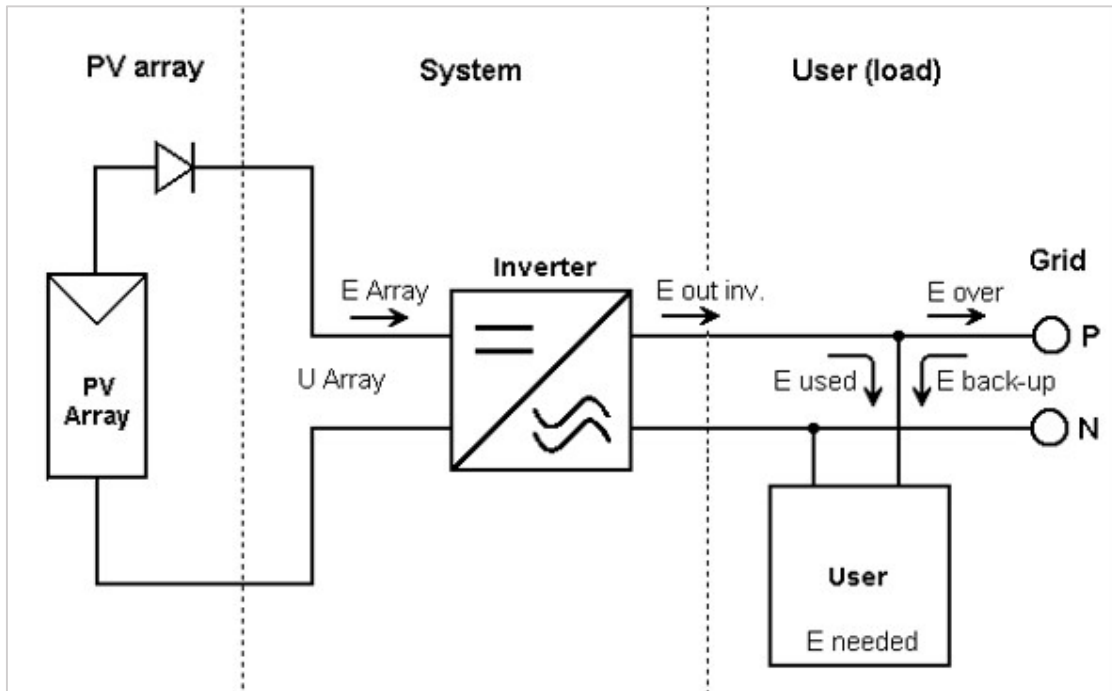Figure A.2. Technical specifications of the grid connected PV system (PVSYST 6.73)

Figure A.3. Grid-connected PV system schema

APPENDIX B – CAPE TOWN METEOROLOGICAL DATA

PVSYST V6.73		11/07/18	Page 1/1

Definition of a geographical site

Geographical Site	Cape Town	Country	South Africa

File Cape Town of 00/00/00 00h00

Situation		Latitude	-33.97° S	Longitude	18.60° E
Time defined as		Legal Time	Time zone UT+2	Altitude	50 m

Monthly Meteo Values Source MeteoNorm 7.1 station

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Year	
Hor. global	255.0	205.0	188.7	129.7	93.1	75.5	85.1	110.3	148.5	196.8	231.6	257.6	1976.9	kWh/m².mth
Hor. diffuse	64.7	57.3	44.8	39.5	36.4	27.8	32.4	39.1	49.4	63.0	62.4	71.9	588.7	kWh/m².mth
Extraterrestrial	371.0	301.2	281.5	210.1	165.7	136.4	149.5	190.3	242.8	311.0	346.6	379.8	3085.8	kWh/m².mth
Clearness Index	0.687	0.681	0.670	0.617	0.562	0.554	0.569	0.580	0.612	0.633	0.668	0.678	0.641	
Amb. temper.	21.2	21.3	19.7	17.1	15.0	12.9	12.5	12.9	14.2	16.6	18.2	20.3	16.8	°C
Wind velocity	6.2	6.0	5.3	4.2	3.8	3.6	3.9	4.3	4.6	5.1	5.8	6.2	4.9	m/s

Solar paths at Cape Town, (Lat. -33.97° S, long. 18.60° E, alt. 50 m) - Legal Time

1: 22 June
2: 22 may - 23 July
3: 20 apr - 23 aug
4: 20 mar - 23 sep
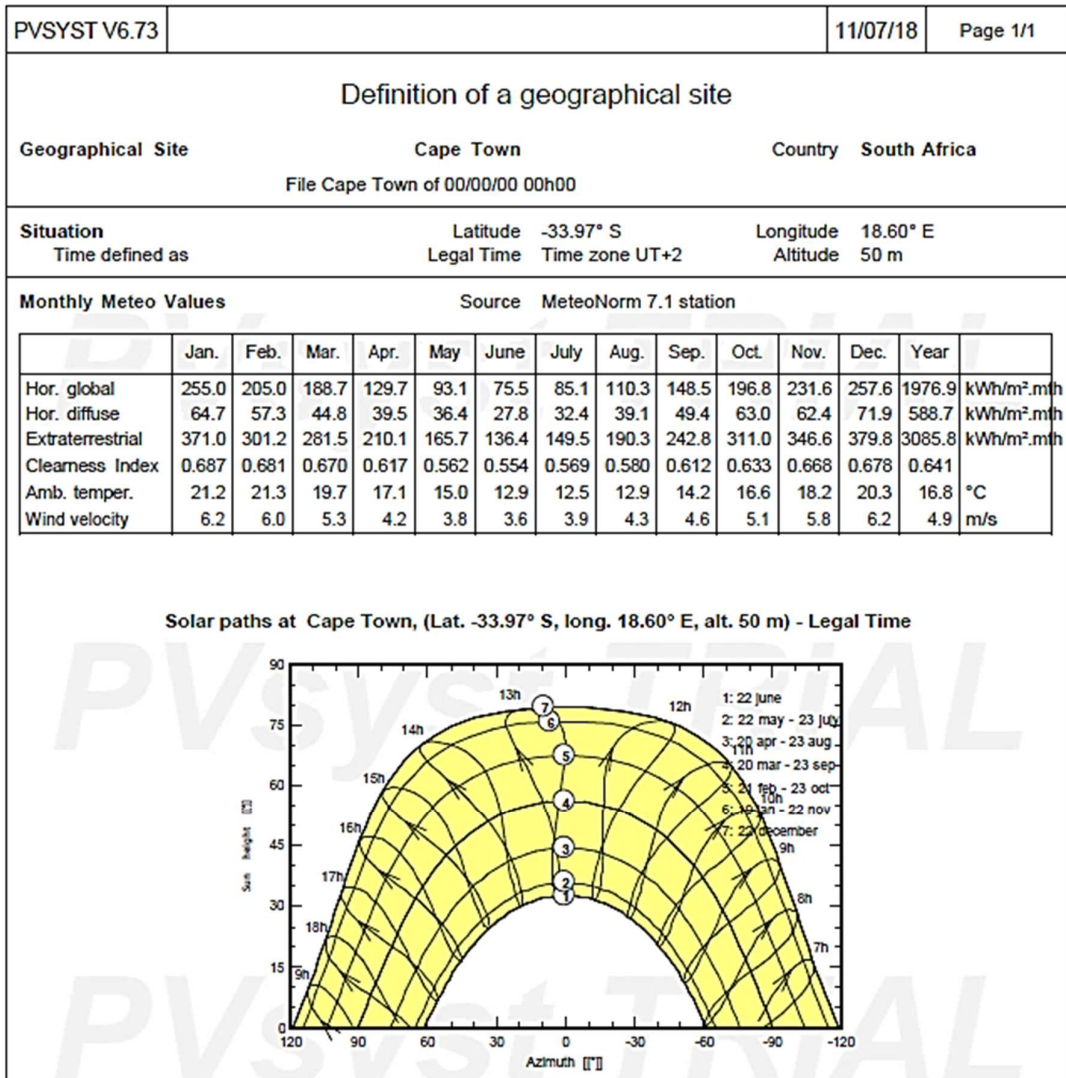5: 21 feb - 23 oct
6: 19 jan - 22 nov
7: 22 december

Figure A.4. Monthly meteorological values for the site of Cape Town (PVSYST 6.73, Meteonorm 7.1)