Investigating the Effect of Solar Modelling using Different Solar Irradiation Data Sets/ Sources within South Africa

Prepared by: Justin Dekker, DKKJUS001

Supervisors: Professor S P Chowdhury

Dr S Chowdhury

Date: 31 August 2011

Submitted to the Department of Electrical Engineering, in Fulfilment of the Requirements for the Degree: Masters of Science in Electrical Engineering

ACKNOWLEDGMENTS

I would like to thank the following people for their help and time in helping me realise the final goal of completing my master’s thesis:

- Professor S P Chowdhury and Dr S Chowdhury for always being available for queries and help with regard to subject matter and processes undergone throughout the writing of my thesis.
- NRF fund for funding the majority of my tuition fees
- Dr A Keen, for providing me with my load profile data for simulation purposes. For allowing me into his home to give me a demonstration on how his current photovoltaic setup supplying his household works.
- Riaan Meyer from the Centre for Renewable and Sustainable Energy Studies in Stellenbosch for providing me with accurate solar data from their local solar station.

PLAGIARISM DECLARATION

1. This thesis is my own work.

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TERMS OF REFERENCE

In meeting the final goal of determining the variances in solar modelling through the usage of differing solar irradiation data sets, the following requirements are listed. These should be met to ensure that an accurate representation of data, results and conclusions can be made based on the completion of the thesis:

- Explore the current research on similar topics within the field of solar modelling using different sources of solar irradiation data sets.
- Determine South Africa’s current energy situation with regards to generation, distribution and whether or not renewable energy supplies play a role in meeting any of the energy needs within South Africa.
- Determine what solar irradiation data sets are freely available in the public domain for the typical individual who seeks to model solar energy systems.
- Determine the acceptable methods of determining solar irradiation quantities for a given geographical point or site.
- Determine what suitable components should be included in the system architecture of a photovoltaic power system.
- Determine a feasible component sizing range to be considered in the simulation of the photovoltaic power system for optimisation purposes.
- Determine the costs of each component included in the design to allow for the simulation of all costs experienced over the entire lifespan of the project.
- Obtain reliable solar irradiation data from two different forms of solar irradiation measuring methods (i.e. ground and satellite data) for two differing geographical sites within South Africa.
- Obtain a reliable load profile to represent the average load drawn from a residential house within South Africa.
- Run simulations for all of the solar irradiation data sets for both geographical sites including the information discussed above.
- Report the findings of the simulation.
- Make conclusions and recommendations based on the findings regarding the following points:

- Determine the feasibility of going fully off grid with a solar photovoltaic system at either geographical locations based on the various solar irradiation data sets used
- Determine the sizing and quantity of the system components in a photovoltaic energy system based on the various solar irradiation data sets, and battery sizing’s used as an input
- Determine the performance of each optimized photovoltaic power supply system based on the various solar irradiation data sets used
- Determine the cost and electrical supply implications experienced by over predicting or under predicting the availability of solar irradiation at a specific geographical location through the use of the different solar irradiation data sources.

ABSTRACT

When designing a solar energy system, accurate solar data for the specific site in which one plans to install the system is required in order to accurately determine the sizing of the system components based on the available amount of energy. The access to accurate data is however not always freely available, and the designer of the system will either have to pay for the accurate data if it is viewed to be financially viable, or settle for less accurate freely available data from one of the many solar irradiation data providers. Not only is the source of the data a key point for the designer to take into consideration, but the actual method used for measuring the solar irradiation data is also a key issue to consider. There are two methods for measuring the amount of solar irradiation at ground level, namely being ground monitored solar stations and satellite based estimations. The solar irradiation can therefore differ for the exact same location depending on the method used for capturing the data due to a number of reasons such as:

- Estimation of data verse actual measurement
- Resolution of data
- Maintenance of equipment
- Quality control procedures applied to the data

When designing a solar energy system, the main aim of the designer is to optimize the system through the correct choice in sizing of system components (ie: size of PV array verse number of batteries for storage), whilst at the same time keeping the overall systems costs as low as possible. The choice of data provider and method for measuring the solar irradiation data is therefore a critical determinant to ensure the desired level of accuracy for the system design is maintained. The use of a data set which either over predicts or under predicts the amount of available solar irradiation at a specific location will therefore affect the electrical performance of the system, as the real world conditions may differ considerably to the data set used in the modelling of the system design.

This paper specifically deals with the modelling of an off grid photovoltaic power supply system using three different sources of solar irradiation data for two specific geographical locations within South Africa. The paper then goes on to investigate the financial implications in terms of using free solar irradiation data which is available to the public verse accurate ground measured data for a specific site and how it affects the systems component sizing.

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1 INTRODUCTION

The knowledge of the amount of solar irradiation available on the earth's surface at a particular geographical location is essential for architects, engineers and scientists to design system requirements for solar energy systems [1]. Access to accurate solar data is also a major determining factor for investors in determining whether a particular site is ideal for the installation of a solar energy systems based on the available solar resources and whether it will be economically viable to go ahead with the installation thereof [3]. This paper specifically deals with the modelling of an off grid photovoltaic power supply system using three different sources of solar irradiation data for two specific geographical locations within South Africa. The paper then goes on to investigate the financial implications in terms of using free solar irradiation data which is available to the public verse accurate ground measured data for a specific site and how it affects the systems component sizing.

1.1 Background of Research

The traditional production of energy relies largely upon the usage of fossil fuels such as coal and oil. These resources are limited and over the years mankind has overindulged in these natural reserves [8]. Since the 1970's oil crisis, a new trend has emerged through the utilization and development of RES such as solar and wind [9]. The global population of today is also expanding at an enormous rate, and so too is it's continually growing demand for energy. Solar energy and power generation, through the use of photovoltaic arrays, is arguably the most nature friendly, emission free, and sustainable sources of energy known to man. This is due to the fact that the suns energy is inexhaustible and un-intrusive, and as a result is slowly becoming an increasingly favourable source of energy for countries with a daily average of solar radiation levels in the range of 3-6kWh/m^2 [10].

Another major issue with the burning of fossil fuels for energy purposes is the emission of green house gasses (GHG). On the contrary, renewable energy sources are virtually emission free and consequently help the fight against global warming by reducing the amount of carbon dioxide being released into the atmosphere [11]. Scientists predict that if nothing is done about the current global warming situation, it could have drastic effects on the world's weather patterns and climate. These changes in weather patterns have been directly linked to the gradual melting of the polar caps through elevated climate temperatures. This poses the potential threat of changing the earth's terrain as we know it today. In light of this, in the December of 1997 the Kyoto Protocol was developed in which 160 nations signed an agreement in order to cut/ reduce carbon emissions through carbon taxes and the Clean Development Mechanism (CDM) [10]. This agreement has been one of the backbone catalysts in promoting empirical research and development into renewable energy sources such as solar. More importantly, it has raised further awareness into the importance of reducing one's carbon footprint. The emission of green house gasses can be minimised by either implementing energy efficient measures, or by installing RES systems such as solar or wind for complete autonomous supply [12].

Emerging Markets (EM) such as Indonesia, Mexico, Saudi Arabia, China and India are excellent examples of how rural electrification can be achieved. Studies within these EM's confirm that it is becoming more viable to incorporate RES systems into everyday life [13]. Popular uses include water pumping for communities and irrigation, water heating, lighting, power for telecommunication towers and billboard illumination [8].

South Africa, like many of the EM's mentioned above, also has a complex cultural, political and economic environment and is faced with a similar set of energy related issues. Rural communities endured poor access to electricity for decades, much of which is due to the lack of funding and the introduction of grid connected power lines. It is therefore the ideal place to conduct a study on the modelling and feasibility of introducing photovoltaic power supplies within South Africa, and the cost implications experienced through the use of different solar irradiation data sets.

1.2 South African Energy Generation Mix

South Africa is a mineral rich country with enormous reserves in low grade coal. Research conducted by the Department of Minerals and Energy (DME) indicated that the majority of electricity created comes from coal powered plants. The coal produced is relatively cheap compared to international standards and is the primary reason to the widespread use of coal powered power plants. Other energy supplying sources within South Africa include nuclear power plants, hydro power plants, pumped storage schemes, gas fired power plants and a wind powered plant. Figure 1 clearly illustrates that these other sources form a small portion of the energy supply in comparison to coal (86%) [14].

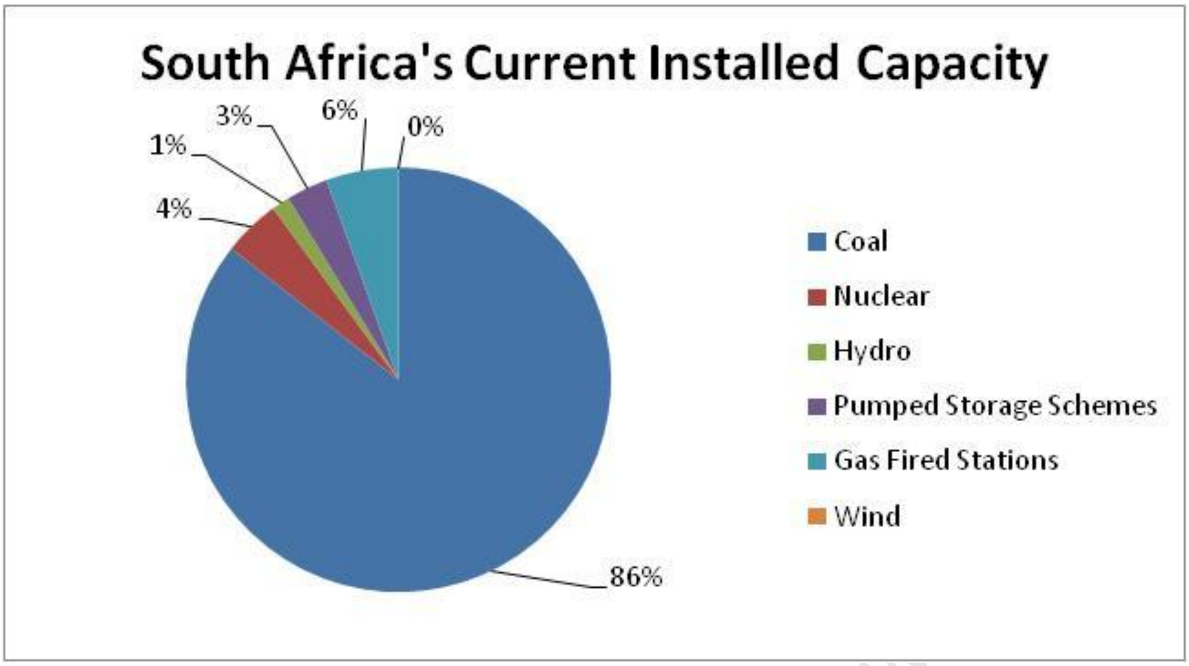

Figure 1: South Africa's Current Installed Generating Capacity. [30]

As mentioned previously, the burning of fossil fuels such as coal releases harmful gasses into the atmosphere. These gasses promote the effects of global warming. In order to offset the major carbon footprint imprinted by the burning of coal, more research that explores how we can incorporate renewable energy supplies in South Africa is required. An extract from a report conducted by the DME stated; "With the setting of renewable energy targets and with carbon trading under the Kyoto Protocol, the role of renewable energy is expected to expand" [14].

Figure 2 represents the different energy consumptions of the different sectors within South Africa including industry, commerce, residential, mining, agriculture, transport, non-specified and non-energy use. The residential sector makes up 17.9% of the energy consumption in South Africa. Due to this relatively high demand for energy, more research that incorporates renewable energy sources into the residential sector is also required.

Another extract from the report conducted by the DME supported the fact that photovoltaics could be a viable renewable energy source; "South Africa's abundant sunshine is only beginning to be tapped in more remote areas for electricity generation for domestic and institutional applications"[14].

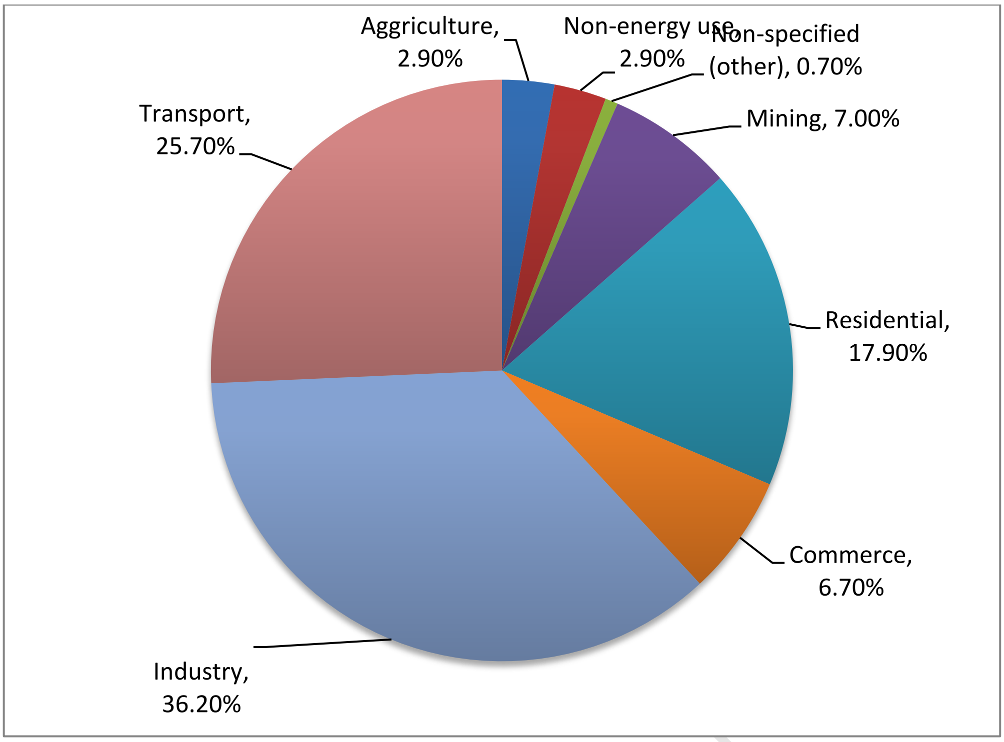

Figure 2: Sector Energy Consumption- South Africa [14]

The main supplier of electricity to South Africa is Eskom. Eskom provides the country with 95% of its electricity needs [14].

1.3 Solar Irradiation Basics

1.3.1 What is solar irradiation?

Solar irradiation is a form of electromagnetic energy originating at the suns core through the process of fusion, where hydrogen and helium atoms are fused together which in turn gives off an immense amount of energy [21]. The electromagnetic energy then radiates from the suns core outwards towards the suns surface, eventually leaving the suns body to radiate throughout space towards other planetary bodies including the earth's atmosphere. It is estimated that the amount of energy leaving the suns surface is at a rate of approximately 63,000,000 W/m^2 [21]. However, only a small fraction of this energy actually hits the earth's atmosphere. Scientists were able to calculate the amount of available power at the surface of the earth's atmosphere based on the known distance of the earth from the sun, conservation of energy principles and energy flux density formula's. The value that was calculated was approximately 1,368 W/m^2. This value is fairly constant across the earth's entire atmosphere and is therefore known as the solar constant [21].

1.3.2 What affects solar irradiation?

Once the electromagnetic energy hits the earth's atmosphere, approximately 30% of the total energy is reflected back towards space through what is known as the earth's albedo effect [21]. Once the additional electromagnetic energy has passed through the earth's atmosphere, another large portion of the energy is lost where it is either absorbed or reflected by gasses or particles within the earth's atmosphere before it reaches the earth's surface. The main factors that influence solar irradiation within the earth's atmosphere are:

- Ozone (O_3)
- Air molecules (ie: Oxygen, CO_2 and Nitrogen)
- Aerosols (particles suspended in the atmosphere ie:sand)
- Water Vapour (H_2O)
- Clouds [21,22]

Cloud cover represents the greatest potential losses in solar irradiation within the earth's atmosphere, where in some instances it can lead to 0 W/m^2 of energy reaching the earth's surface [5].

Typically the solar irradiation experienced on the earth's surface on a clear sunny day will be around 1,000 W/m^2 when the suns path reaches its highest point of its trajectory throughout the day, or more commonly at midday depending on the latitude, altitude and time of year of a specific location [8].

A key variable affecting the amount of solar irradiation experienced at a specific point throughout the day is what is known as air mass. Air mass is a spectrum index based on the amount of energy experienced at a point on the earth's surface as a function of the distance from this point to the outer surface of the atmosphere. When the sun is at the top of its trajectory, or at the midday point, the air mass value on a clear day is AM 1 or approximately 1,000 W/m^2 at sea level. As the angle from the vertical increases, the air mass will vary to its limit being AM 10 which would occur at sunrise or sun set [21].

The figure below depicts the concept of air mass and how it will increase before or after the midday point. The reason for this is that the solar irradiation will have a greater length to travel through the earth's atmosphere before reaching the same point on the earth's surface [22].

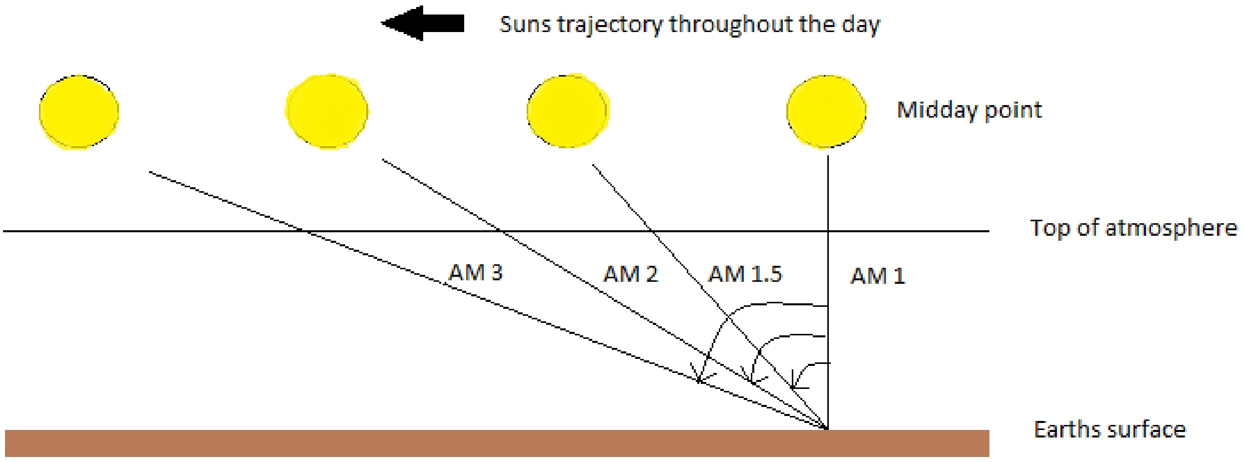

Figure 3: Example of Air Mass [22]

The amount of available solar irradiation at a specific geographical point will therefore change throughout the day based on the trajectory of the sun, the time of year (season) and the amount of additional aerosol content, water vapour and cloud content present in the atmosphere at a specific instance in time [10]. The figure below represents how solar irradiation may vary throughout the day as measured from a solar ground monitoring station.

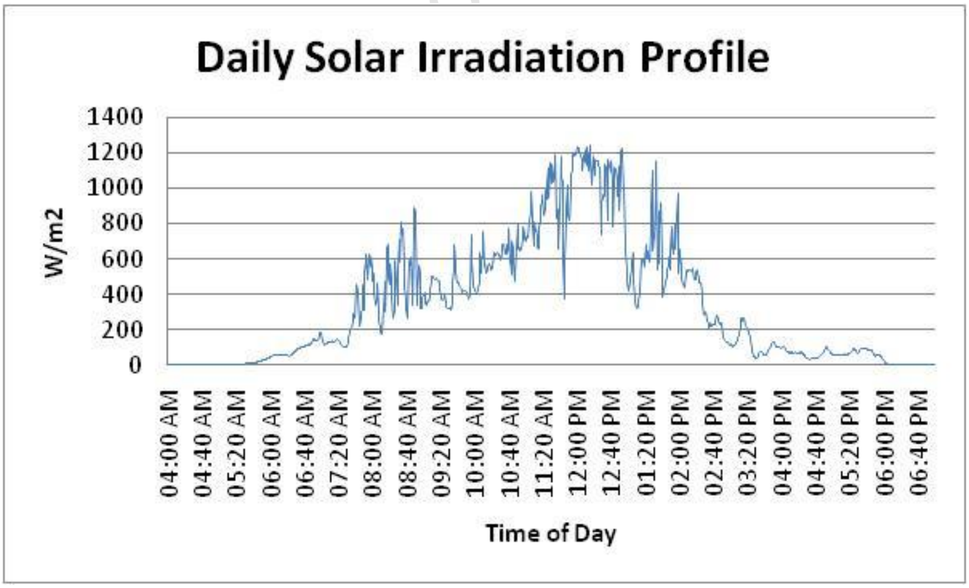

Figure 4: Example of a Daily Solar Irradiation Profile

From the figure above, one can clearly see the midday peak of the available solar irradiation throughout the day. The additional spikes and dips throughout the day will be due to the ever changing atmosphere conditions such as a cloud passing over the monitoring station at a specific instance in time.

1.3.3 DNI, DHI, and GHI Solar Irradiation Components

When measuring the amount of solar irradiation available at a specific geographical location, the total amount of solar irradiation can be broken up into two main components, namely being direct normal irradiation (DNI) and diffused horizontal irradiation (DHI). The direct normal component is referred to as the portion of irradiation that is measured on a horizontal plane that is normal to the angle of the suns beam. Typically direct irradiation hasn't been subjected to any disturbances in its path from the earth's atmosphere to the earth's surface. The diffused horizontal component refers to the portion of irradiation measured on a horizontal surface that has entered the earth's atmosphere and has either been reflected or scattered by aerosols, water vapour or clouds in the atmosphere and then redirected towards the earth's surface [21].

In addition to the DNI and DHI data, global horizontal irradiation (GHI) can be determined by adding the zenith cosine angle of the DNI component to the DHI component. The zenith angle is the angle that the sun beam makes with the vertical [4,21]. The figure below represents a graphical interpretation of the three defining variables to the amount of solar irradiation available at a specific geographical location.

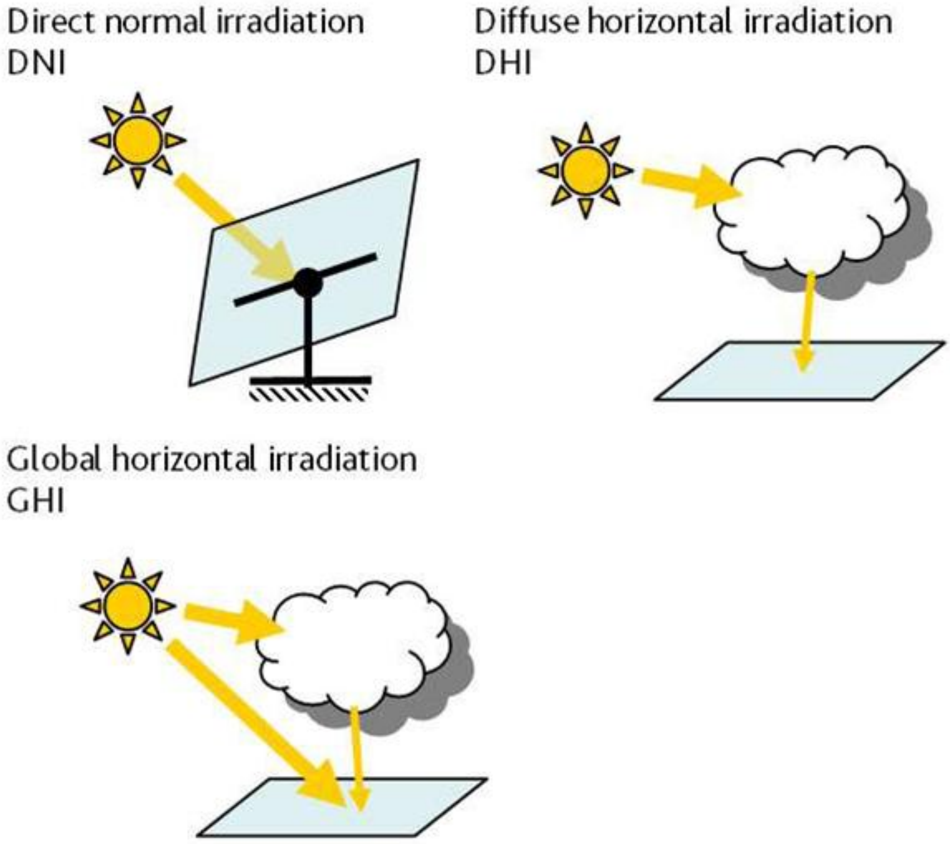

Figure 5: Solar Irradiation Components [21]

When considering which solar irradiation component to include in solar modelling applications, the type of solar collector or solar converter is needed to be known in order to ascertain accurate power output calculations of that specific energy system. Applications such as concentrated solar thermal plants, which actively track the suns beam throughout the day in order to optimize the total amount of solar energy captured, typically require the DNI component as it is this component which will ensure the best operation of the plant. However for most static photovoltaic applications, GHI data should be used as the horizontal or inclined surface area of the panel will receive both DNI and DHI components throughout the day which will then be converted into electrical energy [21].

2 WAYS OF MEASURING SOLAR IRRADIATION

2.1 The Need for Accurate Solar Irradiation Data

When designing solar energy systems, accurate solar irradiation data is required in order to determine the systems potential power output over the year, and hence determine the optimum required system architecture. In a photovoltaic installation for example, the available solar resources in a particular area will therefore determine how many solar photovoltaic panels or batteries are required in order for the system to meet the required load throughout the year. On large scale projects, accurate hourly, monthly and yearly solar irradiation data is a key factor for investors to determine how financially viable a specific site is for the installation of a solar energy system [3]. Therefore the concept of solar prospecting is critical to the long term success of integrating renewable energy sources into the worlds energy mix.

Geographical information systems (GIS) look at mapping out solar irradiation resources for entire regions, countries or continents [7]. They also often include information such as topographical features for a specific location such as mountain ranges or rivers, the location of settlements, roads and infrastructure in order to locate the most ideal area for a solar energy system to be installed [7].

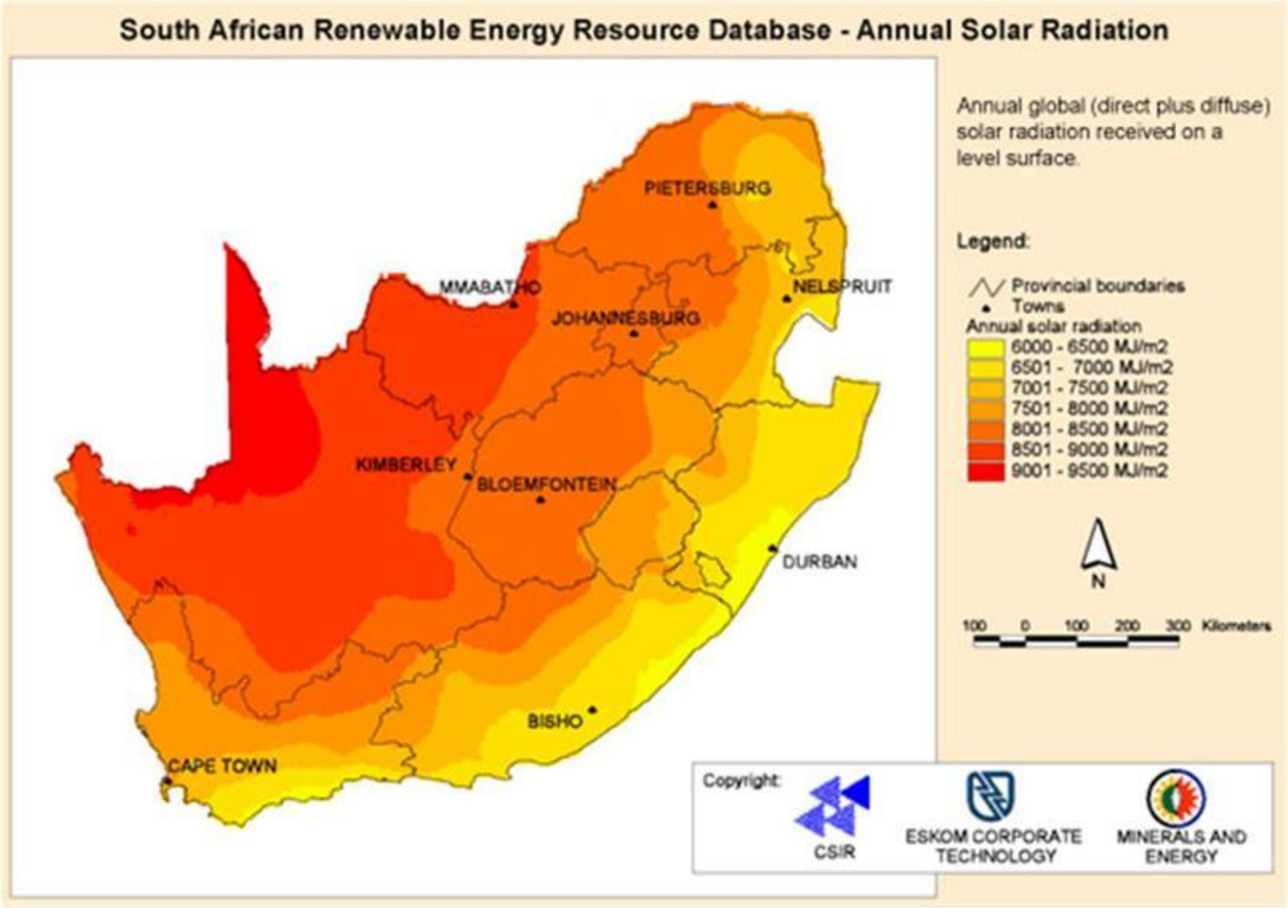

Figure 6: South African Renewable Energy Resource Database- Annual Solar Radiation [30]

The figure above represents the average solar irradiation around South Africa. The accuracy of the solar radiation represented in the figure however would not be sufficient for accurately determining performances of solar energy systems in the various areas around South Africa. The figure represents a very high level solar irradiation distribution across South Africa, whereas when designing solar energy systems, accurate location specific data is required [3].

There are two main methods for determining the available solar irradiation at ground level, namely being direct measurements taken by a solar ground monitoring station or by satellite based models which try to predict the amount of solar irradiation at ground level based on images taken of the earth and the amount of thermal reflectance off the earth's surface [21].

However appealing the thought may sound of acquiring accurate solar resource data for entire countries and continents, accurate solar prospecting comes at a large expense. For instance several hundred ground monitoring stations would be required to map out a large area such as South Africa, due to the fact that a ground monitoring station measures a single points solar irradiation with a spatial resolution of at most 25km x 25km. Any measurements taken outside this spatial zone from a ground monitoring station may differ due to elements such as cloud cover, topographical features such as mountains or increased land elevation. Therefore the main barrier to acquiring accurate solar data comes down to financial cost. This is due to the inherent high price of monitoring equipment (ground or satellite based), the continual labour intensive process of maintaining the equipment and the actual screening and quality control of the data [5].

2.2 Ground monitoring stations

Ground monitoring stations typically include three separate instruments to measure the three different components of solar irradiation, namely being the DNI, DHI and GHI components. A Pyranometer typically measures all radiation falling over the sensors dome over an angle of 180^0 [21]. A single Pyranometer with no shading will therefore measure the total GHI component of the solar irradiation falling on a horizontal surface (ie: DNI and DHI components). When a shading ball is included, as seen in the figure below, the Pyranometer will therefore only measure the DHI component of the solar irradiation as the DNI component will be continually blocked out by the shading ball. The third instrument included in a ground monitoring station is called a Pyrheliometer, which only measures the DNI component of the solar irradiation. The Pyrheliometer and shading ball will therefore need to track the suns beam throughout the day in order to both measure and block out the suns direct irradiance beam respectively [21]. The figure below depicts how all three instruments are included together in a single unit.

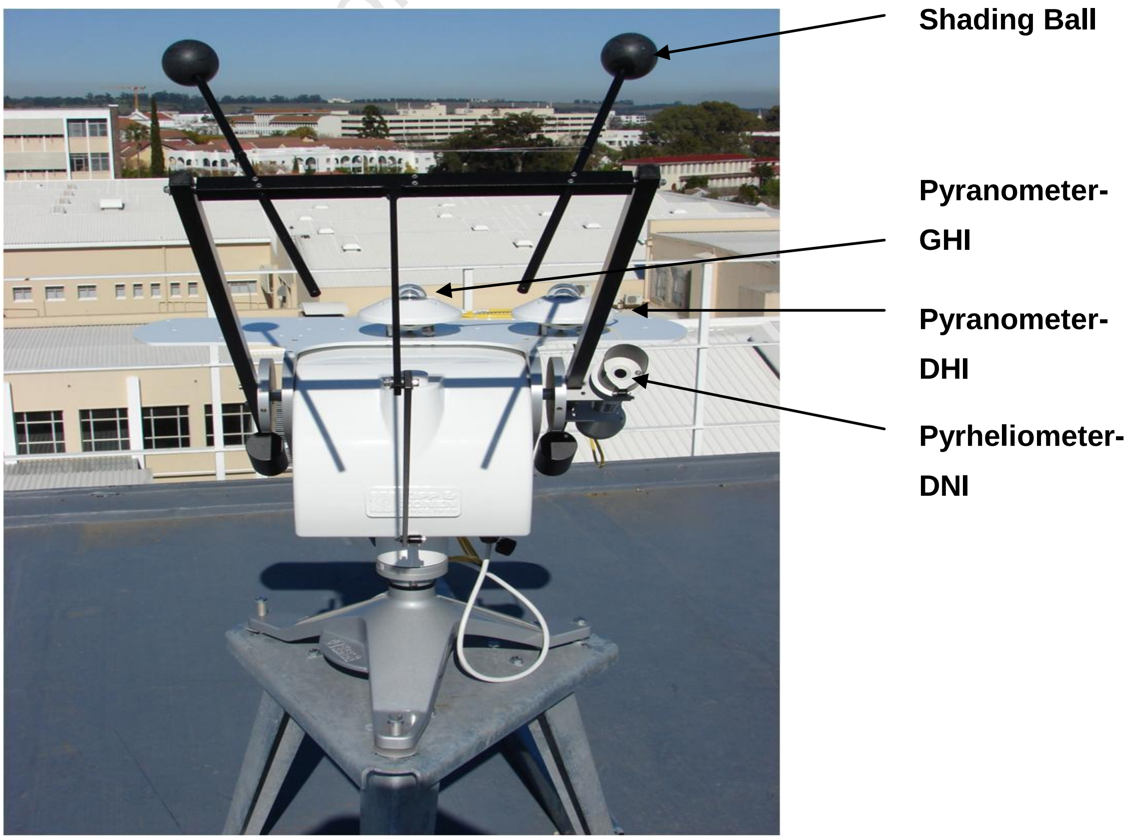

Figure 7: Solys 2 by Kipp & Zonnen- Sonbessie [21]

By measuring all three separate components of the suns irradiation individually, each component can therefore be checked against each other due to the relationship between the GHI, DNI and DHI components. Once again this is due to the fact that the GHI component is equal to the sum of the DNI and DHI components with taking the zenith angle into account [22]. This enables operators to perform a quality control test of the measured data in order to ensure each sensor is operating correctly and measuring accurate data. The intervals between measurements are typically either every minute or hourly averaged values, where each single measurement will represent the total amount of solar irradiation available at that specific site in W/m^2 for that specific time interval.

Ground monitoring stations do however come with certain setbacks, or potential area's where errors may arise in the measured data. If certain precautions aren't taken to avoid these errors, studies have shown that the accuracy of certain ground monitored data could deviate up to +2% to -10% from data measured by pyranometers and ± 2% from data measured from pyrheliometers [1].

Sources of these potential errors include:

- Operation related problems and errors
- Complete or partial shade-ring misalignment
- Dust, snow, dew, water droplets, bird droppings, etc
- Incorrect sensor levelling
- Shading caused by building structures
- Electric fields in the vicinity of cables
- Mechanical loading of cables (When the cables are placed under a mechanical stress such as tension or compression, this may cause electrical polarisation of the cable. This is generally known as the piezoelectric effect and can cause errors in the data)
- Station shutdown [1]

Data storage and filing also becomes critical when measuring solar irradiation over a long period of time, especially when measuring on a minute or hourly based interval throughout the day for every day over the year.

When taking all these possible sources of error in the data into mind, it is evident that constant quality control of data and maintenance of sensors is needed to be performed on a regular basis to ensure the quality of the data is as accurate as possible. This constant maintenance and upkeep however comes at a cost and therefore adds to the expenses of implementing a ground monitoring station at single geographical site, let alone multiple sites around a country [22].

With this in mind, the source of quality data from ground monitoring stations around the world where correct preventative measures have been taken to avoid these potential errors are not always well known or documented. Therefore when acquiring solar data for solar modelling applications, free data available to the public through certain web based portals is not always the most accurate representation of the actual solar irradiation occurring in a specific area as the source and quality of the data is not always well known [1].

Another key aspect is the spatial resolution of ground monitoring stations. As previously mentioned, a ground monitoring station's resolution is at best 25km x 25km square. Anywhere outside this perimeter and the solar irradiation can vary dramatically from the point of measurement and therefore cannot be used for investment grade solar modelling purposes.

2.3 Satellite Derived Data

Solar irradiation data can be estimated at ground level from satellite based images of the earth's surface and mathematical models that include the atmospheric parameters such as aerosol content, water vapour, ozone, O_2 and CO_2 which are derived from global observation data sets around the world [5]. As previously mentioned, clouds have the greatest effect on the losses of solar irradiation on its path through the earth's atmosphere. However, due to clouds erratic and unpredictable nature, it is often difficult to determine the presence of clouds in the atmosphere on a local or global basis. Satellite images, such as the figure below, are therefore used in order to try and determine the presence of clouds in the earth's atmosphere.

Figure 8: Example Image of the Earth's Surface to derive the Cloud Index [5]

A geostationary satellite scans the earth's surface taking photos on regular intervals measuring the amount of reflectance off the earth's surface on both the visible and infrared spectrum and compares the images to a reference image which represents a cloud free, clear sky image [5]. The more reflectance received by the satellite represents the presence of clouds in a specific area when compared to the reference image due to the albedo affect. The less reflectance received by the satellite represents the lack of clouds in a specific area.

A cloud index is therefore defined on the scale of 0 to 100, with 0 indicating zero cloud cover or clear sky conditions and 100 indicating complete cloud cover with a high optical thickness [5].

Each pixel in the photo is then compared to a reference cloud free image where a cloud index is determined from 0 to 100 in order to be applied to a mathematical model which includes all the atmospheric parameters described above. The outcome of the model is the estimation of the amount of solar irradiation present at ground level for a specific geographical site. This process is then continually repeated in order to achieve an hourly solar irradiation profile at a specific site [5].

Currently there are a number of sources for satellite based solar irradiation data including NASA SSE, Meteonorm, Solemi, Helioclim, EnMerSol and Satel-light.Spatial. However the time period over which the data is available, the resolution of the data and cost of the data will vary across each provider [22].

The accuracy of the satellite data will also therefore vary between the different satellite data sources due to the factors mentioned above and the varying quality control protocols applied for each data set. Studies have shown that when comparing satellite solar irradiation data to ground monitored solar irradiation data, satellite data typically overestimates the solar irradiation for a specific site by up to 10% [2].

3 DATA SETS USED IN MODELLING OUTPUTS

Two different geographical sites in South Africa were chosen for the purpose of this research, where both ground and satellite solar irradiation data was acquired for each site respectively. The two geographical locations within South Africa included Stellenbosch and Kwazulu-Natal, where two respective universities are currently monitoring the solar irradiation using ground monitoring stations for research purposes. In addition to the two ground monitored datasets for each geographical site, two free/ publicly accessible solar irradiation data sets were used to compare to the ground monitored data sets when applied to a solar modelling program such as HOMER for residential applications. The two free/ publicly available data sets used were from the NASA SSE and SODA databases. Each data source is discussed further below.

3.1 Stellenbosch (Sonbessie)

A full years worth of hourly logged solar irradiation data was provided by the Centre for Renewable and Sustainable Energy Studies in Stellenbosch. The ground monitoring station composed of the following instrumentation:

- 1 x Kipp & Zonen Solys2 Tracker and shading ring assembly
- 1 x CHP1 Pyrheliometer
- 2 x CMP6 Pyranometer

The location of the station was at the following coordinates:

- Latitude: -33.928^0
- Longitude: 18.865^0

The ground monitoring station is used for research purposes by academics at the University of Stellenbosch in the field of renewable energy and is therefore viewed as a credible source of accurate solar irradiation ground data [25].

3.2 Kwazulu-Natal (Howard College)

A full years worth of minute averaged logged solar irradiation data was provided by the University of Kwazulu-Natal. The ground monitoring station composed of the following instrumentation:

- 1 x Tracker and shading ball assembly
- 1 x Eppley Normal Incidence Pyrheliometer
- 2 x Eppley Precision Spectral Pyranometer

The location of the station was at the following coordinates:

- Latitude: -29.9^0
- Longitude: 30.98^0

The ground monitoring station starts logging its data 20 minutes before sunrise and stops logging 20 minutes after sunset.

The ground monitoring station is used for research purposes by academics at the University of Kwazulu-Natal in the field of renewable energy and is therefore viewed as a credible source of accurate solar irradiation ground data [26].

3.3 NASA SSE

The NASA SSE database provides free satellite data for users online for sites all around the world. The free database however is only available from the year 1983 to 2005. For the purposes of the study, ten years of data (ie: 1995-2005) for both geographical sites was included to determine the average daily solar irradiation for every month of the year (kWh/m^2/day) to be inserted into the modelling software HOMER [22, 23].

The only required input for the data is the latitude and longitude for the desired geographical location, and the required solar irradiation component (ie: GHI component for modelling solar PV). The resolution of the data is typically on a 100km by 100km square.

3.4 SODA

The SODA database provides free satellite data for users online for the whole of Africa, Europe, the Mediterranean Basin, the Atlantic Ocean and part of the Indian Ocean. SODA typically receives its data from either the Helioclim 1 or 3 satellites depending on the required year for data. The free Helioclim 1 database however is only available from the year 1985 to 2005, whereas all other required data is on a pay per site basis for the desired year and location. For the purposes of the study, ten years of data (ie: 1995-2005) for both geographical sites was included to determine the average daily solar irradiation for every month of the year (kWh/m^2/day) to be inserted into the modelling software HOMER [22, 24].

The only required input for the data is the latitude and longitude for the desired geographical location. The resolution of the data is typically on a 30km by 30km square.

3.5 Determining Monthly Solar Irradiation Averages (kWh/m^2/day)

Each different data set is typically supplied in a spreadsheet with a timestamp for each solar irradiation parameter over a specific time interval. The solar irradiation components (DNI, DHI and GHI) are typically measured as instantaneous power measurements per meter squared or W/m^2.

Table 1: Example of Solar Irradiation Data in Spreadsheet Form- 24 hours

Timestamp	DNI (W/m^2)	DHI (W/m^2)	GHI (W/m^2)
2011/07/05 00:00	0.0	0.0	0.0
2011/07/05 01:00	0.0	0.0	0.0
2011/07/05 02:00	0.0	0.0	0.0
2011/07/05 03:00	0.0	0.0	0.0
2011/07/05 04:00	0.0	0.0	0.0
2011/07/05 05:00	0.0	0.0	0.0
2011/07/05 06:00	0.0	0.0	0.0
2011/07/05 07:00	0.0	0.0	0.0
2011/07/05 08:00	0.0	1.1	1.1
2011/07/05 09:00	170.6	27.3	56.3
2011/07/05 10:00	631.3	48.6	231.1
2011/07/05 11:00	762.3	62.0	384.0
2011/07/05 12:00	578.8	123.0	415.4
2011/07/05 13:00	643.7	127.6	487.2
2011/07/05 14:00	833.1	77.9	536.9
2011/07/05 15:00	796.4	74.3	464.3
2011/07/05 16:00	721.2	65.0	339.7
2011/07/05 17:00	559.2	48.8	178.7
2011/07/05 18:00	165.1	16.3	32.1
2011/07/05 19:00	0.0	0.0	0.0
2011/07/05 20:00	0.0	0.0	0.0
2011/07/05 21:00	0.0	0.0	0.0
2011/07/05 22:00	0.0	0.0	0.0
2011/07/05 23:00	0.0	0.0	0.0

Most solar modelling software programs require the average daily available energy per m^2 or kWh/m^2/day at a specific latitude and longitude for each month of the year. For photovoltaic applications, the required solar irradiation component is the GHI data. The raw data in the spreadsheets therefore needs to be converted into kWh/m^2/day as per the method described below.

$$Ave\ daily\ energy = \sum Daily\ GHI\ \left(\frac{W}{m^2}\right) \times \frac{1}{1000}\left(\frac{kW}{W}\right) \times \frac{1}{num\ of\ intervals\ per\ hour}$$

$$Ave\ daily\ energy = kWh/m^2/day$$

This method is then applied to all of the data sets for each day of the year in order to acquire the average monthly solar irradiation.

3.6 Summary of Data Sets Used in Modelling Software

After processing all of the acquired databases using the method described above, monthly averages were acquired for both geographical locations.

The table below represents the summary of the data sets used for the simulation of a solar PV energy system in Stellenbosch.

Table 2: Stellenbosch Data - Lat:-33.98^0, Long:18.86^0

Month of Year	Stellenbosch, Sonbessie- Ground data (kWh/m^2/day)	SODA- Satellite data (kWh/m^2/day)	NASA SSE- Satellite data (kWh/m^2/day)
January	8.57	7.57	8.18
February	7.82	6.93	7.43
March	5.67	5.59	5.99
April	4.52	3.98	4.36
May	2.61	2.94	3.08
June	2.22	2.55	2.62
July	2.89	2.82	2.90
August	3.42	3.39	3.58
September	4.76	4.57	4.97
October	6.05	5.94	6.38
November	7.23	6.93	7.55
December	8.23	7.55	8.06
Average	**5.33**	**5.06**	**5.42**

The table below represent the summary of the data sets used for the simulation of a solar PV energy system in Kwazulu-Natal.

Table 3: KZN Data- Lat: -29.0, Long: 30.98

Month of Year	KZN, Howard- Ground data (kWh/m^2/day)	SODA- Satellite data (kWh/m^2/day)	NASA SSE- Satellite data (kWh/m^2/day)
January	4.95	5.41	5.44
February	5.97	5.23	5.55
March	5.34	4.91	5.07
April	4.16	4.06	4.33
May	3.42	3.54	3.77
June	2.86	3.12	3.42
July	3.11	3.26	3.57
August	3.66	4.00	4.29
September	4.25	4.21	4.70
October	4.29	4.68	4.79
November	4.81	5.02	4.98
December	4.73	5.59	5.25
Average	**4.24**	**4.42**	**4.60**

From the tables above it is evident that on average the NASA SSE predicts the highest amount of solar irradiation available at ground level per day for both geographical sites. Whereas both the ground monitoring stations recorded the least amount of solar irradiation at ground level per day on average for both geographical sites.

3.6.1 Mean Bias Error

The mean bias error indicates the deviation between satellite and ground measured solar irradiation data. The formula for the mean bias error is given below: [27]

$$MBE = \frac{\sum_{t=1}^{N} I_{sat}(t) - I_{ground}(t)}{N}$$

The Table below represents the mean bias errors between the summarized data sets for Stellenbosch.

Table 4: Mean Bias Errors for Different data Sets- Stellenbosch

Month	**Stellenbosch Ground Data (kWh/m^2/day)**	**SODA satellite data minus ground data**	**NASA Satellite data minus ground data**
January	8.57	-1.00	-0.39
February	7.82	-0.89	-0.40
March	5.67	-0.08	0.32
April	4.52	-0.54	-0.16
May	2.61	0.32	0.47
June	2.22	0.33	0.40
July	2.89	-0.07	0.01
August	3.42	-0.04	0.16
September	4.76	-0.19	0.22
October	6.05	-0.11	0.34
November	7.23	-0.30	0.32
December	8.23	-0.68	-0.17
Mean Bias Error (W/m^2)		**-0.27**	**0.09**

The Table below represents the mean bias errors between the summarized data sets for Kwazulu-Natal.

Table 5: Mean Bias Errors for Different data Sets- KZN

Month	**KZN Howard Ground Data (kWh/m^2/day)**	**SODA satellite data minus ground data**	**NASA Satellite data minus ground data**
January	4.95	0.46	0.49
February	5.97	-0.74	-0.42
March	5.34	-0.43	-0.27
April	4.16	-0.10	0.16

May	3.42	0.13	0.35
June	2.86	0.25	0.55
July	3.11	0.15	0.46
August	3.66	0.34	0.63
September	4.25	-0.04	0.45
October	4.29	0.40	0.51
November	4.81	0.22	0.17
December	4.73	0.86	0.52
Mean Bias Error (W/m^2)		**0.12**	**0.30**

A negative mean bias error indicates an under prediction in solar irradiation data at ground level by the satellite data, and a positive mean bias error indicates an over prediction in solar irradiation data at ground level by the satellite data [2].

Therefore looking at the results represented in the two tables above, the NASA SSE data set over predicts the solar irradiation at ground level for both geographical sites, whereas the SODA data set on average under predicts the solar irradiation at ground level at the Stellenbosch site and over predicts for the KZN site.

4 OFF GRID RENEWABLE SYSTEM

The section below describes the components included in the modelling software and design of a solar PV energy system. The research scenario is for a complete off grid residential house with solar PV being the primary energy source, with battery backup for storage purposes to account for the suns erratic nature.

4.1 Panels

There are two classifications that are able to be made from the type of conversion/ collector used to convert the suns solar rays into energy. These are solar thermal collectors and solar electric converters. Apparatus that convert solar energy into electric energy are generally classified as photovoltaics (PVs) [10]. There are currently a number of different types of solar PV panel technologies on the market today including crystalline silicone, multi-crystalline silicone, polycrystalline silicon, amorphous silicon, copper indium diselenide and cadmium telluride [21]. In order to correctly install and utilise PV arrays to its full potential, it is extremely useful to have accurate knowledge of global solar irradiation of the specific location of installation.

Solar panels can either actively track the sun to obtain the maximum possible power output throughout the day, or it can be permanently mounted in a fixed position [15]. Some of the benefits of solar PV systems include the fact that they are modular in design and can be expanded at any stage to increase their output, and they are extremely low maintenance stand alone devices. These aspects make them the perfect candidates for off grid applications [10].

4.2 Batteries

Due to the erratic nature of solar irradiation, some form of battery storage is needed for solar energy systems to buffer the power output during periods of low solar irradiance during the day or for when there is zero solar irradiation available such as during the evening period.

The size and number of the batteries depend on the size of the load it will need to supply when there are no other available energy sources. The common term used for the period of operation of the battery when there is an absence of other energy sources to the load, is days of autonomy. The number of days of autonomy should generally be around 2-3 days. Other battery sizing standards include maximum depth of discharge, temperature correction, rated battery capacity and battery life [17].

4.3 System configuration

The figure below is a representation of how the components of the solar energy system would typically be arranged. The inverter converts the DC component from either the solar panel or battery bank into an AC signal in order to run many appliances within the home. Hence, it is necessary to include an inverter for optimum power control and conversion.

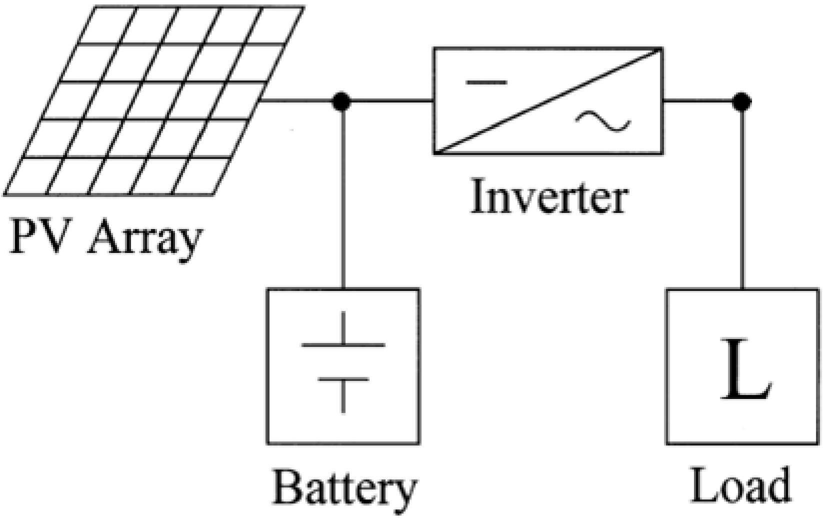

Figure 9: System Configuration

4.4 Load profile

There are two methods of inputting load data into HOMER. The first includes a year's worth of detailed hourly time stepped load data, which would be acquired from a data logging management system for the specific location/ site being analysed. This would give the most accurate simulation results, however, due to both constraints in time and resources this information was not possible to obtain. The second method involves capturing load data over a 24-hour period and using HOMER to extend the data over one year. This uses randomisation functions and correlations to annual temperatures related to global latitudes and longitudes [12]. This method was chosen for the specific purpose of this research and the 24-hour load data was acquired from a typical residential home situated in the Western Cape, which included a solar PV array, battery bank and inverter with data logging capabilities supplying the house in addition to a grid connection. The household in mention was used as a baseline for estimating the general load consumption for the average residential house in South Africa.

The system included:

- A 3.8 kWp array of 20 Sanyo HIT 190W PV panels
- Solar regulator
- Single phase 6 kW “MLT Drives Power Star” bi-directional inverter/charger
- Data logging system
- A battery bank of 24, 2V deep cycle lead/acid cells (Millennium Solar SA Mil 21 F by National Battery , South Africa) of 750 amp hour (C 100) [16]

The system was connected in such a way that the photovoltaic system provided power to all lights and plug power points. The stove, oven, and geyser however were connected directly to the main grid supplier line (Eskom). In the majority of solar energy applications, and especially in rural areas, “heavy consumers” such as the stove, oven and geyser would generally be independently supplied either by gas or wood fired cookers and solar water geysers if possible. Heating loads specifically require a large amount of energy, and the solar photovoltaic system needed to supply such an electrical demand would be extremely large and costly. With this setup in mind, it supports the idea of using the load profile obtained as a good representation of the average load drawn for both urban and rural residential homes in South Africa.

The general appliances that are possible to be run off the solar photovoltaic system installed at the household include:

- fridge 300W
- dishwasher 1700W
- 8×60W incandescent lights
- 2×11W Compact fluorescent lights
- washing machine 2000W
- kettle 2000W
- toaster 1050W
- colour TV 100W
- laptop 50W
- Hi-Fi 80W
- vacuum cleaner 1800W
- borehole pump 750W etc

It is important to note that these appliances are used at various stages or times throughout the day and not simultaneously. The simultaneous use of all appliances (especially in a rural application where there is no grid supply as backup) would cause an overload of the system and possible power outages.

The figure below represents the load profile obtained from the residential house described above.

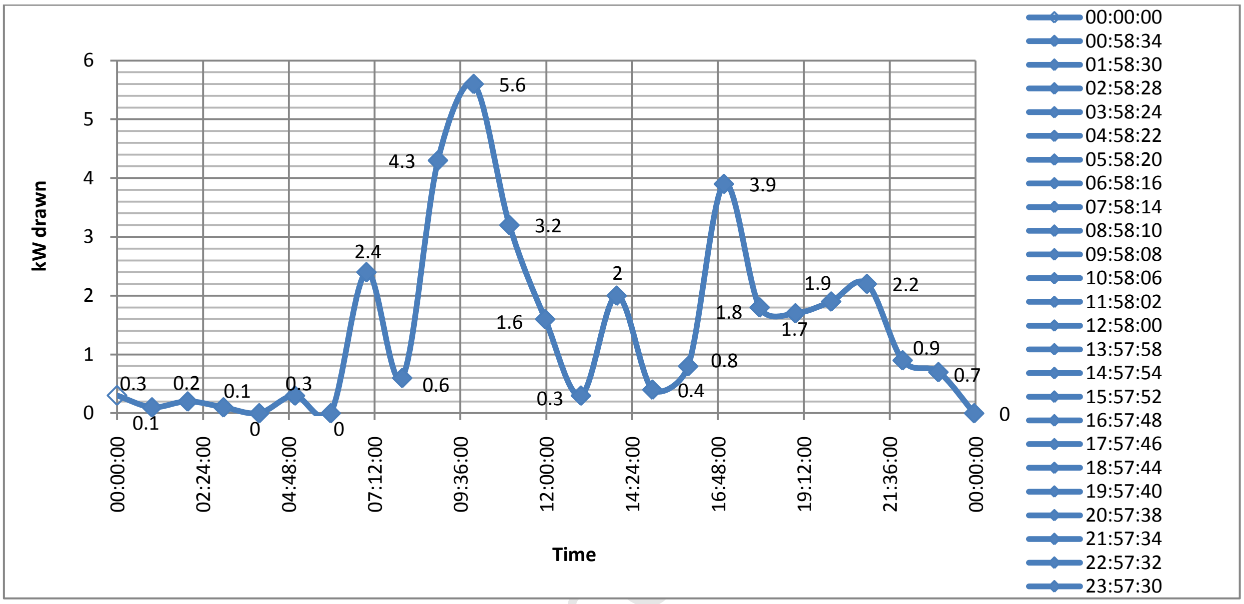

Figure 10: Cumulative Hourly Load Profile of a Residential House over a 24 Hour Period.

5 MODELLING SOFTWARE AND SYSTEM INPUTS

5.1 HOMER

HOMER is a public domain software package created by the National Renewable Energy Laboratory, US. The software has been chosen for its modelling capabilities due to its extensive use in other research papers. Consequently it is viewed as a credible distributed power generation modelling software package [17]. HOMER allows the complete simulation of a renewable energy system based on the hourly time stepped load data profile and the average monthly solar irradiation data for a specific location over a period of one year. With this information and the choice of component sizing and pricing, HOMER is able to simulate the most economically and technically feasible solution for the specific location.

5.2 Evaluation Criteria and Input Data for HOMER

One of the main evaluation criteria that HOMER uses to determine which is the most optimum system design for a specific location based on the available renewable resources is the net present cost (NPC) of the project over its entire lifespan of operation. NPC includes expenses such as components, component replacements, operation and maintenance (OM) costs, and initial capital costs over the life span of the project [12, 18]. Before the NPC is calculated, HOMER first decides whether the system is technically feasible i.e. whether the size of the solar panels chosen will or will not meet the electrical load profile entered by the user. If the system is viewed as being technically feasible then the simulation will run.

G.J. Dalton, D.A. Lockington and T.E. Baldock [12, 18] wrote two extensive papers on investigating the possibilities of incorporating renewable energy supplies in small to medium sized hotels in Australia using HOMER's simulation package, and suggested some parameters to include. For the purposes of this paper, the parameters suggested by Dalton, Lockington and Baldock were used and discussed below.

The NPC is calculated within HOMER using the following equation:

$$NPC(\$) = \frac{TAC}{CRF}, \qquad (1)$$

where TAC is the total annualised cost (which is the sum of all annualised costs of each system component). The capital recovery factor (CRF) is given by

$$CRF(\$) = \frac{i(1+i)^N}{(1+i)^N-1}, \qquad (2)$$

where N is the number of years and 'i' is the annual real interest rate (%).

The number of years N, defined for the project lifetime was set to be 25 years with the annual real interest rate set to 6%. HOMER assumes all prices escalate at the same rate, and uses ‘annual real interest rate’ rather than the ‘nominal interest rate’. This allows inflation to be factored out of the analysis [12, 18].

The annual capacity shortage for the system was set to be zero due to the fact that this paper seeks to determine the feasibility of taking a residential load fully off grid.

5.3 Choices of Component Sizing and Pricing to be entered into HOMER

The initial choices of components were based around the information obtained from the residential house from which the load profile was taken and from the two papers written by Dalton, Lockington and Baldock.

5.3.1 Batteries

The HOMER software package includes a built in list of batteries from which the user can select a battery depending on the needs of the system. Due to the high costs of batteries, and the possible use for them in rural applications without grid backup, the life span of the battery is important. Hence a good quality, deep cycle cell with a relatively high amp hour rating is needed to ensure maximum output from the cells over a longer duration. The battery bank from the residential house included 24, 2V lead acid deep cycle cells at 750ah at 100% discharge rate. However, this paper seeks to investigate the feasibility of going completely off grid, to which the system design needs to be able to meet the electrical load of the facility at all time with zero annual capacity shortage. Therefore a range of battery sizes were included in the simulation to ascertain the impact of system performance and capital cost based on the various battery sizes and costs chosen for storage purposes.

The table below represents the amp hour discharge rate and cost of four differing batteries. The cost and available sizing of the batteries was taken from a price list from a local supplier of renewable energy and distributed power components MLT drives [19].

Table 6: Battery Size and Cost Scenarios

Scenario	Nominal Discharge (Ah)	Full discharge (Ah)	Cost (R)
1	648	900	R 2,510
2	756	1050	R 2,730
3	990	1380	R 3,050
4	1188	1660	R 3,530

HOMER includes a built in list of batteries and their operating characteristics that the user can choose from. The batteries used in the simulation were therefore matched to the above list of battery scenarios and sizing and are represented in the list below:

Scenario	Battery	Cost (R)
1	Hoppecke 6OPzS 600	R 2,510
2	Hoppecke 8OPzS 800	R 2,730
3	Hoppecke 10OPzS 1000	R 3,050
4	Hoppecke 15OPzS 1500	R 3,530

The Hoppecke battery range included above were all 2V deep cycle batteries. HOMER also requires the input from the user the number of batteries included per string. Six batteries per string were therefore used with a 12V bus. The maximum number of batteries considered in the simulation was 108 batteries, or 18 strings of 6 batteries per string.

The typical maintenance of a battery would include topping up the battery with distilled water or periodic adding of battery acid. However, the operation and maintenance cost of the batteries was taken to be R0/yr/battery in the simulation due to the fact that this variable can vary drastically between individual installations and is negligible compared to the overall capital costs of the system.

5.3.2 Converter

The peak load drawn during the 24-hour load profile that will be used in the simulation is 5.6kW. Therefore a 6KVA converter was considered for the simulation to ensure the converter can handle the maximum required power of the residential house over the period of a year. The lifetime of the converter was taken to be 15 years with an efficiency of 90% and the operation and maintenance costs of the converter was chosen to be $0/kW [12, 18].

5.3.3 Solar Panels

HOMER does not include the input of the exact make or size in m^2 of the solar panels chosen for the project. Instead, it includes the price per kilowatt of power produced and assumes that the output is linearly proportional to the incident radiation [12, 18]. Hence, the current price of R30.00 per watt was used for simulation purposes.

The solar panel power range included in the simulation was therefore 1-22kW's increasing in 1 kW intervals. The simulation was limited to 22kW due to the fact that the simulation is considered for a residential application where space is often limited. The more panels used would therefore require a larger area to be allocated for the installation of the solar panels which isn't always available.

The derating factor, which takes into account the reduction in efficiency of the panels due to temperature, dust and wiring losses, was taken to 0.9 over a lifetime of 20 years for the solar panels [8,17]. The operation and maintenance cost of the solar panels was taken to be R0/yr/kW due to the fact that this variable can vary drastically between individual installations and is negligible compared to the overall capital costs of the system. The system was modelled on static panels (no active solar tracking) with a default tilt of the panels set to the latitude for both geographical locations.

HOMER also includes the affect of ambient air temperature of a geographical location on the power output of a PV installation. The required parameters that HOMER requires for the solar PV panels include the temperature coefficient of power (%/^{0}C), nominal operating cell temperature (^{0}C) and efficiency of the panel at standard test conditions. The table below represents the values used for the parameters in the simulation described above based on a 240W panel that MLT drives supplies to the local South African market [19].

Table 7: Required PV Panel Parameters to Investigate the affect of Average Ambient Temperature

Parameter	Value used
Temperature coefficient of power (%/^{0}C)	-0.46
Nominal operating cell temperature (^{0}C)	45
Efficiency of the panel at standard test conditions (%)	15

The temperature coefficient of power (%/^{0}C) indicates how strongly the power output of a PV panel relates to the temperature of the surface of the solar panel. The value is negative due to the fact that the power output decreases with the increased temperature of the PV panel [32].

5.3.4 Ambient Air Temperature Input

The power generation of a solar PV panel in theory increases with the increased amount of sunlight falling upon it. However, it is also negatively affected by the increased temperature of the panel due to the increased operating temperature of the circuitry and electronics of the PV panel [21]. The graph below indicates the affect of the increased operating temperature of a PV panel to the current flowing through the PV panel's cells.

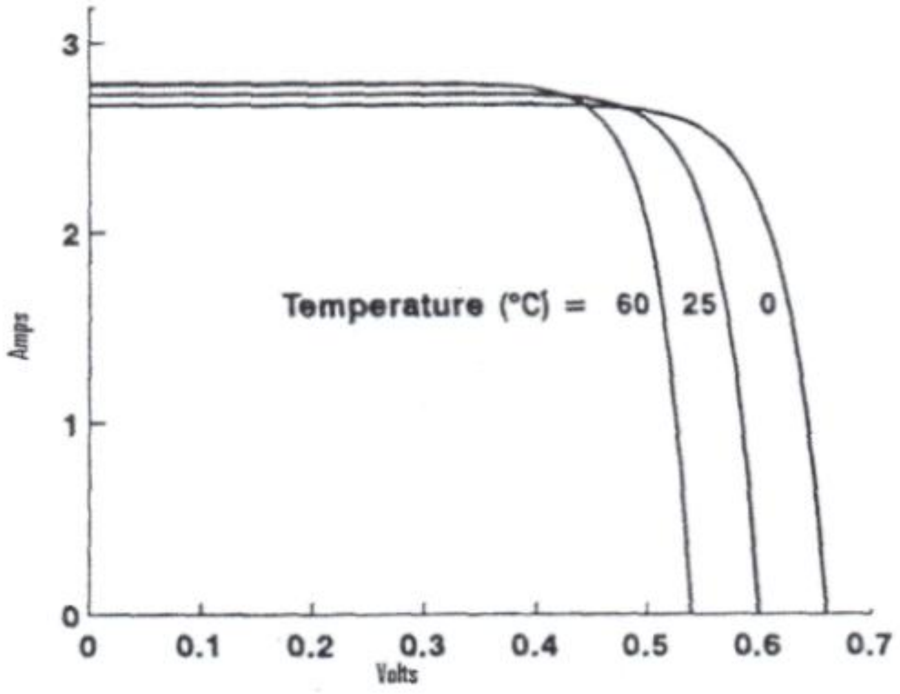

Figure 11: Increase In Temperature Produces a Lower Performance [21]

Therefore the average ambient temperature of a specific geographical location is also an important parameter to include when modelling solar PV energy systems.

The table below represents the average ambient air temperature of both geographical locations. The data was sourced from NASA's global meteorology database and averaged over a 22 year period [23]. The data was entered into HOMER for both geographical locations as well as the PV panel's standard operating conditions as described in the previous section 5.3.3.

Table 8: Average Monthly Ambient Air Temperature

Month	Stellenbosch (^{0}C)	Kwazulu-Natal (^{0}C)
January	21.9	21.1
February	22.4	21.2
March	21	20.6
April	18.5	18.8
May	15.9	16.8
June	13.3	14.4
July	12.6	14.4
August	13.1	16.4
September	14.7	18.2
October	17.1	18.5
November	19.1	19.5
December	20.7	20.5
Average	**17.53**	**18.37**

5.3.5 Summary of Components and Individual Pricings

The prices represented in the table below are a rough estimate on the general pricing of components based on quotes from MLT drives, being a local distributors of power generation and distribution products within South Africa [19]. These prices may vary between component distributors and manufacturers and do not include any of the optional extras that a user may choose to include depending on the desired output, geographical location, specific needs or size of the specific project. Similarly with that of the solar panels, in the cases where the price per kilowatt is used in considering various sizing of components for optimization purposes, the base pricing of the component is scaled linearly up or down to obtain an average price per kilowatt. Hence, the prices of components proposed by HOMER after simulation may vary considerably compared to that of the actual price of the component on the market, as a detailed list of component prices for all possible sizes is not entered into HOMER.

Table 9: Summary of System Component Costs

Component	**Cost (R)**
Batteries (4 scenarios) • Scenario 1 (600Ah) • Scenario 2 (800Ah) • Scenario 3 (1000Ah) • Scenario 4 (1500Ah)	 R 2,510 R 2,730 R 3,050 R 3,530
Solar panel (price per kW)	R 30,000
Converter (6 kVA)	R 39,950

6 FINDINGS

The finalised data sets, system components and sizing of components discussed in the previous sections above were inserted into the solar modelling program HOMER in order to find the optimized system set up and design for both geographical sites based on the use of the various solar irradiation data sets and battery sizing. The results of the simulations are represented below with all efforts taken to relate the findings to the terms of reference at the beginning of the paper. The process of reporting the findings of the simulations are as follows:

- Run the simulations for both geographical locations using the three solar irradiation data sources (1 ground monitored and 2 satellite based data sets) to determine the optimum system design for each dataset based around the use of four different battery types.
- The optimum system design for each data set will be defined as the system with the lowest initial capital and net present cost.
- The electrical performance for each optimum system design for each data set will then be examined in terms of PV electrical performance, battery electrical performance and overall system electrical performance.
- For each geographical location, the three optimum system designs for each different data source (ie: 1 ground data based system and 2 satellite data based systems) will then be compared to determine how the system architecture and initial capital and net present costs vary for the same location.
- A final simulation will then be run for both geographical sites to examine how the lowest capital cost satellite based system design will perform when the ground monitored solar irradiation data is used to run the simulation (ie: satellite system architecture will remain unchanged while the ground monitored solar irradiation data will be applied).
- The electrical performance of this system will then be compared to the actual required system design for the ground monitored solar irradiation data set to determine the financial and system performance implications through designing a solar PV energy system using a free public domain satellite based dataset.

6.1 Stellenbosch- Sonbessie Ground Monitored Data

The following headings within this section refer to the system designs for the Stellenbosch site.

The ground monitored data is viewed to be the most accurate solar irradiation data to model the system architecture due to the fact that it is measuring the actual solar irradiation experienced at ground level as if it were to be a solar PV panel sitting on the roof of a facility. The system architecture, and therefore cost, could differ from the satellite simulations due to the fact that the satellite data is based on an estimation of solar irradiation at ground level using mathematical models.

The table below represents the summary of the average daily solar irradiation measured by the ground monitoring station.

Table 10: Stellenbosch - Sonbessie Ground Monitored Data (GHI)

Month of Year	Stellenbosch, Sonbessie- Ground data ($kWh/m^2/day$)
January	8.57
February	7.82
March	5.67
April	4.52
May	2.61
June	2.22
July	2.89
August	3.42
September	4.76
October	6.05
November	7.23
December	8.23
Average	**5.33**

From the above data it is evident that there is a major discrepancy between the winter and summer months in terms of the available solar irradiation at ground level. The difference between the maximum solar irradiation per day and the minimum solar irradiation per day is 6.35 kWh/m^2/ day. The amount of battery storage should therefore be a critical determinant in terms of system architecture and system cost.

6.1.1 System Summary Based on Battery Type

The table below represents the four different battery type scenarios based on the amp hour capacity and cost of the battery.

Table 11: Battery Size and Cost Scenarios

Scenario	Battery	Cost (R)
1	Hoppecke 6OPzS 600	R 2,510

2	Hoppecke 8OPzS 800	R 2,730
3	Hoppecke 10OPzS 1000	R 3,050
4	Hoppecke 15OPzS 1500	R 3,530

The above scenarios were individually run in the simulation program for the same solar irradiation data set in order to determine the sensitivity of the system architecture and financial costs of the system based on the type of battery used. The system representing the lowest capital cost and net present cost will be viewed as the optimum system to install at this specific geographical location.

The table below represents the different system architectures and financial costs based on the above scenarios in order to ensure the entire daily load for the facility is met throughout the year with zero capacity shortages and full off grid status.

Table 12: System Summary's Based on Battery Type Used- Sonbessie

Scenario	PV Array (kW)	Num of batteries	Converter (kW)	Initial Capital (R)	Operating cost per year (R/year)	Net Present Cost (R)	Cost of Energy (R/kWh)
1	22	96	6	940,910	10,721	1,077,959	6.55
2	21	84	6	899,270	10,274	1,030,612	6.26
3	21	66	6	871,250	9,974	998,752	6.06
4	20	54	6	830,570	9,538	952,496	5.78
Difference between 1 and 4	**2 kW**	**42**	**0**	**R 110,340**	**R 1,183**	**R 125,463**	**R 0.77**

Scenario 4 (1500 Ah battery) therefore represents the optimum system to install at this specific geographical location based on the use of the Sonbessie ground monitored data. The difference between scenario 1 and scenario 4 in terms of initial capital is **11.7%.**

6.1.2 Electrical Performance of Optimum System Design

Based on the four different simulations ran for the four different battery scenarios above, the section below investigates the electrical performance of the optimum solar PV system design to install at the Stellenbosch site.

The table below represents the electrical performance of the solar PV panels for the optimum system architecture based on the Sonbessie ground monitored solar irradiation.

Table 13: PV Electrical Performance for Optimum System Design- Sonbessie

Component	PV Array
Rated capacity	20 kW
Production per Year (kWh/yr)	28,105
Maximum Output (kW)	16.2
Mean Output (kW)	3.21
Mean Output (kWh/day)	77
Capacity Factor (%)	16

The table below represents the electrical performance of the batteries for the optimum system architecture based on the Sonbessie ground monitored solar irradiation.

Table 14: Batteries Electrical Performance for Optimum System Design- Sonbessie

Component	Batteries
Number of batteries	54
String Size	6
Strings in parallel	9
Energy In (kWh/yr)	6,289
Energy Out (kWh/yr)	5,417
Autonomy (hrs)	77.1

The table below represents the summary of the electrical performance for the entire system based on the Sonbessie ground monitored solar irradiation.

Table 15: Summary Electrical Performance for Optimum System Design-Sonbessie

Load Consumption (kWh/yr)	12,874
Excess electricity (kWh/yr)	12,929
Capacity Shortage (kWh/yr)	11.6
Capacity Shortage (%)	0.0

6.2 Stellenbosch- SODA Satellite Data

The table below represents the summary of the average daily solar irradiation provided by the SODA satellite database.

Table 16: Stellenbosch - SODA Satellite Derived Data

Month of Year	SODA- Satellite data ($kWh/m^2/day$)
January	7.57
February	6.93
March	5.59
April	3.98
May	2.94
June	2.55
July	2.82
August	3.39
September	4.57
October	5.94
November	6.93
December	7.55
Average	**5.06**

From the above data it is evident that there is a major discrepancy between the winter and summer months in terms of the available solar irradiation at ground level. The difference between the maximum average solar irradiation per day and the minimum solar irradiation per day is 5.02 kWh/m^2/ day. The amount of battery storage should therefore be a critical determinant in terms of system architecture and system cost.

6.2.1 System Summary Based on Battery Type

The table below represents the four different battery type scenarios based on the amp hour capacity and cost of the battery.

Table 17: Battery Size and Cost Scenarios

Scenario	Battery	Cost (R)
1	Hoppecke 6OPzS 600	R 2,510
2	Hoppecke 8OPzS 800	R 2,730
3	Hoppecke 10OPzS 1000	R 3,050
4	Hoppecke 15OPzS 1500	R 3,530

The above scenarios were individually run in the simulation program for the same solar irradiation data set in order to determine the sensitivity of the system architecture and financial costs of the system based on the type of battery used. The system representing the lowest capital cost and net present cost will be viewed as the optimum system to install at this specific geographical location.

The table below represents the different system architectures and financial costs based on the above scenarios in order to ensure the entire daily load for the facility is met throughout the year with zero capacity shortages and full off grid status.

Table 18: System Summary's Based on Battery Type Used- SODA

Scenario	PV Array (kW)	Num of batteries	Converter (kW)	Initial Capital (R)	Operating cost per year (R/year)	Net Present Cost (R)	Cost of Energy (R/kWh)
1	18	96	6	820,910	9,434	941,512	5.72
2	16	84	6	749,270	8,666	860,053	5.22
3	16	66	6	721,250	8,366	828,193	5.03
4	15	54	6	680,570	7,930	781,938	4.75
Difference between 1 and 4	**3 kW**	**42**	**0**	**R 140,340**	**R 1,504**	**R 159,574**	**R 0.97**

Scenario 4 (1500Ah battery) therefore represents the optimum system to install at this specific geographical location based on the use of the SODA satellite based data. The difference between scenario 1 and scenario 4 in terms of initial capital is **17.0%**.

6.2.2 Electrical Performance of Optimum System Design

Based on the four different simulations ran for the four different battery scenarios above, the section below investigates the electrical performance of the optimum solar PV system design to install at the Stellenbosch site.

The table below represents the electrical performance of the solar PV panels for the optimum system architecture based on the SODA satellite monitored solar irradiation.

Table 19: PV Electrical Performance for Optimum System Design- SODA

Component	PV Array
Rated capacity	15 kW
Production per Year (kWh/yr)	21,505
Maximum Output (kW)	12.7
Mean Output (kW)	2.45
Mean Output (kWh/day)	58.9

Capacity Factor (%)	16.4

The table below represents the electrical performance of the batteries for the optimum system architecture based on the SODA satellite monitored solar irradiation.

Table 20: Batteries Electrical Performance for Optimum System Design- SODA

Component	Batteries
Number of batteries	54
String Size	6
Strings in parallel	9
Energy In (kWh/yr)	6,994
Energy Out (kWh/yr)	6,027
Autonomy (hrs)	77.1

The table below represents the summary of the electrical performance for the entire system based on the SODA satellite monitored solar irradiation.

Table 21: Summary Electrical Performance for Optimum System Design-SODA

Load Consumption (kWh/yr)	12,876
Excess electricity (kWh/yr)	6,231
Capacity Shortage (kWh/yr)	10.4
Capacity Shortage (%)	0.0

6.3 Stellenbosch- NASA SSE Satellite Data

The table below represents the summary of the average daily solar irradiation provided by the NASA SSA satellite database.

Table 22: Stellenbosch - NASA SSE Satellite Derived Data

Month of Year	**NASA SSE- Satellite data (kWh/m^2/day)**
January	8.18
February	7.43
March	5.99
April	4.36
May	3.08

June	2.62
July	2.90
August	3.58
September	4.97
October	6.38
November	7.55
December	8.06
Average	**5.42**

From the above data it is evident that there is a major discrepancy between the winter and summer months in terms of the available solar irradiation at ground level. The difference between the maximum average solar irradiation per day and the minimum solar irradiation per day is 5.56 kWh/m^2/ day. The amount of battery storage should therefore be a critical determinant in terms of system architecture and system cost.

6.3.1 System Summary Based on Battery Type

The table below represents the four different battery type scenarios based on the amp hour capacity and cost of the battery.

Table 23: Battery Size and Cost Scenarios

Scenario	Battery	Cost (R)
1	Hoppecke 6OPzS 600	R 2,510
2	Hoppecke 8OPzS 800	R 2,730
3	Hoppecke 10OPzS 1000	R 3,050
4	Hoppecke 15OPzS 1500	R 3,530

The above scenarios were individually run in the simulation program for the same solar irradiation data set in order to determine the sensitivity of the system architecture and financial costs of the system based on the type of battery used. The system representing the lowest capital cost and net present cost will be viewed as the optimum system to install at this specific geographical location.

The table below represents the different system architectures and financial costs based on the above scenarios in order to ensure the entire daily load for the facility is met throughout the year with zero capacity shortages and full off grid status.

Table 24: System Summary's Based on Battery Type Used- NASA SSE

Scenario	PV Array (kW)	Num of batteries	Converter (kW)	Initial Capital (R)	Operating cost per year (R/year)	Net Present Cost (R)	Cost of Energy (R/kWh)
1	18	96	6	820,910	9,434	941,512	5.72
2	18	72	6	776,510	8,958	891,027	5.41
3	17	66	6	751,250	8,687	862,305	5.23
4	17	42	6	698,210	8,119	801,995	4.87
Difference between 1 and 4	**1 kW**	**54**	**0**	**R 122,700**	**R 1,315**	**R 139,517**	**R 0.85**

Scenario 4 (1500Ah battery) therefore represents the optimum system to install at this specific geographical location based on the use of the NASA SSE satellite based data. The difference between scenario 1 and scenario 4 in terms of initial capital is **14.9%**.

6.3.2 Electrical Performance of Optimum System Design

Based on the four different simulations ran for the four different battery scenarios above, the section below investigates the electrical performance of the optimum solar PV system design to install at the Stellenbosch site.

The table below represents the electrical performance of the solar PV panels for the optimum system architecture based on the NASA SSE satellite monitored solar irradiation.

Table 25: PV Electrical Performance for Optimum System Design- NASA SSE

Component	PV Array
Rated capacity	17 kW
Production per Year (kWh/yr)	24,215
Maximum Output (kW)	13.6
Mean Output (kW)	2.76
Mean Output (kWh/day)	66.3
Capacity Factor (%)	16.3

The table below represents the electrical performance of the batteries for the optimum system architecture based on the NASA SSE satellite monitored solar irradiation.

Table 26: Batteries Electrical Performance for Optimum System Design- NASA SSE

Component	Batteries
Number of batteries	42
String Size	6

Strings in parallel	7
Energy In (kWh/yr)	6,532
Energy Out (kWh/yr)	5,627
Autonomy (hrs)	60

The table below represents the summary of the electrical performance for the entire system based on the NASA SSE satellite monitored solar irradiation.

Table 27: Summary Electrical Performance for Optimum System Design-NASA SSE

Load Consumption (kWh/yr)	12,873
Excess electricity (kWh/yr)	9,007
Capacity Shortage (kWh/yr)	12.0
Capacity Shortage (%)	0.0

6.4 Summary of the Three Different Data Sets Optimum System Design

The table below represents the optimum system summary for all three solar irradiation data sets for Stellenbosch.

Table 28: Summary of Three Data Sets Optimum System Design- Stellenbosch

Scenario	PV Array (kW)	Num of batteries	Converter (kW)	Initial Capital (R)	Operating cost per year (R/year)	Net Present Cost (R)	Cost of Energy (R/kWh)
Sonbessie - Ground Monitored Data	20	54	6	830,570	9,538	952,496	5.78
SODA - Satellite Derived Data	15	54	6	680,570	7,930	781,938	4.75
NASA SSE - Satellite Derived Data	17	42	6	698,210	8,119	801,995	4.87

In both cases the satellite based system design represented a lower initial capital cost system, and hence a lower operating cost per year, net present cost per year and cost of energy per kWh.

From the table above, the system design which represents the lowest initial capital is the system based on the SODA satellite solar irradiation. The difference in initial capital compared to the Sonbessie ground monitored solar irradiation system design is R 150 000, or 18%.

6.5 System Performance of SODA's Optimum Design, Using Sonbessie Ground Monitored Solar Irradiation

The following analysis aims to investigate how the electrical output of the system will be affected if the user had to of installed the satellite based optimum system design with the lowest initial capital cost (SODA) at the Stellenbosch site with the actual ground measured solar irradiation applied to the system.

6.5.1 Electrical Performance Comparison

The table below represents the PV electrical performance comparison between the two system architectural designs; with both the systems output being modelled with the Sonbessie ground monitored data. A negative percentage represents a decrease in the corresponding value from the original Sonbessie based system design to the original SODA based system design. A positive percentage therefore represents an increase in the corresponding value respectively.

Table 29: PV Electrical Performance Comparison for SODA Optimum System Design using Sonbessie Solar Data

	Sonbessie Optimum Design –Sonbessie Ground Data	**SODA Optimum Design- Sonbessie Ground Data**	**Percentage Difference (%)**
Component	PV Array	PV Array	N/A
Rated capacity	20 kW	15 kW	- 25.0
Production per Year (kWh/yr)	28,105	21,079	- 25.0
Maximum Output (kW)	16.7	12.2	- 24.7
Mean Output (kW)	3.21	2.41	- 24.9
Mean Output (kWh/day)	77	57.8	- 24.9
Capacity Factor (%)	16.0	16.0	0

The table below represents the batteries electrical performance comparison between the two system designs when modelled using the Sonbessie ground monitored data.

Table 30: Batteries Electrical Performance Comparison for SODA Optimum System Design using Sonbessie Solar Data

	Sonbessie Optimum Design –Sonbessie Ground Data	**SODA Optimum Design- Sonbessie Ground Data**	**Percentage Difference (%)**

Component	Batteries	Batteries	N/A
Number of batteries	54	54	0
String Size	6	6	0
Strings in parallel	9	9	0
Energy In (kWh/yr)	6,289	6,541	+ 4
Energy Out (kWh/yr)	5,417	5,636	+ 4
Autonomy (hrs)	77.1	77.1	0

The table below represents the systems overall electrical performance comparison between the two system designs when modelled using the Sonbessie ground monitored data.

Table 31: Summary of Electrical Performance Comparison for SODA Optimum System Design using Sonbessie Solar Data

	Sonbessie Optimum Design –Sonbessie Ground Data	**SODA Optimum Design- Sonbessie Ground Data**	**Percentage Difference (%)**
Load Consumption (kWh/yr)	12,874	12,511	- 2.8
Excess electricity (kWh/yr)	12,929	6,273	- 51.5
Capacity Shortage (kWh/yr)	11.6	422	+ 3537.9
Capacity Shortage (%)	0.0	3.3	+ 3.3

From the table above, it is clear that the overall system performance of the satellite based optimum design decreases when the actual ground monitored data is applied to the system. The system experiences an annual capacity shortage of 3.3% over the year.

6.6 Kwazulu-Natal- Howard Ground Monitored Data

The following headings within this section refer to the system designs for the Kwazulu-Natal site.

The ground monitored data is viewed to be the most accurate solar irradiation data to model the system architecture due to the fact that it is measuring the actual solar irradiation experienced at ground level as if it were to be a solar PV panel sitting on the roof of a facility. The system architecture, and therefore cost, could differ from the satellite simulations due to the fact that the satellite data is based on an estimation of solar irradiation at ground level using mathematical models.

The table below represents the summary of the average daily solar irradiation measured by the Howard ground monitoring station.

Table 32: Kwazulu-Natal - Howard Ground Monitored Data

Month of Year	KZN, Howard- Ground data ($kWh/m^2/day$)
January	4.95
February	5.97
March	5.34
April	4.16
May	3.42
June	2.86
July	3.11
August	3.66
September	4.25
October	4.29
November	4.81
December	4.73
Average	**4.24**

From the above data it is evident that there isn't as much of a discrepancy between the winter and summer months in terms of the available solar irradiation at ground level when compared to the Stellenbosch site. The difference between the maximum average solar irradiation per day and the minimum solar irradiation per day is 3.11 kWh/m^2/ day. The system design should therefore be more dependent on the solar PV array sizing then the battery storage due to the lesser degree of variation in the solar irradiation between winter and summer months.

6.6.1 System Summary Based on Battery Type

The table below represents the four different battery type scenarios based on the amp hour capacity and cost of the battery.

Table 33: Battery Size and Cost Scenarios

Scenario	Battery	Cost (R)
1	Hoppecke 6OPzS 600	R 2,510
2	Hoppecke 8OPzS 800	R 2,730
3	Hoppecke 10OPzS 1000	R 3,050
4	Hoppecke 15OPzS 1500	R 3,530

The above scenarios were individually run in the simulation program for the same solar irradiation data set in order to determine the sensitivity of the system architecture and financial costs of the system based on the type of battery used. The system representing the lowest capital cost and net present cost will be viewed as the optimum system to install at this specific geographical location.

The table below represents the different system architectures and financial costs based on the above scenarios in order to ensure the entire daily load for the facility is met throughout the year with zero capacity shortages and full off grid status.

Table 34: System Summary's Based on Battery Type Used- Howard

Scenario	PV Array (kW)	Num of batteries	Converter (kW)	Initial Capital (R)	Operating cost per year (R/year)	Net Present Cost (R)	Cost of Energy (R/kWh)
1	16	96	6	760,910	8,791	873,289	5.30
2	15	84	6	719,270	8,345	825,942	5.01
3	15	66	6	691,250	8,044	794,081	4.82
4	12	66	6	632,930	7,419	727,768	4.42
Difference between 1 and 4	**4 kW**	**30**	**0**	**R 127,980**	**R 1,372**	**R 145,521**	**R 0.88**

Scenario 4 (1500Ah Battery) therefore represents the optimum system to install at this specific geographical location based on the use of the Howard ground monitored solar data. The difference between scenario 1 and scenario 4 in terms of initial capital is **16.8%**.

6.6.2 Electrical Performance of Optimum System Design

Based on the four different simulations ran for the four different battery scenarios above, the section below investigates the electrical performance of the optimum solar PV system design to install at the Kwazulu-Natal site.

The table below represents the electrical performance of the solar PV panels for the optimum system architecture based on the Howard ground monitored solar irradiation.

Table 35: PV Electrical Performance for Optimum System Design- Howard

Component	PV Array
Rated capacity	12 kW
Production per Year (kWh/yr)	17,560
Maximum Output (kW)	11.2
Mean Output (kW)	2.00

Mean Output (kWh/day)	48.1
Capacity Factor (%)	16.7

The table below represents the electrical performance of the batteries for the optimum system architecture based on the Howard ground monitored solar irradiation.

Table 36: Batteries Electrical Performance for Optimum System Design- Howard

Component	Batteries
Number of batteries	66
String Size	6
Strings in parallel	11
Energy In (kWh/yr)	7,846
Energy Out (kWh/yr)	6,819
Autonomy (hrs)	94.2

The table below represents the summary of the electrical performance for the entire system based on the Howard ground monitored solar irradiation.

Table 37: Summary Electrical Performance for Optimum System Design- Howard

Load Consumption (kWh/yr)	12,877
Excess electricity (kWh/yr)	2,226
Capacity Shortage (kWh/yr)	8.31
Capacity Shortage (%)	0.0

6.7 Kwazulu-Natal- SODA Satellite Data

The table below represents the summary of the average daily solar irradiation provided by the SODA satellite database.

Table 38: Kwazulu-Natal - SODA Satellite Derived Data

Month of Year	SODA- Satellite data ($kWh/m^2/day$)
January	5.41
February	5.23
March	4.91
April	4.06

May	3.54
June	3.12
July	3.26
August	4.00
September	4.21
October	4.68
November	5.02
December	5.59
Average	**4.42**

From the above data it is evident that there isn't as much of a discrepancy between the winter and summer months in terms of the available solar irradiation at ground level when compared to the Stellenbosch site. The difference between the maximum average solar irradiation per day and the minimum solar irradiation per day is 2.47 kWh/m^2/ day. The system design should therefore be more dependent on the solar PV array sizing then the battery storage due to the lesser degree of variation in the solar irradiation between winter and summer months.

6.7.1 System Summary Based on Battery Type

The table below represents the four different battery type scenarios based on the amp hour capacity and cost of the battery.

Table 39: Battery Size and Cost Scenarios

Scenario	Battery	Cost (R)
1	Hoppecke 6OPzS 600	R 2,510
2	Hoppecke 8OPzS 800	R 2,730
3	Hoppecke 10OPzS 1000	R 3,050
4	Hoppecke 15OPzS 1500	R 3,530

The above scenarios were individually run in the simulation program for the same solar irradiation data set in order to determine the sensitivity of the system architecture and financial costs of the system based on the type of battery used. The system representing the lowest capital cost and net present cost will be viewed as the optimum system to install at this specific geographical location.

The table below represents the different system architectures and financial costs based on the above scenarios in order to ensure the entire daily load for the facility is met throughout the year with zero capacity shortages and full off grid status.

Table 40: System Summary's Based on Battery Type Used- SODA

Scenario	PV Array (kW)	Num of batteries	Converter (kW)	Initial Capital (R)	Operating cost per year (R/year)	Net Present Cost (R)	Cost of Energy (R/kWh)
1	15	90	6	715,850	8,308	822,053	4.99
2	14	72	6	656,510	7,672	754,580	4.58
3	13	66	6	631,250	7,401	725,858	4.41
4	12	54	6	590,570	6,965	679,603	4.12
Difference between 1 and 4	**3 kW**	**36**	**0**	**R 125,280**	**R 1,343**	**R 142,450**	**R 0.87**

Scenario 4 (1500Ah battery) therefore represents the optimum system to install at this specific geographical location based on the use of the SODA satellite data. The difference between scenario 1 and scenario 4 in terms of initial capital is **17.5%**.

6.7.2 Electrical Performance of Optimum System Design

Based on the four different simulations ran for the four different battery scenarios above, the section below investigates the electrical performance of the optimum solar PV system design to install at the Kwazulu-Natal site.

The table below represents the electrical performance of the solar PV panels for the optimum system architecture based on the SODA satellite monitored solar irradiation.

Table 41: PV Electrical Performance for Optimum System Design- SODA

Component	PV Array
Rated capacity	12 kW
Production per Year (kWh/yr)	17,585
Maximum Output (kW)	10.9
Mean Output (kW)	2.01
Mean Output (kWh/day)	48.2
Capacity Factor (%)	16.7

The table below represents the electrical performance of the batteries for the optimum system architecture based on the SODA satellite monitored solar irradiation.

Table 42: Batteries Electrical Performance for Optimum System Design- SODA

Component	Batteries
Number of batteries	54
String Size	6
Strings in parallel	9
Energy In (kWh/yr)	7,805
Energy Out (kWh/yr)	6,750
Autonomy (hrs)	77.1

The table below represents the summary of the electrical performance for the entire system based on the SODA satellite monitored solar irradiation.

Table 43: Summary Electrical Performance for Optimum System Design- SODA

Load Consumption (kWh/yr)	12,877
Excess electricity (kWh/yr)	2,226
Capacity Shortage (kWh/yr)	8.31
Capacity Shortage (%)	0.0

6.8 Kwazulu-Natal- NASA SSE Satellite Data

The table below represents the summary of the average daily solar irradiation provided by the NASA SSA satellite database.

Table 44: Kwazulu-Natal - NASA SSE Satellite Derived Data

Month of Year	NASA SSE- Satellite data (kWh/m^2/day)
January	5.44
February	5.55
March	5.07
April	4.33
May	3.77
June	3.42
July	3.57
August	4.29
September	4.70
October	4.79

November	4.98
December	5.25
Average	**4.60**

From the above data it is evident that there isn't as much of a discrepancy between the winter and summer months in terms of the available solar irradiation at ground level when compared to the Stellenbosch site. The difference between the maximum average solar irradiation per day and the minimum solar irradiation per day is 2.13 kWh/m^2/ day. The system design should therefore be more dependent on the solar PV array sizing then the battery storage due to the lesser degree of variation in the solar irradiation between winter and summer months.

6.8.1 System Summary Based on Battery Type

The table below represents the four different battery type scenarios based on the amp hour capacity and cost of the battery.

Table 45: Battery Size and Cost Scenarios

Scenario	Battery	Cost (R)
1	Hoppecke 6OPzS 600	R 2,510
2	Hoppecke 8OPzS 800	R 2,730
3	Hoppecke 10OPzS 1000	R 3,050
4	Hoppecke 15OPzS 1500	R 3,530

The above scenarios were individually run in the simulation program for the same solar irradiation data set in order to determine the sensitivity of the system architecture and financial costs of the system based on the type of battery used. The system representing the lowest capital cost and net present cost will be viewed as the optimum system to install at this specific geographical location.

The table below represents the different system architectures and financial costs based on the above scenarios in order to ensure the entire daily load for the facility is met throughout the year with zero capacity shortages and full off grid status.

Table 46: System Summary's Based on Battery Type Used- NASA SSE

Scenario	PV Array (kW)	Num of batteries	Converter (kW)	Initial Capital (R)	Operating cost per year (R/year)	Net Present Cost (R)	Cost of Energy (R/kWh)

1	16	84	6	730,790	8,468	839,041	5.09
2	15	72	6	686,510	7,993	788,692	4.79
3	14	66	6	661,250	7,723	759,970	4.61
4	13	54	6	620,570	7,286	713,714	4.33
Difference between 1 and 4	**3 kW**	**30**	**0**	**R 110,220**	**R 1,182**	**R 125,327**	**R 0.76**

Scenario 4 (1500Ah battery) therefore represents the optimum system to install at this specific geographical location based on the NASA SSE satellite based data. The difference between scenario 1 and scenario 4 in terms of initial capital is **15.0%**.

6.8.2 Electrical Performance of Optimum System Design

Based on the four different simulations ran for the four different battery scenarios above, the section below investigates the electrical performance of the optimum solar PV system design to install at the Kwazulu-Natal site.

The table below represents the electrical performance of the solar PV panels for the optimum system architecture based on the NASA SSE satellite monitored solar irradiation.

Table 47: PV Electrical Performance for Optimum System Design- NASA SSE

Component	PV Array
Rated capacity	13 kW
Production per Year (kWh/yr)	19,317
Maximum Output (kW)	11.5
Mean Output (kW)	2.21
Mean Output (kWh/day)	52.9
Capacity Factor (%)	17.0

The table below represents the electrical performance of the batteries for the optimum system architecture based on the NASA SSE satellite monitored solar irradiation.

Table 48: Batteries Electrical Performance for Optimum System Design- NASA SSE

Component	Batteries
Number of batteries	54
String Size	6
Strings in parallel	9
Energy In (kWh/yr)	7,745

Energy Out (kWh/yr)	6,470
Autonomy (hrs)	77.1

The table below represents the electrical performance of the batteries for the optimum system architecture based on the NASA SSE satellite monitored solar irradiation.

Table 49: Summary Electrical Performance for Optimum System Design- NASA SSE

Load Consumption (kWh/yr)	12,878
Excess electricity (kWh/yr)	4,004
Capacity Shortage (kWh/yr)	6.94
Capacity Shortage (%)	0

6.9 Summary of the Three Different Data Sets Optimum System Design

The table below represents the optimum system summary for all three solar irradiation data sets for Kwazulu-Natal.

Table 50: Summary of the Three Data Sets Optimum System Design- Kwazulu-Natal

Scenario	PV Array (kW)	Num of batteries	Converter (kW)	Initial Capital (R)	Operating cost per year (R/year)	Net Present Cost (R)	Cost of Energy (R/kWh)
Howard - Ground Monitored Data	12	66	6	632,930	7,419	727,768	4.42
SODA - Satellite Derived Data	12	54	6	590,570	6,965	679,603	4.12
NASA SSE - Satellite Derived Data	13	54	6	620,570	7,286	713,714	4.33

In both cases the satellite based system design represented a lower initial capital cost system, and hence a lower operating cost per year, net present cost per year and cost of energy per kWh.

From the table above, the system design which represents the lowest initial capital is the system based on the SODA satellite solar irradiation. The difference in initial capital compared to the Howard ground monitored solar irradiation system design is R 40 360, or 6.37%.

6.10 System Performance for SODA's Optimum Design, Using Howards Ground Monitored Solar Irradiation

The following analysis aims to investigate how the electrical output of the system will be affected if the user had to of installed the satellite based optimum system design with the lowest initial capital cost (SODA) at the Kwazulu-Natal site with the actual ground measured solar irradiation applied to the system.

6.10.1 Electrical Performance Comparison

The table below represents the PV electrical performance comparison between the two system architectural designs; with both the systems output being modelled with the Howard ground monitored data. A negative percentage represents a decrease in the corresponding value from the original Howard based system design to the original SODA based system design. A positive percentage therefore represents an increase in the corresponding value respectively.

Table 51: PV Electrical Performance Comparison for SODA Optimum System Design using Howard Solar Data

	Howard Optimum Design- Howard Solar Data	SODA Optimum Design- Howard Solar Data	Percentage Difference (%)
Component	PV Array	PV Array	N/A
Rated capacity	12 kW	12 kW	0
Production per Year (kWh/yr)	17,585	17,560	0
Maximum Output (kW)	11.2	11.2	0
Mean Output (kW)	2.00	2.00	0
Mean Output (kWh/day)	48.1	48.1	0
Capacity Factor (%)	16.7	16.7	0

The table below represents the batteries electrical performance comparison between the two system designs when modelled using the Howard ground monitored data.

Table 52: Batteries Electrical Performance Comparison for SODA Optimum System Design using Howard Solar Data

	Howard Optimum Design- Howard Solar Data	SODA Optimum Design- Howard Solar Data	Percentage Difference (%)
Component	Batteries	Batteries	N/A
Number of batteries	66	54	- 18.2

String Size	6	6	0
Strings in parallel	11	9	- 18.2
Energy In (kWh/yr)	7,846	7,813	- 0.4
Energy Out (kWh/yr)	6,819	6,791	- 0.4
Autonomy (hrs)	94.2	77.1	- 18.2

The table below represents the systems overall electrical performance comparison between the two system designs when modelled using the Howard ground monitored data.

Table 53: Summary of Electrical Performance Comparison for SODA Optimum System Design using Howard Solar Data

	Howard Optimum Design- Howard Solar Data	**SODA Optimum Design- Howard Solar Data**	**Percentage Difference (%)**
Load Consumption (kWh/yr)	12,877	12,851	- 0.2
Excess electricity (kWh/yr)	2,226	2,258	+ 1.4
Capacity Shortage (kWh/yr)	8.31	34.8	+ 318.8
Capacity Shortage (%)	0.0	0.0	0.0

From the table above, it is clear that the overall system performance of the satellite based optimum design does not decrease dramatically when the actual ground monitored data is applied to the system. In both instances there is no real annual capacity shortage over the year, and hence the system can meet the load of the facility year round regardless of the solar irradiation data set used.

7 CONCLUSION

This thesis primarily aims at determining the effect that different sources of solar irradiation data , and methods for capturing the solar irradiation data will have on a solar energy system in terms of the system architecture and hence capital cost when designing a system for a specific location. The secondary aims include:

i) The investigation into the effect that the choice of battery sizing will have on the system design in order to install the optimum system at a specific location.
ii) The investigation into the electrical performance of the optimum satellite based designs when the ground monitored solar irradiation data is applied to the system, as the method for capturing ground monitored data is similar to that of what the actual PV panel will receive on its surface at ground level.

The following headings below represent the conclusions of the research based on the findings represented in this paper.

7.1 Solar Irradiation Datasets

When designing a solar energy system, accurate solar data for the specific site in which one plans to install the system is required in order to accurately determine the sizing of the system components based on the available amount of energy. The access to accurate data is however not always freely available, and the designer of the system will either have to pay for the accurate data if it is viewed to be financially viable, or settle for less accurate freely available data from one of the many solar irradiation data providers. Not only is the source of the data a key point for the designer to take into consideration, but the actual method used for measuring the solar irradiation data is also a key issue to consider. There are two methods for measuring the amount of solar irradiation at ground level, namely being ground monitored solar stations and satellite based estimations. The solar irradiation can therefore differ for the exact same location depending on the method used for capturing the data due to a number of reasons such as:

- Estimation of data verse actual measurement
- Resolution of data
- Maintenance of equipment
- Quality control procedures applied to the data

When designing a solar energy system, the main aim of the designer is to optimize the system through the correct choice in sizing of system components (ie: size of PV array verse number of batteries for storage), whilst at the same time keeping the overall systems costs as low as possible. The choice of data provider and method for measuring the solar irradiation data is therefore a critical determinant to ensure the desired level of accuracy for the system design is maintained. The use of a data set which either over predicts or under predicts the amount of available solar irradiation at a specific location will therefore affect the electrical performance of the system, as the real world conditions may differ considerably to the data set used in the modelling of the system design.

This paper therefore looks at the variation in system design through the use of three different solar irradiation data sources for the same location, with two different methods of capturing the solar irradiation data. For the purpose of the research, all comparisons will be made against the system design derived through the use of the ground monitored data at each specific location. This is due to the fact that the ground monitored data is viewed as being the closest representation of real world conditions, as it is measuring the actual solar irradiation at ground level as if it were to be a solar panel sitting on a roof of a facility receiving solar irradiation throughout the day.

The datasets included in this paper therefore include:

- Two ground monitored solar irradiation datasets
  - Stellenbosch- Sonbessie Ground Monitored Data (Lat:-33.98^0, Long: 18.86^0)
  - Kwazulu-Natal- Howard Ground Monitored Data (Lat:-29.9^0, Long: 30.98^0)
- Two freely available public domain satellite based datasets:
  - SODA satellite based solar irradiation
  - NASA SSE satellite based solar irradiation

The figures below represent the average monthly solar irradiation at ground level for the two geographical sites with the three sources of solar irradiation data.

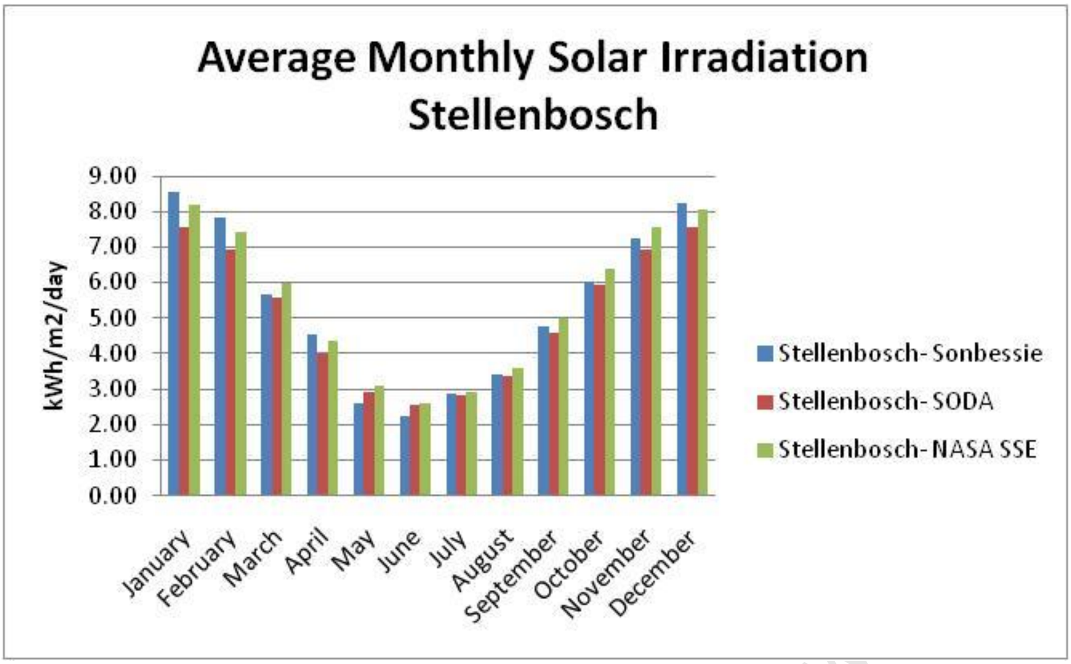

Figure 12: Average Monthly Solar Irradiation- Stellenbosch

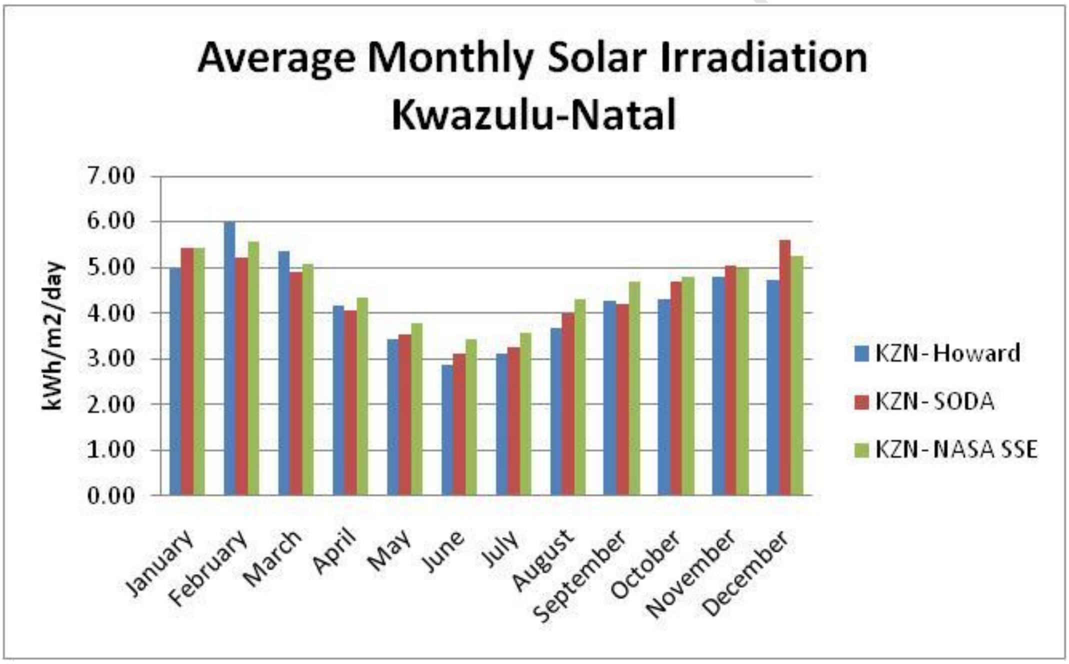

Figure 13: Average Monthly Solar Irradiation- Kwazulu-Natal

The following points can be made about the three solar irradiation data sources and the available solar irradiation at ground level:

- One can clearly see the transition between the summer and winter months for both locations
- The Stellenbosch location has a large variation of available solar irradiation between the winter and summer months. Battery storage for this location will therefore be a critical parameter for the modelling of an off grid system in order to cope with the low amount of available solar irradiation during the winter months.

- The ground monitoring stations for both geographical locations on average depict lower solar irradiation values at ground level when compared to the two satellite based databases.
- The NASA SSE database over predicts the available solar irradiation at ground level for both sites

7.2 Affect of Battery Sizing to System Architecture

After completing the simulations, it is evident that it is technically feasible to go fully off grid using solar PV with battery backup for storage to meet the demand of the provided load profile year round at both geographical locations regardless of the solar irradiation data set used for modelling purpose. This is however largely dependent on the size of the battery used for storage purposes, as this has been shown in the findings to dramatically increase the costs of the system when a smaller battery size has been specified in the simulation. This is particularly evident at the Stellenbosch location, due to the large fluctuations between the average monthly solar irradiation experienced at ground level between the winter and summer months.

For example in the instance of using a 600 Ah battery for the Stellenbosch site using the Sonbessie solar irradiation data for simulation purposes, the size of the PV array turned out to be 22kW with 96 batteries for storage purposes (see table 12). If one had to assume the PV array was made up of panels with a rated output of 200W with an average surface area of 1.5 m^2, the total number of panels required to meet the load would be 110 panels and would require 165 m^2 of space to install the solar array. Depending on the location for the installation, this amount of space with direct sunlight throughout the day may not always be available due to the fact that the system is designed for a residential application. Not only may space be an issue for the PV array, but the same would apply for the 96 batteries required for the systems storage needs. In addition, although the actual maintenance costs of the batteries were not included in the simulations, the physical maintenance of topping up water and battery acid levels for 96 batteries would also require a lot of time in a system that is supposed to be as rugged and maintenance free as possible in an off grid application. The system is therefore technically feasible to meet the loads demand; however it may not be the most practical in terms of required space and the monthly maintenance required for the various components of the solar energy system.

The table below therefore represents the summary of the differences in overall system design between the 600 Ah battery scenario verse the 1500 Ah battery scenario for all three solar irradiation data sets at the Stellenbosch site. All values in the table below represent a decrease in system architecture sizing and cost when the larger battery is used for simulation purposes.

Table 54: Differences in System Architecture through the use of the 1500 Ah Batteries as opposed to the 600 Ah batteries- Stellenbosch

Stellenbosch	PV Array (kW)	Num of batteries	Converter (kW)	Initial Capital (R)	Operating cost per year (R/year)	Net Present Cost (R)	Cost of Energy (R/kWh)
Sonbessie	2 kW	42	0	110,340	1,183	125,463	0.77
SODA	3 kW	42	0	140,340	1,504	159,574	0.97
NASA SSE	1 kW	54	0	122,700	1,315	139,517	0.85
Average	**2 kW**	**46**	**0**	**R 124,460**	**R 1,334**	**R 141,518**	**R 0.86**

From the table above, the system architecture from all three solar irradiation datasets for Stellenbosch on average decreased in size by 2 kW of PV panels and 46 batteries when the 1500 Ah battery was used for simulation purposes as opposed to the 600Ah battery. This amounts to on average a decrease in initial capital of R 124,460.

The table below represents the same scenario as presented above, yet for the Kwazulu-Natal site.

Table 55: Differences in System Architecture from the 600 Ah batteries to the 1500 Ah batteries- Kwazulu-Natal

Kwazulu-Natal	PV Array (kW)	Num of batteries	Converter (kW)	Initial Capital (R)	Operating cost per year (R/year)	Net Present Cost (R)	Cost of Energy (R/kWh)
Howard	4 kW	30	0	127,980	1,372	145,521	0.88
SODA	3 kW	36	0	125,280	1,343	142,450	0.87
NASA SSE	3 kW	30	0	110,220	1,182	125,327	0.76
Average	**3 kW**	**32**	**0**	**R 121,160**	**R 1,299**	**R 137,766**	**R 0.84**

From the table above, the system architecture from all three solar irradiation datasets for Kwazulu-Natal on average decreases in size by 3 kW of PV panels and 32 batteries when the 1500 Ah battery was used for simulation purposes as opposed to the 600Ah battery. This amounts to on average a decrease in initial capital of R 121,160.

It is therefore evident that the choice of the battery size used when designing solar energy systems is critical to determine the feasibility of the system in terms of practical design considerations (eg: spatial and maintenance issues) and overall cost.

7.3 Optimum System Design for Three Datasets

The table below represents the summary of all optimum system designs with a comparison between the optimum ground monitored system design and the optimum satellite based system design.

Table 56: System Design Comparison

Stellenbosch	**PV Array (kW)**	**Num of batteries (1,500 Ah)**	**Converter (kW)**	**Initial Capital (R)**
Sonbessie - Ground Monitored Optimum Design	20	54	6	830,570
SODA - Satellite Derived Optimum Design	15	54	6	680,570
NASA SSE - Satellite Derived Optimum Design	17	42	6	698,210
	% Difference	**% Difference**	**% Difference**	**% Difference**
SODA Design - % Diff to Ground Monitored Design	-25%	0	0	-18%
NASA SSE - % Diff to Ground Monitored Design	-15%	-22%	0	-16%
Average % Diff	**-20%**	**-11%**	**0**	**-17%**
Kwazulu-Natal	**PV Array (kW)**	**Num of batteries (1,500 Ah)**	**Converter (kW)**	**Initial Capital (R)**
Howard - Ground Monitored Optimum Design	12	66	6	632,930
SODA -Satellite Derived Optimum Design	12	54	6	590,570
NASA SSE - Satellite Derived Optimum Design	13	54	6	620,570
	% Difference	**% Difference**	**% Difference**	**% Difference**
SODA Design - % Diff to Ground Monitored Design	0	-18%	0	-7%
NASA SSE - % Diff to Ground Monitored Design	+8%	-18%	0	-2%
Average % Diff	**+4%**	**-18%**	**0**	**-4%**
Combined Average % Difference for Both Locations	**-8%**	**-15%**	**0**	**-11%**

From the table above, it is evident that on average for both geographical locations the satellite based system designs under specify the sizing of the system components by 8% for the PV panels and 15% for the number of batteries when compared to the required ground monitored system design. The converter stayed constant for all designs due to the fact that the peak load for the facility was 5.6 kVA and a 6 kVA converter was therefore suitable for all system designs. The difference in initial capital for the satellite based system designs is on average 11% cheaper in cost compared to the ground based system due to the reduced sizing of components.

As previously mentioned, the ground monitored solar irradiation system will be viewed as the optimum system design to install at each specific geographical location due to the fact that a ground monitoring station measures the actual solar irradiation at ground level as if it were to be a solar panel sitting on a roof of a facility receiving solar irradiation throughout the day.

It is therefore plausible to suggest that if satellite based data is used to design a solar energy system for off grid applications that the user increases the sizing of the PV array by 8% and the number of batteries by 15% to ensure the system can meet the facilities daily load consistently throughout the year. The main reason for this is the satellite based data has been seen on average to over predict the available daily solar irradiation.

7.4 Electrical Performance

When examining the electrical performance of the lowest capital cost satellite based system design under the ground monitored solar irradiation data set for each location, the main factor to assess the actual performance of the system is the annual capacity shortage factor.

Table 57: Capacity Shortage Comparison

Stellenbosch	**Sonbessie Optimum Design- Sonbessie Solar Data**	**SODA Optimum Design- Sonbessie Solar Data**	**Percentage Difference (%)**
Capacity Shortage (kWh/yr)	11.6	422	+ 3537.9
Capacity shortage (%)	0	3.3	+ 3.3
Kwazulu-Natal	**Howard Optimum Design- Howard Solar Data**	**SODA Optimum Design- Howard Solar Data**	**Percentage Difference (%)**
Capacity Shortage (kWh/yr)	8.31	34.8	+ 76.1
Capacity shortage (%)	0	0	0

When looking at the information presented in the table above, it is evident that the satellite based design (SODA) for Stellenbosch was not able to meet the loads demand throughout the year when the ground monitored solar data is applied to the system. The difference in initial capital from the ground based optimum system design verse the satellite based optimum system design is R150,000, which ultimately ends up in a 3.3% capacity shortage over the years operation.

The Kwazulu-Natal satellite based design however does not experience significant capacity shortage when compared to the ground based system even though the satellite system design differs by 12 batteries.

Therefore when designing a solar energy system, the source and method of capturing the solar irradiation data could potentially have a negative effect on the electrical performance of the system when it is installed in a real world situation depending on the geographical location.

7.5 Cost of Energy

The cost of energy for each solar energy system design is an annualised cost of energy based on the initial capital cost of the system and replacement and salvage costs of the system components over the 25 year lifespan of the project.

The table below represents the cost of energy for each optimum system design for both geographical locations. A comparison is made to the actual Eskom residential tariff for both geographical locations, to compare the costs of being connected to the national grid verse going completely off grid with a solar energy system [28, 29].

Table 58: Cost of Energy Comparison

Stellenbosch	**Off grid system- Cost of energy (R/kWh)**	**Current Eskom Tariff (R/kWh)**	**Difference (R/kWh)**	**Multiplication Factor (Off grid vs Eskom)**
Sonbessie- optimum system design	5.78	0.995	4.79	5.8
SODA- optimum system design	4.75	0.995	3.76	4.8
NASA SSE- optimum system design	4.87	0.995	3.88	4.9
Kwazulu-Natal				
Howard- optimum system design	4.42	1.06	3.36	4.2
SODA- optimum system design	4.12	1.06	3.06	3.9
NASA SSE- optimum system design	4.33	1.06	3.27	4.1
Average	**4.71**	**1.03**	**3.68**	**4.6**

From the table above, the average cost of energy for the six different solar energy systems is 4.71 R/kWh verse the average cost of 1.03 R/kWh for an Eskom based residential connection. Therefore, on average an off grid solar energy system is 4.6 times more expensive to run when compared to a typical Eskom based residential energy tariff.

7.6 Final Words

Through the research of this paper, it has been concluded that it is both technically and financially feasible to take a residential load off grid using solar energy. However, when compared to the traditional method of supplying electricity to a residential house such as the use of a national grid connection, solar energy is still significantly more expensive to run in terms of cost per kWh.

When making the decision in terms of which solar irradiation dataset to use when modelling a solar energy system, one needs to first assess the risk or impact that may arise by either over estimating or under estimating the amount of available solar energy available for a specific location. By using a dataset that over estimates the amount of solar irradiation available at a specific location, this will ultimately end up in a system design with a smaller PV array or reduced number of batteries used for storage purposes. When this specific system is introduced in a real world scenario where there is less solar irradiation available then what the system was designed for, this will ultimately lead to capacity shortages where the system will not be able to meet the loads demand at all times throughout the year. Relating this back to the risk or impact that this capacity shortage may have on the end user will ultimately depend on the primary use for the solar energy system. For a residential application, this capacity shortage may not be as critical to the inhabitants to actually merit the extra capital expenditure to increase the size of the system components to ensure the loads demand is met year round. However, if the solar energy system was designed for an off grid commercial application such as a farms packaging or production warehouse, any capacity shortages could have major implications on the production of the facility which then may lead to significant financial losses.

In conclusion, when designing solar energy systems it is critical to perform a sensitivity analyses to determine how the systems architecture, electrical performance and capital cost will be affected depending on the type of battery used and if expected amount of available solar irradiation had to differ significantly from the actual available solar irradiation at a specific location.

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10 APPENDIX A .... LOAD PROFILE USED IN SIMULATION

Time	Load kW L1 (kW)
00:00:00	0.3
00:58:34	0.1
01:58:30	0.2
02:58:28	0.1
03:58:24	0
04:58:22	0.3
05:58:20	0
06:58:16	2.4
07:58:14	0.6
08:58:10	4.3
09:58:08	5.6
10:58:06	3.2
11:58:02	1.6
12:58:00	0.3
13:57:58	2.0
14:57:54	0.4
15:57:52	0.8
16:57:48	3.9
17:57:46	1.8
18:57:44	1.7
19:57:40	1.9
20:57:38	2.2
21:57:34	0.9
22:57:32	0.7
23:57:30	0

11 APPENDIX B .... SCREENSHOTS

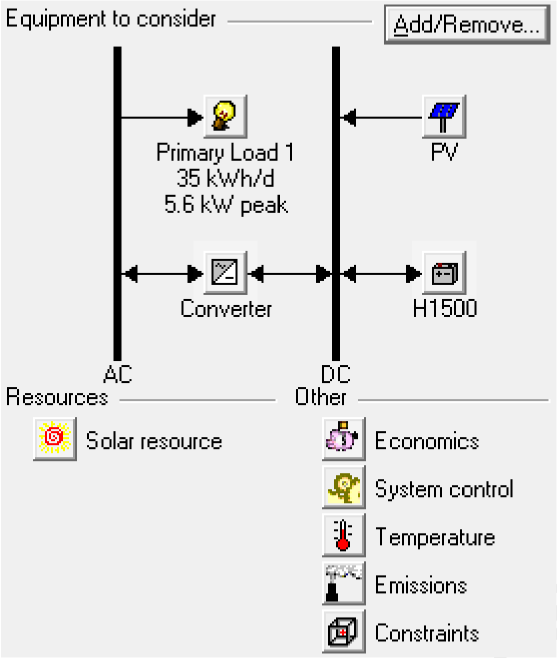
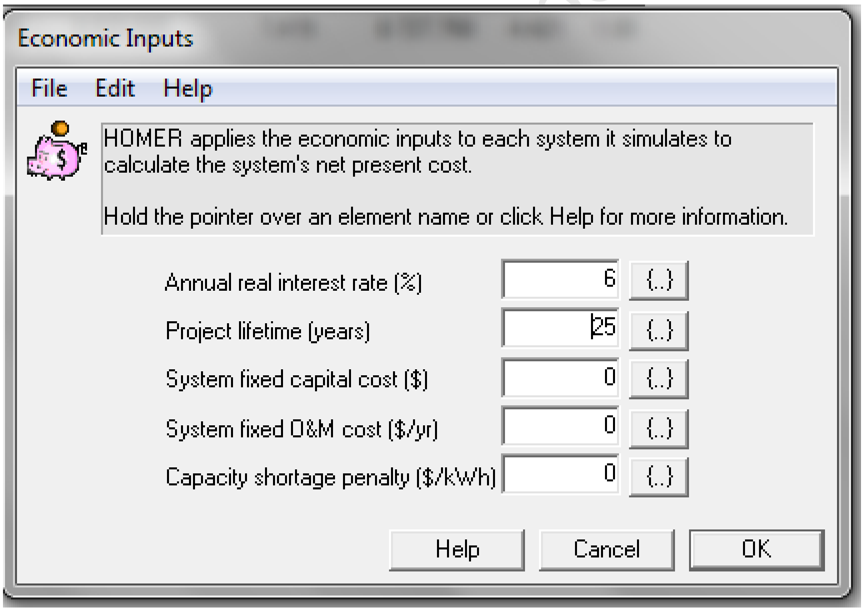


Figure 14: Parameter Inclusion Prompt

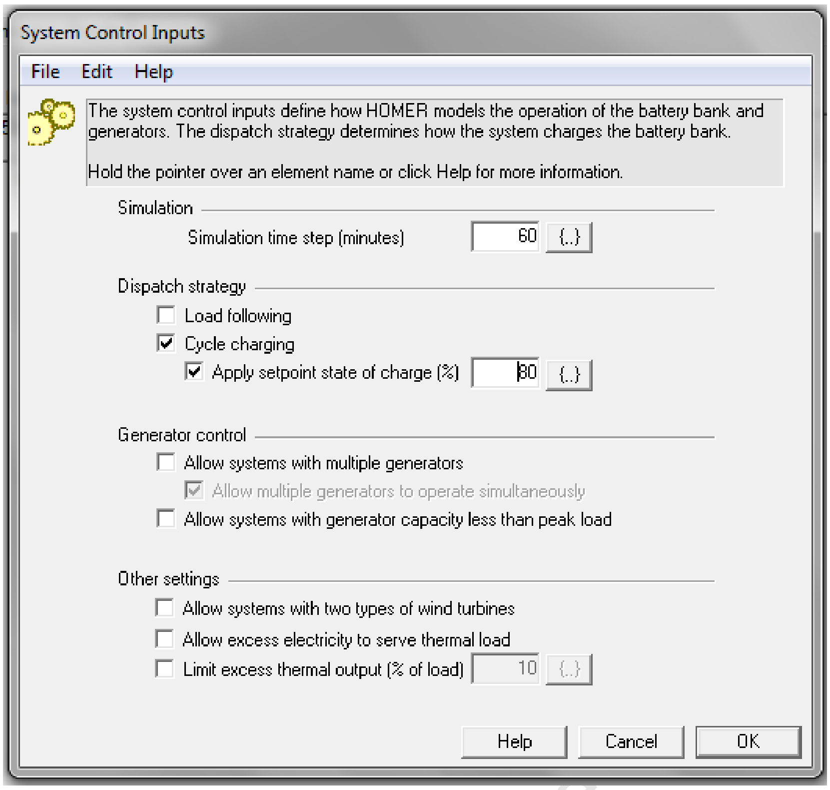


HOMER applies the economic inputs to each system it simulates to calculate the system's net present cost.

Hold the pointer over an element name or click Help for more information.

Annual real interest rate (%)	6	{..}
Project lifetime (years)	25	{..}
System fixed capital cost ($)	0	{..}
System fixed O&M cost ($/yr)	0	{..}
Capacity shortage penalty ($/kWh)	0	{..}

Figure 15: Economics Input Window



The system control inputs define how HOMER models the operation of the battery bank and generators. The dispatch strategy determines how the system charges the battery bank.

Hold the pointer over an element name or click Help for more information.

Simulation

Simulation time step (minutes) 60 {..}

Dispatch strategy

☐ Load following
☑ Cycle charging
☑ Apply setpoint state of charge (%) 80 {..}

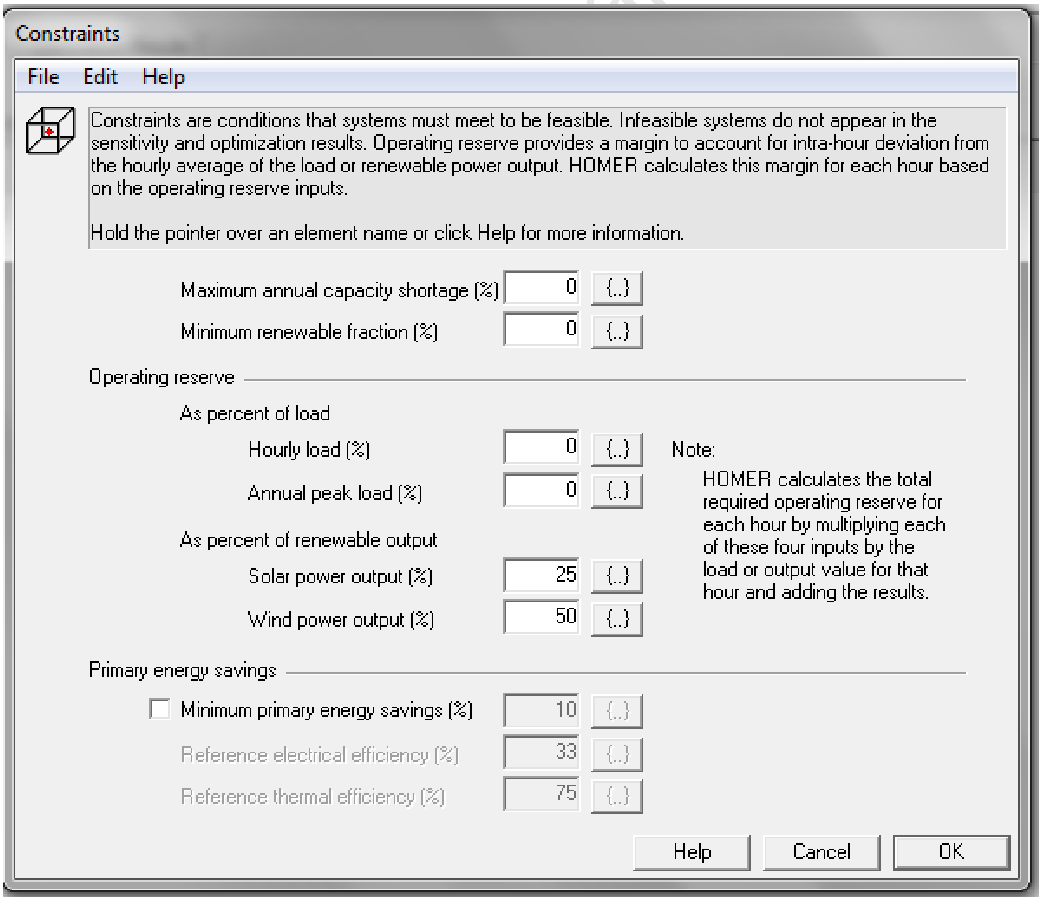
Generator control

☐ Allow systems with multiple generators
☑ Allow multiple generators to operate simultaneously
☐ Allow systems with generator capacity less than peak load

Other settings

☐ Allow systems with two types of wind turbines
☐ Allow excess electricity to serve thermal load
☐ Limit excess thermal output (% of load) 10 {..}

Figure 16: System Control Input Window



Constraints are conditions that systems must meet to be feasible. Infeasible systems do not appear in the sensitivity and optimization results. Operating reserve provides a margin to account for intra-hour deviation from the hourly average of the load or renewable power output. HOMER calculates this margin for each hour based on the operating reserve inputs.

Hold the pointer over an element name or click Help for more information.

Maximum annual capacity shortage (%) 0 {..}
Minimum renewable fraction (%) 0 {..}

Operating reserve

As percent of load
Hourly load (%) 0 {..}
Annual peak load (%) 0 {..}

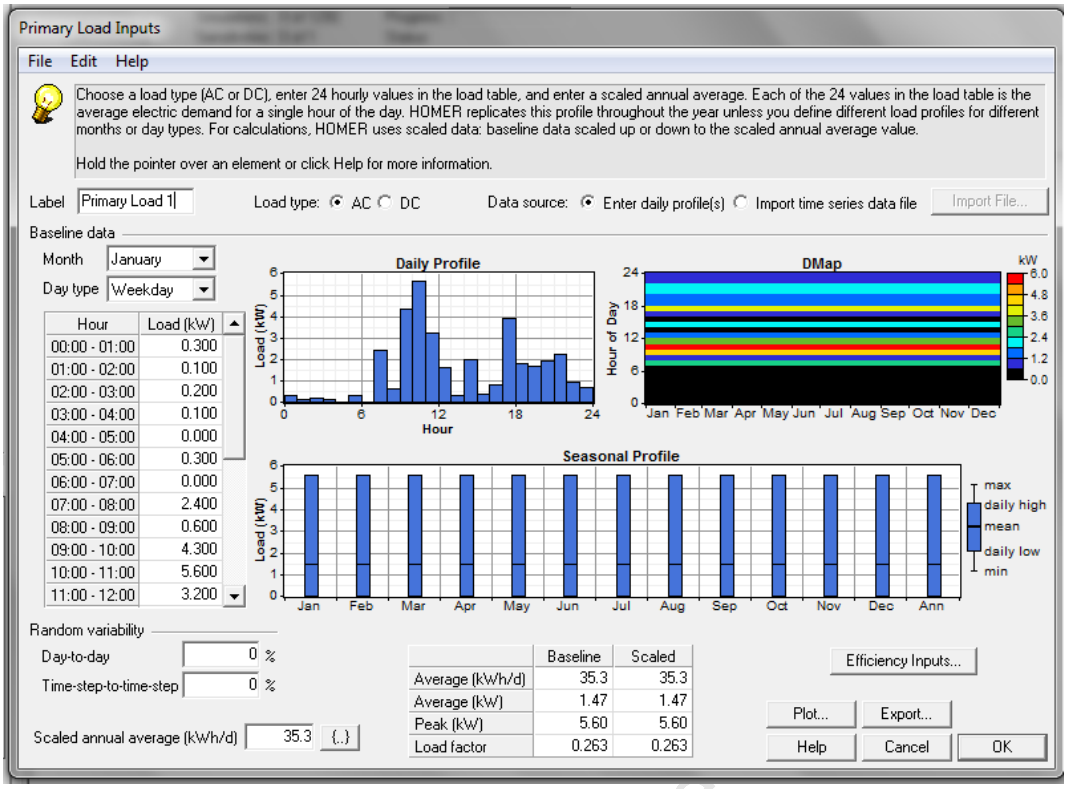
As percent of renewable output
Solar power output (%) 25 {..}
Wind power output (%) 50 {..}

Note:
HOMER calculates the total required operating reserve for each hour by multiplying each of these four inputs by the load or output value for that hour and adding the results.

Primary energy savings

☐ Minimum primary energy savings (%) 10 {..}
Reference electrical efficiency (%) 33 {..}
Reference thermal efficiency (%) 75 {..}

Figure 17: System Constraints Input Window



Choose a load type (AC or DC), enter 24 hourly values in the load table, and enter a scaled annual average. Each of the 24 values in the load table is the average electric demand for a single hour of the day. HOMER replicates this profile throughout the year unless you define different load profiles for different months or day types. For calculations, HOMER uses scaled data: baseline data scaled up or down to the scaled annual average value.

Hold the pointer over an element or click Help for more information.

Label: Primary Load 1

Load type: ● AC ○ DC

Data source: ● Enter daily profile(s) ○ Import time series data file

Baseline data

Month: January

Day type: Weekday

Hour	Load (kW)
00:00 - 01:00	0.300
01:00 - 02:00	0.100
02:00 - 03:00	0.200
03:00 - 04:00	0.100
04:00 - 05:00	0.000
05:00 - 06:00	0.300
06:00 - 07:00	0.000
07:00 - 08:00	2.400
08:00 - 09:00	0.600
09:00 - 10:00	4.300
10:00 - 11:00	5.600
11:00 - 12:00	3.200

Random variability

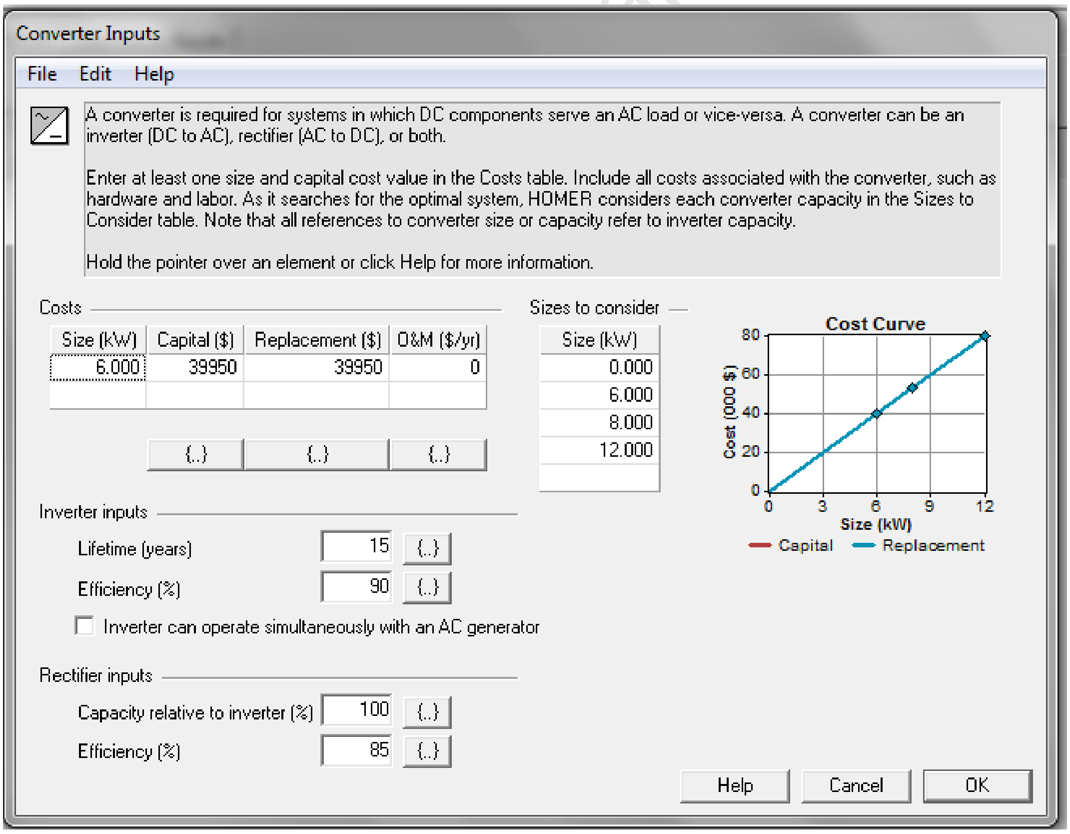
Day-to-day: 0 %

Time-step-to-time-step: 0 %

Scaled annual average (kWh/d): 35.3 {..}

	Baseline	Scaled
Average (kWh/d)	35.3	35.3
Average (kW)	1.47	1.47
Peak (kW)	5.60	5.60
Load factor	0.263	0.263

Figure 18: Load Profile Input Window



A converter is required for systems in which DC components serve an AC load or vice-versa. A converter can be an inverter (DC to AC), rectifier (AC to DC), or both.

Enter at least one size and capital cost value in the Costs table. Include all costs associated with the converter, such as hardware and labor. As it searches for the optimal system, HOMER considers each converter capacity in the Sizes to Consider table. Note that all references to converter size or capacity refer to inverter capacity.

Hold the pointer over an element or click Help for more information.

Costs

Size (kW)	Capital ($)	Replacement ($)	O&M ($/yr)
6.000	39950	39950	0

Sizes to consider

Size (kW)
0.000
6.000
8.000
12.000

Inverter inputs

Lifetime (years): 15 {..}

Efficiency (%): 90 {..}

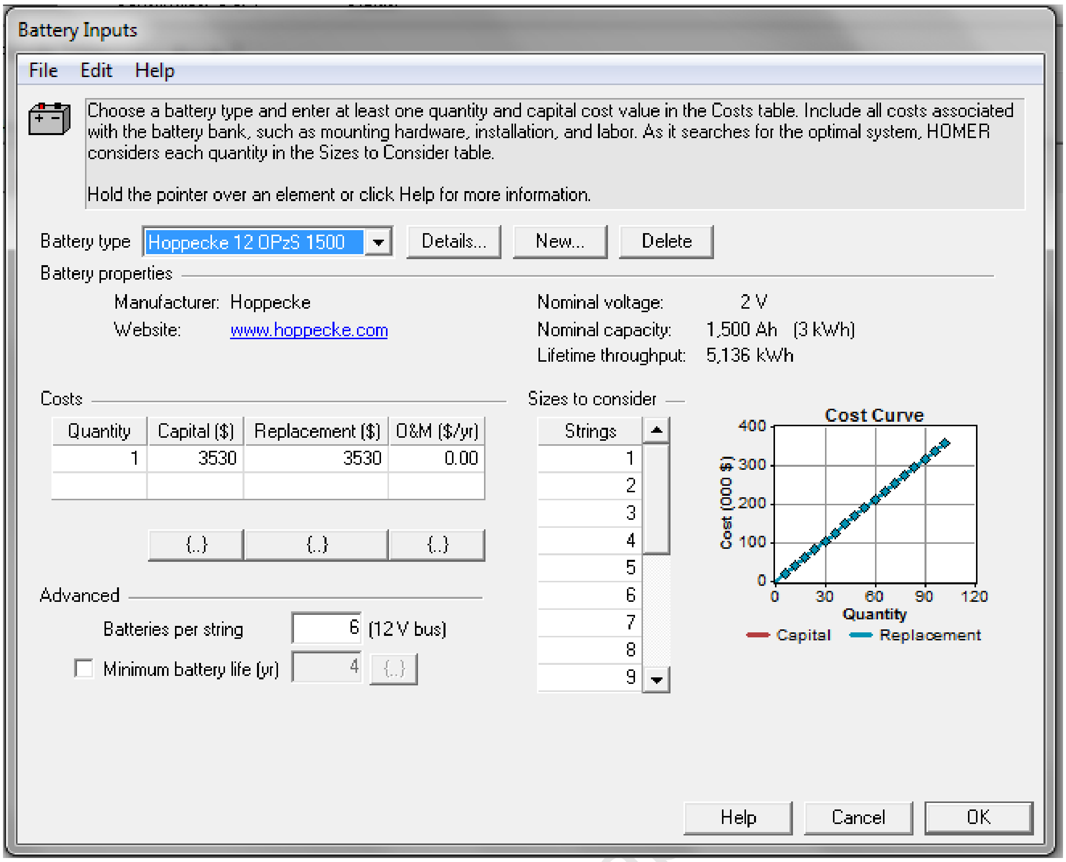
☐ Inverter can operate simultaneously with an AC generator

Rectifier inputs

Capacity relative to inverter (%): 100 {..}

Efficiency (%): 85 {..}

Figure 19: Converter Sizing Input Window



Choose a battery type and enter at least one quantity and capital cost value in the Costs table. Include all costs associated with the battery bank, such as mounting hardware, installation, and labor. As it searches for the optimal system, HOMER considers each quantity in the Sizes to Consider table.

Hold the pointer over an element or click Help for more information.

Battery type: Hoppecke 12 OPzS 1500

Battery properties

Manufacturer: Hoppecke
Website: www.hoppecke.com
Nominal voltage: 2 V
Nominal capacity: 1,500 Ah (3 kWh)
Lifetime throughput: 5,136 kWh

Costs

Quantity	Capital ($)	Replacement ($)	O&M ($/yr)
1	3530	3530	0.00

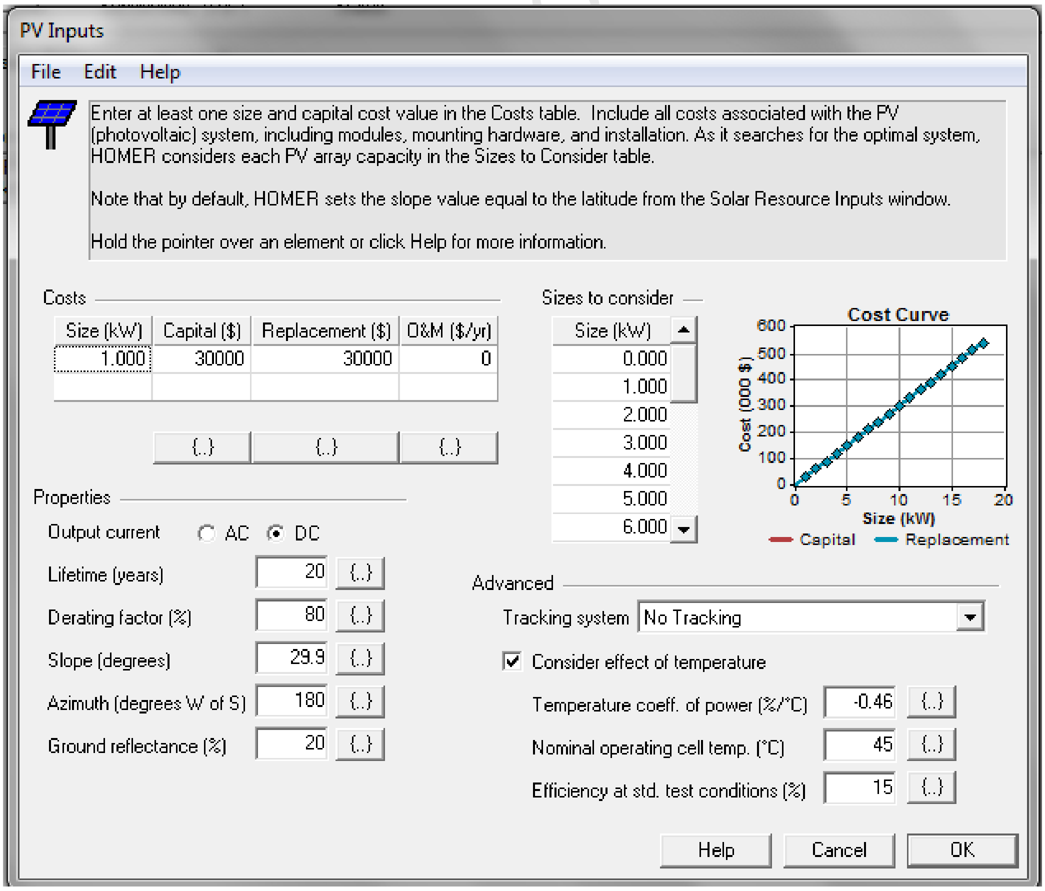
Sizes to consider

Strings
1
2
3
4
5
6
7
8
9

Advanced

Batteries per string: 6 (12 V bus)
☐ Minimum battery life (yr): 4

Figure 20: Battery Input Parameter Window



Enter at least one size and capital cost value in the Costs table. Include all costs associated with the PV (photovoltaic) system, including modules, mounting hardware, and installation. As it searches for the optimal system, HOMER considers each PV array capacity in the Sizes to Consider table.

Note that by default, HOMER sets the slope value equal to the latitude from the Solar Resource Inputs window.

Hold the pointer over an element or click Help for more information.

Costs

Size (kW)	Capital ($)	Replacement ($)	O&M ($/yr)
1.000	30000	30000	0

Sizes to consider

Size (kW)
0.000
1.000
2.000
3.000
4.000
5.000
6.000

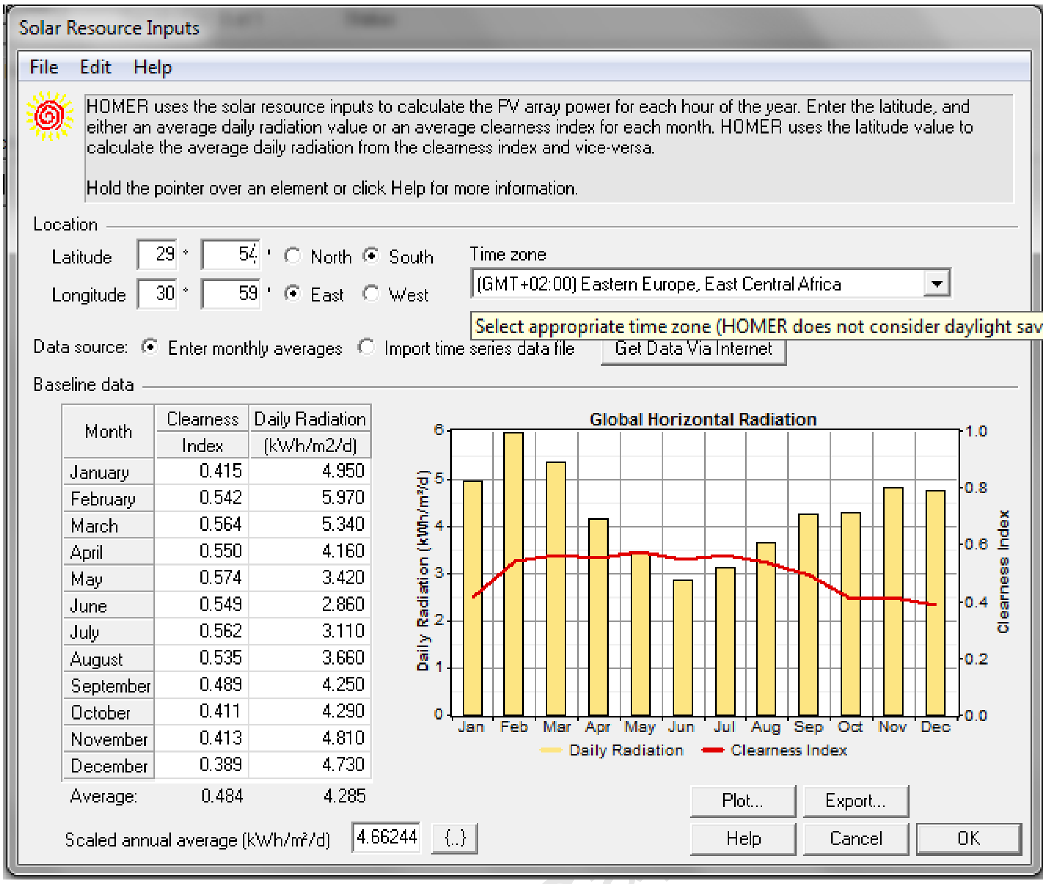
Properties

Output current ○ AC ● DC
Lifetime (years): 20
Derating factor (%): 80
Slope (degrees): 29.9
Azimuth (degrees W of S): 180
Ground reflectance (%): 20

Advanced

Tracking system: No Tracking
☑ Consider effect of temperature
Temperature coeff. of power (%/°C): -0.46
Nominal operating cell temp. (°C): 45
Efficiency at std. test conditions (%): 15

Figure 21: Solar Panel Parameter Input Window



HOMER uses the solar resource inputs to calculate the PV array power for each hour of the year. Enter the latitude, and either an average daily radiation value or an average clearness index for each month. HOMER uses the latitude value to calculate the average daily radiation from the clearness index and vice-versa.

Hold the pointer over an element or click Help for more information.

Location

Latitude 29 ° 54 ' ○ North ● South

Longitude 30 ° 59 ' ● East ○ West

Time zone (GMT+02:00) Eastern Europe, East Central Africa

Select appropriate time zone (HOMER does not consider daylight sav

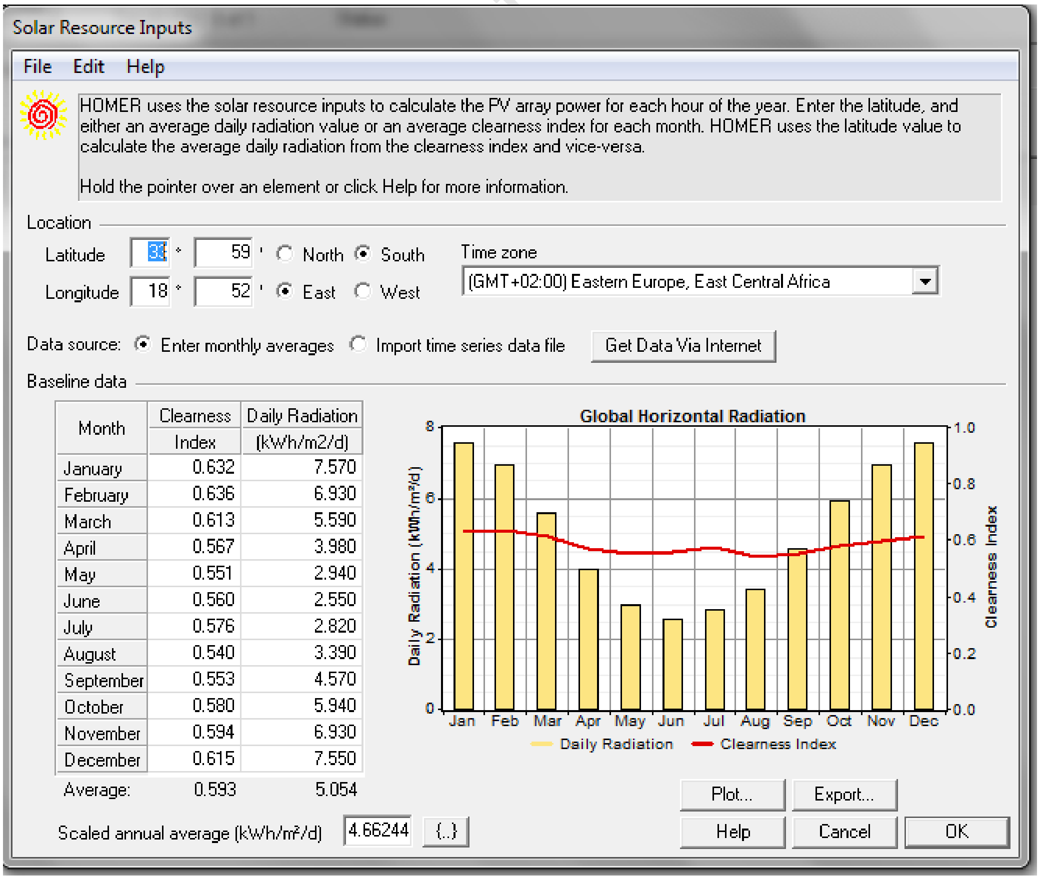
Data source: ● Enter monthly averages ○ Import time series data file

Baseline data

Month	Clearness Index	Daily Radiation (kWh/m2/d)
January	0.415	4.950
February	0.542	5.970
March	0.564	5.340
April	0.550	4.160
May	0.574	3.420
June	0.549	2.860
July	0.562	3.110
August	0.535	3.660
September	0.489	4.250
October	0.411	4.290
November	0.413	4.810
December	0.389	4.730
Average:	0.484	4.285

Scaled annual average (kWh/m²/d) 4.66244

Figure 22: Sonbessie Solar Irradiation Input Window



HOMER uses the solar resource inputs to calculate the PV array power for each hour of the year. Enter the latitude, and either an average daily radiation value or an average clearness index for each month. HOMER uses the latitude value to calculate the average daily radiation from the clearness index and vice-versa.

Hold the pointer over an element or click Help for more information.

Location

Latitude 33 ° 59 ' ○ North ● South

Longitude 18 ° 52 ' ● East ○ West

Time zone (GMT+02:00) Eastern Europe, East Central Africa

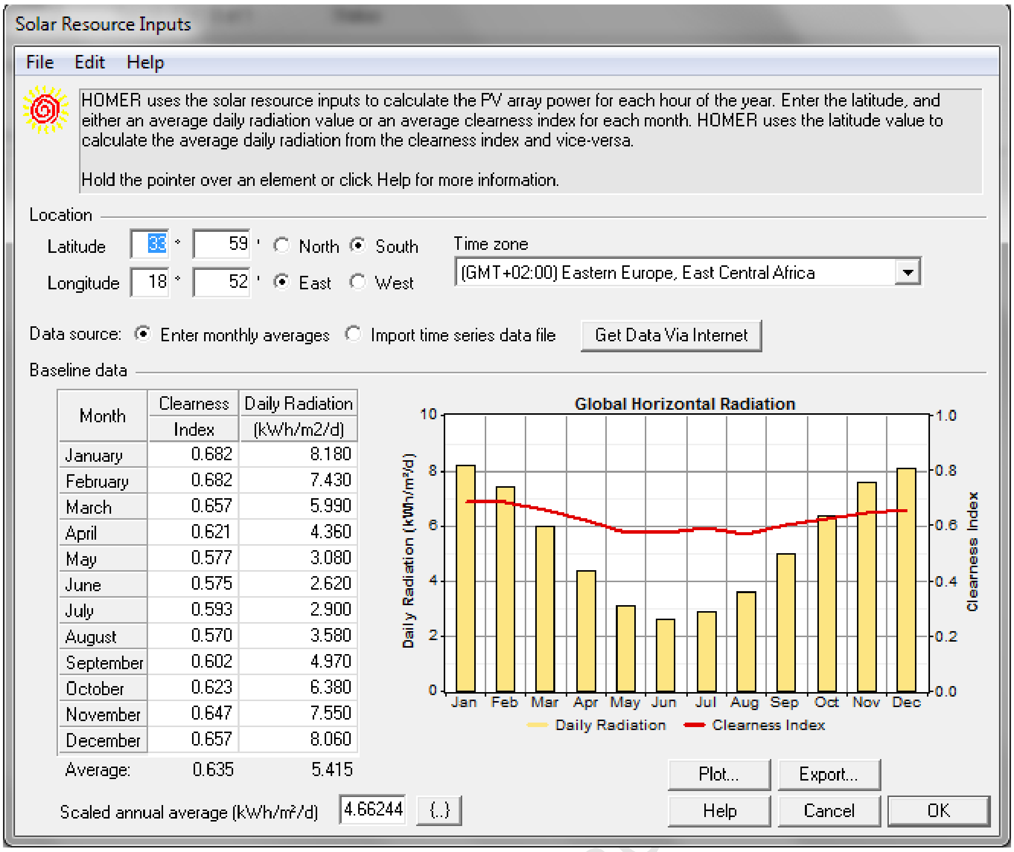
Data source: ● Enter monthly averages ○ Import time series data file

Baseline data

Month	Clearness Index	Daily Radiation (kWh/m2/d)
January	0.632	7.570
February	0.636	6.930
March	0.613	5.590
April	0.567	3.980
May	0.551	2.940
June	0.560	2.550
July	0.576	2.820
August	0.540	3.390
September	0.553	4.570
October	0.580	5.940
November	0.594	6.930
December	0.615	7.550
Average:	0.593	5.054

Scaled annual average (kWh/m²/d) 4.66244

Figure 23: SODA Stellenbosch Solar Irradiation Input Window



HOMER uses the solar resource inputs to calculate the PV array power for each hour of the year. Enter the latitude, and either an average daily radiation value or an average clearness index for each month. HOMER uses the latitude value to calculate the average daily radiation from the clearness index and vice-versa.

Hold the pointer over an element or click Help for more information.

Location

Latitude 33 ° 59 ' ○ North ● South

Longitude 18 ° 52 ' ● East ○ West

Time zone: (GMT+02:00) Eastern Europe, East Central Africa

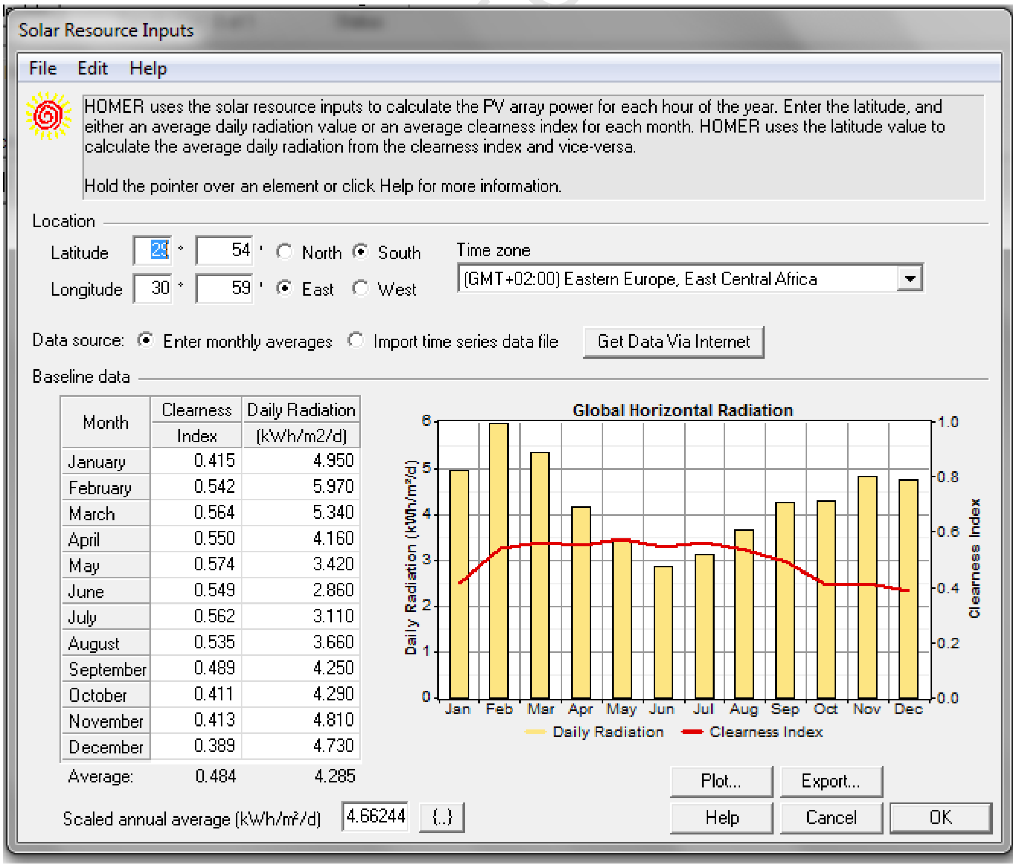
Data source: ● Enter monthly averages ○ Import time series data file

Baseline data

Month	Clearness Index	Daily Radiation (kWh/m2/d)
January	0.682	8.180
February	0.682	7.430
March	0.657	5.990
April	0.621	4.360
May	0.577	3.080
June	0.575	2.620
July	0.593	2.900
August	0.570	3.580
September	0.602	4.970
October	0.623	6.380
November	0.647	7.550
December	0.657	8.060
Average:	0.635	5.415

Scaled annual average (kWh/m²/d) 4.66244

Figure 24: NASA SSE Stellenbosch Solar Irradiation Input Window



HOMER uses the solar resource inputs to calculate the PV array power for each hour of the year. Enter the latitude, and either an average daily radiation value or an average clearness index for each month. HOMER uses the latitude value to calculate the average daily radiation from the clearness index and vice-versa.

Hold the pointer over an element or click Help for more information.

Location

Latitude 29 ° 54 ' ○ North ● South

Longitude 30 ° 59 ' ● East ○ West

Time zone: (GMT+02:00) Eastern Europe, East Central Africa

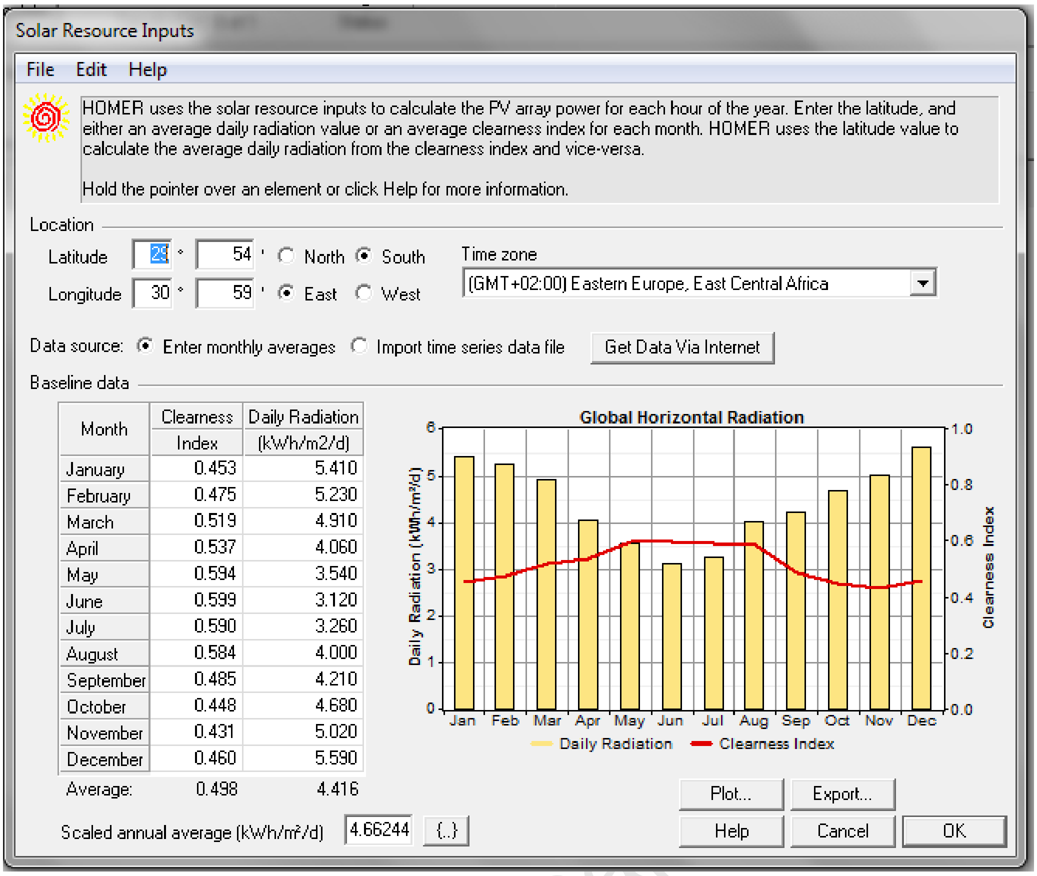
Data source: ● Enter monthly averages ○ Import time series data file

Baseline data

Month	Clearness Index	Daily Radiation (kWh/m2/d)
January	0.415	4.950
February	0.542	5.970
March	0.564	5.340
April	0.550	4.160
May	0.574	3.420
June	0.549	2.860
July	0.562	3.110
August	0.535	3.660
September	0.489	4.250
October	0.411	4.290
November	0.413	4.810
December	0.389	4.730
Average:	0.484	4.285

Scaled annual average (kWh/m²/d) 4.66244

Figure 25: Howard KZN Solar Irradiation Input Window



HOMER uses the solar resource inputs to calculate the PV array power for each hour of the year. Enter the latitude, and either an average daily radiation value or an average clearness index for each month. HOMER uses the latitude value to calculate the average daily radiation from the clearness index and vice-versa.

Hold the pointer over an element or click Help for more information.

Location

Latitude 29 ° 54 ' ○ North ● South

Longitude 30 ° 59 ' ● East ○ West

Time zone (GMT+02:00) Eastern Europe, East Central Africa

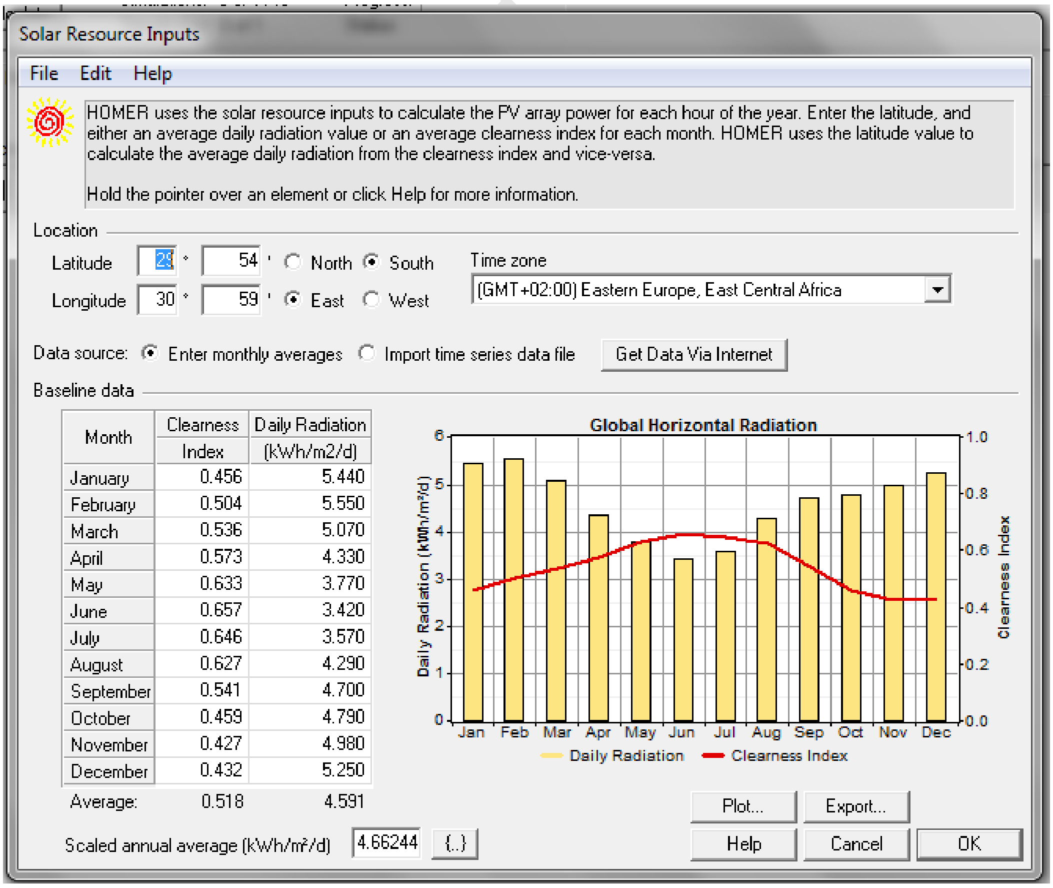
Data source: ● Enter monthly averages ○ Import time series data file

Baseline data

Month	Clearness Index	Daily Radiation (kWh/m2/d)
January	0.453	5.410
February	0.475	5.230
March	0.519	4.910
April	0.537	4.060
May	0.594	3.540
June	0.599	3.120
July	0.590	3.260
August	0.584	4.000
September	0.485	4.210
October	0.448	4.680
November	0.431	5.020
December	0.460	5.590
Average:	0.498	4.416

Scaled annual average (kWh/m²/d) 4.66244

Figure 26: SODA KZN Solar Irradiation Input Window



HOMER uses the solar resource inputs to calculate the PV array power for each hour of the year. Enter the latitude, and either an average daily radiation value or an average clearness index for each month. HOMER uses the latitude value to calculate the average daily radiation from the clearness index and vice-versa.

Hold the pointer over an element or click Help for more information.

Location

Latitude 29 ° 54 ' ○ North ● South

Longitude 30 ° 59 ' ● East ○ West

Time zone (GMT+02:00) Eastern Europe, East Central Africa

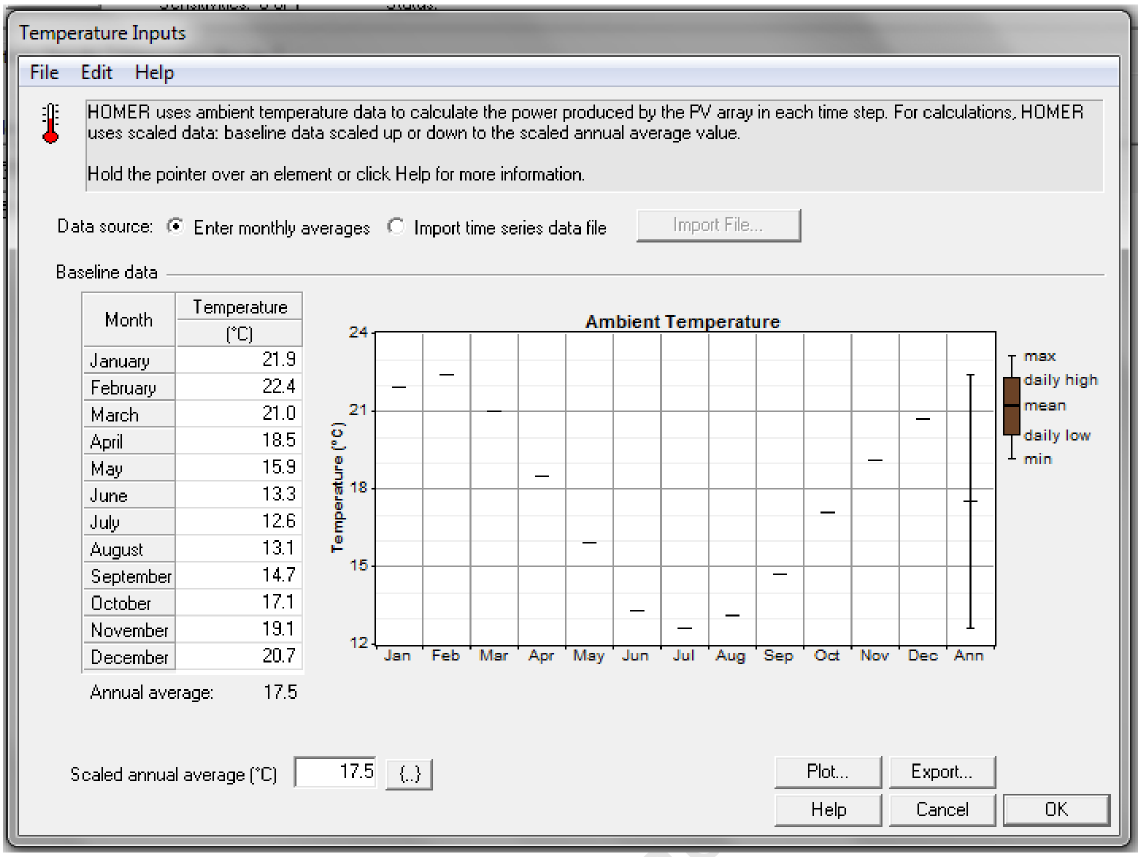
Data source: ● Enter monthly averages ○ Import time series data file

Baseline data

Month	Clearness Index	Daily Radiation (kWh/m2/d)
January	0.456	5.440
February	0.504	5.550
March	0.536	5.070
April	0.573	4.330
May	0.633	3.770
June	0.657	3.420
July	0.646	3.570
August	0.627	4.290
September	0.541	4.700
October	0.459	4.790
November	0.427	4.980
December	0.432	5.250
Average:	0.518	4.591

Scaled annual average (kWh/m²/d) 4.66244

Figure 27: NASA SSE KZN Solar Irradiation Input Window



HOMER uses ambient temperature data to calculate the power produced by the PV array in each time step. For calculations, HOMER uses scaled data: baseline data scaled up or down to the scaled annual average value.

Hold the pointer over an element or click Help for more information.

Data source: ● Enter monthly averages ○ Import time series data file

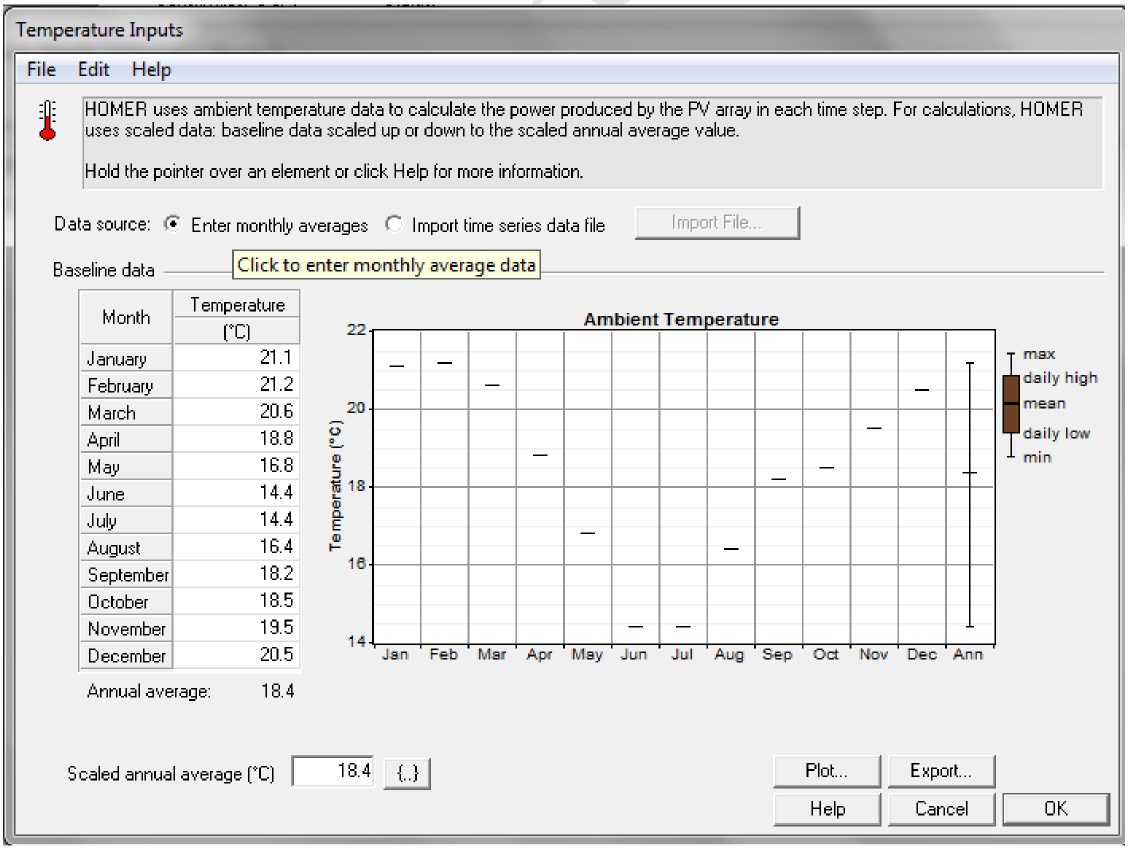
Baseline data

Month	Temperature (°C)
January	21.9
February	22.4
March	21.0
April	18.5
May	15.9
June	13.3
July	12.6
August	13.1
September	14.7
October	17.1
November	19.1
December	20.7

Annual average: 17.5

Scaled annual average (°C) 17.5

Figure 28: Stellenbosch Ambient Temperature Input Window



HOMER uses ambient temperature data to calculate the power produced by the PV array in each time step. For calculations, HOMER uses scaled data: baseline data scaled up or down to the scaled annual average value.

Hold the pointer over an element or click Help for more information.

Data source: ● Enter monthly averages ○ Import time series data file

Baseline data

Click to enter monthly average data

Month	Temperature (°C)
January	21.1
February	21.2
March	20.6
April	18.8
May	16.8
June	14.4
July	14.4
August	16.4
September	18.2
October	18.5
November	19.5
December	20.5

Annual average: 18.4

Scaled annual average (°C) 18.4

Figure 29: KZN Ambient Temperature Input Window