DESIGN AND DEVELOPMENT OF A SOLAR POWERED IRRIGATION SYSTEM MODEL FOR SOUTH AFRICA

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I ....Piwe Piliso.. declare that:

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ABSTRACT

The main source of electricity in South Africa is coal, which is a fossil fuel that negatively impacts the environment and contributes to global warming. The demand for electricity from various sectors of the economy, including agriculture has significantly increased over the years. In South Africa, irrigation consumes most freshwater in the agricultural sector. In addition, most irrigation systems in the country require electrical power to operate. Recently, the country has been experiencing load shedding, which has been affecting farming production negatively. Increases in electricity tariffs increased irrigation costs, thus reducing farm profitability. South Africa receives high levels of solar radiation which can be captured to produce solar energy. Solar energy is a clean renewable energy source that is used as an alternative power source. There is a notable increase in the development of solar powered irrigation systems in the country. There is a lack of research done on the integration of solar power with irrigation in South Africa. This study aimed to first investigate the extent of solar powered irrigation in South Africa and then develop a model to size solar powered irrigation systems (SPIS) for South Africa. The extent of SPIS was investigated using of an online survey tool SurveyMonkey®. The SPIS model was developed in MS Excel and its Visual Basic Application (VBS). The crop water requirements were determined by the use of CropWAT. The climatic data were obtained using the NASA Prediction of Worldwide Energy Resource (POWER) database and CLIMWAT. Three SPIS configurations were implemented into the model for design options for the user. The model was tested for 6 climatic regions and 6 different crops and the results were compared amongst each other. The participants targeted for the survey were SPIS users, SPIS engineers, designers and installers, SPIS former users and SPIS potential users. The total number of respondents that participated and completed the questionnaires were 18 SPIS engineers, installers and designers and 13 SPIS users (farmers). SPIS engineers, installers and designers' results showed that most SPIS they implemented were in the Western Cape and the Eastern Cape at 33 % for both provinces. SPIS engineers, installers and designers have also integrated SPIS mainly with drip and sprinkler irrigation at 33 % for both irrigation techniques. For the SPIS user results, 54 % of the respondents were commercial farmers. The results revealed that 92 % of the SPIS found in the survey were installed between 2010 and 2016. The total area of SPIS found in the survey is 364.415 ha. The dominant irrigation system from the SPIS users is drip and sprinkler irrigation both being 38 %. The

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implementation of SPIS reflected from the questionnaire was mainly motivated by the loadshedding and rise in electricity tariffs that occurred in South Africa. Most of the SPIS are integrated with irrigation techniques with high water use efficiency. A centre pivot irrigation system in the Durban region was used in the model to size the SPIS to irrigate maize. The components sized were for two of the three SPIS configurations, which were the direct-coupled system and the battery-coupled system. The performance of the battery pack and photovoltaic (PV) solar array were then simulated using the Photovoltaic Geographical Information System (PVGIS) tool. The simulated average energy output per day of the PV solar array was 0.11 % less than the average power required per day. The percentage of days when the battery is fully charged was simulated to be 61 % for the critical month of June for the power demand and solar power supply. The electrical power required to pump irrigation water for the six climatic zone scenarios was determined for the temperate coastal climatic zone. A drip irrigation system for grapes obtained the highest electrical power requirement for the direct-coupled system of 0.01809 $kW.mm^{-1}.ha^{-1}.m^{-1}$. The direct-coupled system required few components compared to the battery-coupled system, but the latter offers back up electrical power to operate the pump and SPIS has less solar panels than the direct-coupled system. A linear generic equation relating pump power requirements and the electrical solar power requirement was developed for the nine South African provinces. Of the nine provinces, the Western Cape province, showed that it required the highest solar panel power requirement for irrigation system with a critical month in the winter and with a gradient of the linear graph being 0.5366 and the least number of solar panels when designed for the summer with a gradient of the linear graph being 0.2381. The findings indicate there is SPIS in South Africa. The SPIS model was developed and can size the components of SPIS. The model was tested for different characteristics and a rule of thumb was developed to estimate the number of solar panels required for an irrigation system for a given pump power requirement.

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1. INTRODUCTION

South Africa has a total landmass of 122 million hectares and only 13 % of this area receives sufficient rainfall for dryland crop production (Greyling, *et al.*, 2015). In 2014/15, it was identified that 1 332 562 ha of cultivated land in South Africa is under irrigation, which equates to 1.1 % of South Africa's land surface (Bonthuys, 2018). The agricultural sector consumes 6 % of the energy available in South Africa and electricity accounts for 13 % of this energy (DoE, 2019).

When it comes to electricity, irrigation consumes the largest amount of electricity at 28 % of the agricultural sector (DoE, 2012). Since irrigation consumes the most electricity in the agricultural sector, efforts to reduce the use of electricity from the grid should be considered, such as the use of renewable energy. Using renewable energy technologies for water services such as irrigation in third world countries can address both the need for energy and the need for water services in the most vulnerable areas. Solar PV technology promotes irrigation management and is, therefore, the energy technology of choice for water-scarce remote areas which are not connected to the national electricity grid (Prasad *et al.*, 2012).

With the design of a solar powered irrigation system (SPIS) model, the most important parameters to accurately identify are the required hydraulic head of the system and the solar irradiation of the location during the irrigation months. These will lead to the optimal sizing of an SPIS. With optimal sizing, the system will not be too costly. Most irrigation systems in South Africa, specifically the ones located in commercial farms are powered from the national electricity grid. In 2008, South Africa experienced load shedding, which was a result of the country's worst ever energy crisis at the time. The agricultural sector was highly impacted by the 99 days of load shedding experienced in 2015 because of the drought in some parts of the country (Preez, 2015). Between 2014 and 2015, South Africa experienced an 8.2 % increase in the price of electricity, which was the second highest jump in the world (Writer, 2015a). The increase in electricity in South Africa from 2008 is illustrated in Figure 1.1. The use of SPIS in commercial farms would lead to farmers being less affected by the electricity price increases and load shedding.

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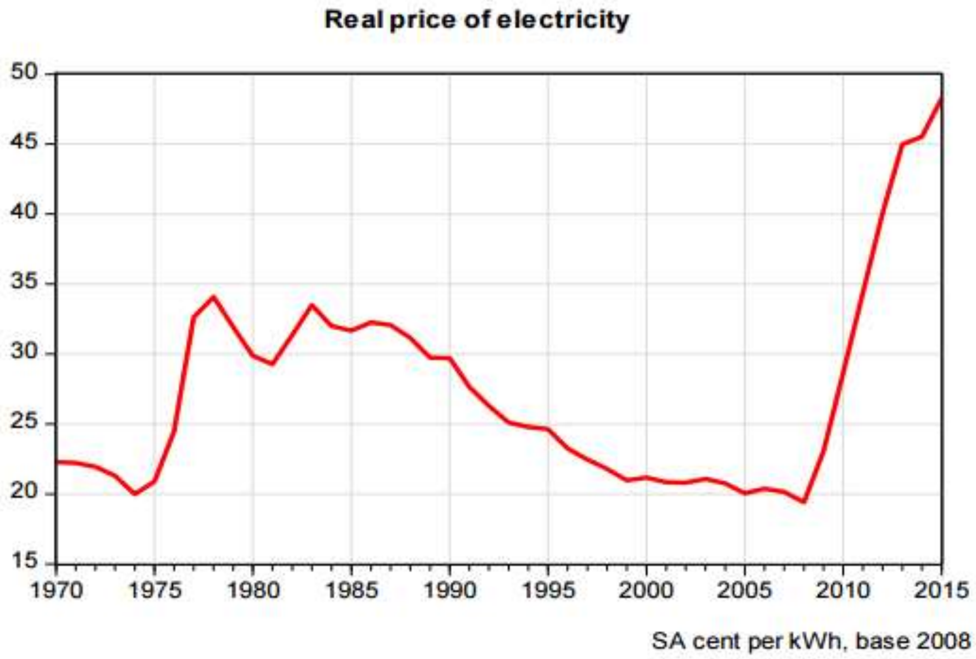

Figure 1.1 Electricity price trends from 1970-2015 in South Africa (Sookdin, 2016).

Despite the diminishing solar energy technology prices, as shown in Figure 1.2, the use of clean energy and having a water efficient system and no fuel and operational cost offered by SPIS in South Africa, there is insufficient research done on the implementation of SPIS. There is a need to develop a model that can assist in sizing a low-cost SPIS in South Africa. The SPIS model is needed to determine the technical limitations of SPIS technology in South Africa in terms of irrigation technique, crop type, soil characteristics and climatic conditions.

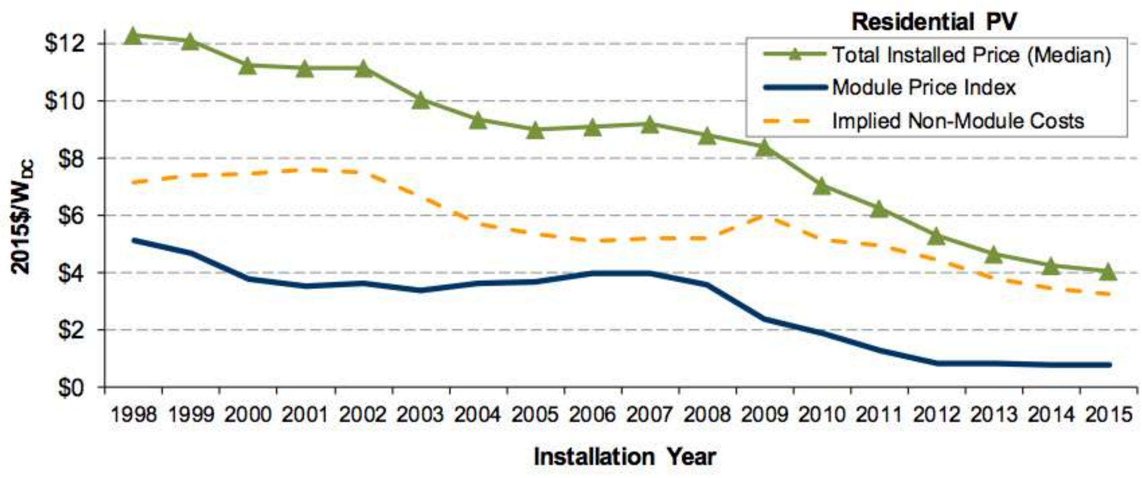

Figure 1.2 Solar technology price trends over time (Fares, 2016)

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Some off-the-shelf PV water pump kits are available for purchase in South Africa. Companies such as LORENTZ that have implemented photovoltaic water pumping systems (PVWPS) in some parts of the country, such as the Eastern Cape and Northern Cape, which range from small scale to large scale systems. The PVWPS are mainly integrated with stock watering and drinking water supply. The flow rate of these systems is between 7.3 $m^3.d^{-1}$ and 570 $m^3.d^{-1}$ (Lorentz, 2016).

The literature available for SPIS is mainly for small scale farmers in other countries such as India, Chile and Kenya not including South Africa. The large scale SPIS systems that have been implemented offer no design procedures for the implementation of SPIS. Drip irrigation has been the irrigation technology mostly integrated with solar power (Nederstigt and Bom, 2014; Kumbhaj *et al.*, 2017).

When the technical feasibility is determined, the economic feasibility of the system will be determined to make sure the system is financially viable and of low cost.

This project aimed to develop a model that will determine whether or not a solar powered irrigation system for a given irrigation technique that is located in South Africa is technically feasible, and identify the limitations of SPIS's in South Africa by sizing the solar panels and other components and comparing them to the current power supply of the irrigation system.

The specific objectives of the project are to:

a) determine the extent of SPIS implementation and the types of systems in use in South Africa,

b) develop a model to identify the most suitable or optimal low-cost SPIS, and

c) test the model for different climatic conditions, crop types and crop selections, soils, irrigation techniques and field size.

The structure of the thesis consists of Chapter 1, which provides the background of the study, the aims and objectives. Chapter 2 discusses the literature review of the study. There is limited literature on SPIS in South Africa compared to the literature internationally. Therefore, the study looks at irrigation practices and techniques; solar energy and technology and the different configurations of SPIS commonly used globally. Chapter 3 consists of an investigation to determine the extent of SPIS in South Africa where a questionnaire was developed and distributed to SPIS users and SPIS installers, engineers and designers. In Chapter 4, a model

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was developed to size SPIS in South Africa using MS Excel and its Visual Basic Application (VBA), which is used with CLIMWAT and CropWAT. Chapter 5 has the testing of the model using the 6 climatic zones in South Africa and the development of a rule of thumb to estimate the number of solar panels required for an irrigation system when given the pump power requirements. Chapter 6 discusses the summary, and conclusions of the study and recommendations for further research into solar powered irrigation.

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2. LITERATURE REVIEW

2.1 Introduction

The production of power from fossil fuels is a dominant course for carbon-based pollution and climate change. There has also been the rising of fossil fuel costs. As a result, the development of clean energy has progressed, which is in demand worldwide (Kelley *et al.*, 2010). One example of such a clean energy is solar energy. There is a large quantity of solar energy that penetrates the earth's atmosphere (Sontake and Kalamkar, 2016). In the last few years, solar energy has grown rapidly among other renewable energy sources. The solar energy sector has been expected to reach large scale competitiveness in less than 10 years (OECD/IEA, 2011).

The potential of solar energy in South Africa is very high as the country receives high levels of solar radiation with solar insolation rates ranging between 4.5 – 6.5 $kWh.m^{-2}$ (Chang *et al.*, 2011; FAO, 2015). The cost of solar system components has been constantly decreasing. This decrease has encouraged its use in various sectors.

In South Africa, the agricultural sector consumes 60 % of the water used in the country and consumes about 8 % of the total electricity (DoE, 2012). The Department of Water and Sanitation revealed that the irrigation sector consumes 60% of the total amount of water used in the agricultural sector (Writer, 2015b). The operational maintenance of irrigation systems contributes to the agricultural sector's energy and water consumption. The use of solar powered irrigation systems (SPIS) offers a chance to lower the energy and water consumption under irrigation systems. This is achieved using solar energy and the increased efficiency in water application (Williamson, 2006). The transportation of SPIS is simple compared to other types of renewable energy systems because the system can be transported in parts and put together on site. (Khatib, 2010).

SPIS is most appropriate to use in regions where there is a lack of electricity. Since the invention of solar powered water pumps, there have been developed in many parts of the world (Yahya and Sambo, 1995; Hammad, 1998; Deveci *et al.*, 2015). SPIS have been well studied and developed for very small farms. In 2003, a demonstration unit was installed by Shell and World Water and Power Corporation for a large scale farm (Kelley *et al.*, 2010). Besides this, solar powered irrigation systems for large-scale farms have not been implemented (Kelley *et al.*, 2010).

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Unlike diesel powered irrigation systems, SPIS can provide water for irrigation without fuel and there are minimal maintenance and repair requirements. The installation and operation processes are easy. The SPIS systems are highly reliable, long lasting and modular, which allows the possibility for further expansion in the future. The SPIS can be assembled at the site, rendering long pipes unnecessary (Shrestha, 1996; Andrada and Castro, 2008). Cuadros *et al.* (2004) developed a method to size an SPIS, which is based on climatic conditions of the region, the geographical location, soil quality and crop water requirements, which was applied to 10 hectares of an olive grove farm in Spain. The economic feasibility of this study was not evaluated.

2.2 Solar Energy

The use of solar energy is growing fast and the potential it possesses is huge. In the last few years, the growth of the solar energy sector has been rapid compared to other renewable energy sectors. Solar energy is expected to reach extensive competitiveness in no more than ten years, although, financial incentives are required for most applications at the moment (OECD/IEA, 2011).

Solar radiation is the emission of electromagnetic energy from the sun. This energy is measured and reported as the solar irradiance, which is the solar radiation received per unit area by a given surface. The units for solar irradiance can be expressed as $W.m^{-2}$ (Cryer, 2020). Solar irradiation is integrated solar irradiance over a given period with units often expressed as $J.m^{-2}$ or $Wh.m^{-2}$. The factors that influence the value of the incident energy on the earth's surface include location, air, pollution and cloud cover.

When the solar radiation penetrates the earth's atmosphere, it gets split into two types of solar radiation. The first is the direct solar radiation which comes directly from the sun's surface to the earth's surface. The other is a diffuse solar radiation, which is a result of solar radiation being scattered by substances within the atmosphere such as gases, aerosols and water vapour. The sum of diffuse and direct solar radiation that is captured on a horizontal surface is referred to as global solar radiation (Kahle *et al.*, 2003).

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2.2.1 Solar radiation in South Africa

In the past, there was a lack of interest in solar energy technology in South Africa. Recently, government and businesses have noticed and the potential of solar energy to reduce the cost of energy, boost job creation and promote local economies (Warner, 2014).

South Africa is a semi-arid country with large areas of flat terrain with high levels of irradiance, (DoE and GIZ, 2015). The climate in South Africa also makes it ideal for solar energy generation, as most of the areas in the country have 2500 hours of sunshine a year (Walker, 2003). The country has one of the world's highest solar irradiation rates in the world, with some provinces having solar irradiation rates ranging from 4.5 – 6.5 $kWh.m^{-2}$ (Chang *et al.*, 2011). South Africa is a country that has a high level of direct normal irradiation (FAO, 2015).

According to Bugaje (2006), when compared to other countries in Africa, the accessibility of solar radiation data in South Africa is considered to be extensive. The sources from which data on the solar radiation obtained in South Africa can be acquired for any location, are as follows (Bekker, 2007):

i) Ground station measurements pyranometers

The precision of the device, its fine-tuning and its spectral sensitivity are functions of the accuracy of the resulting global and diffuse irradiation data.

ii) Ground station measurements of sunshine hours

To estimate the global irradiation at any given area, the percentage of sunshine is used where it is measured for an hour. Diffuse radiation needs more estimation, such as sky clearness indices, with a high potential for errors.

iii) Satellite irradiation measurements

This method of measurement is chosen when there is little to no ground station data available in an area. The observations taken by the satellite do not consider the effects of microclimate and location.

In 2013, the South African Weather Services re-established the national solar radiometric network which consists of 13 new stations within the six climatic zones in South Africa. This was done to meet the demand for reliable and accurate solar radiation data from the development of solar based renewable energy technology and projects (Ntsangwane *et al.*, 2018).

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2.2.2 Photovoltaic technology

Photovoltaic (PV) cells are semiconductor devices that generate electrical power by enabling photons to remove electrons from a molecular lattice, leaving a freed electron and a ‘hole’ pair that diffuse in an electric field to separate contacts (OECD/IEA, 2011). The materials presently used for PV cells are mono-crystalline silicon, poly-crystalline silicon, amorphous silicon, cadmium telluride and copper indium gallium selenide/sulphide (Chu, 2011). The most common types of PV systems are mono or poly-crystalline silicon cells and thin film solar cells. Pure silicon is used to produce mono- or poly-crystalline systems and the price of the system is higher than thin-film systems. This leads to the thin-film system being utilised more often than mono and poly-crystalline systems (Niekerk, 2013).

The electrical power output of a PV system is usually expressed in terms of peak power, such as peak watts (W_p). Peak power is the amount of power generated by the PV system at standard reporting conditions (SRC). SRC is when the temperature of the PV solar panels and the solar radiance of the area is 25 °C and 1000 $W.m^{-2}$, respectively. Since the peak power represents a single value of the rate, a more satisfactory measure is the amount of electrical energy produced over a specific time interval of interest such as kilowatt-hours per day ($kWh.d^{-1}$) or megawatt-hours per year ($MWh.y^{-1}$). This measure, therefore, corresponds to the variability of solar energy daily, seasonally and annually (Stout, 1991). To produce alternating current (AC), an inverter is needed, which will change the direct current (DC) to AC.

In South Africa, small scale embedded generation of electricity for individual use at a location is taken by Eskom and the National Energy Regulator of South Africa as a measure to reduce the demand for electricity on the grid (Knox *et al.*, 2012). Solar Portal is a website used to monitor PV installations worldwide (Portal, 2016). Users of the site can upload the outputs of their systems onto the site. Based on the data on the website, it shows that there are currently no less than 200 installed PV systems ranging from small scale to large scale applications in South Africa (Portal, 2016).

The dominant areas of PV installation are Cape Town, Johannesburg, Durban and Stellenbosch. The users of these PV systems vary from schools, private residences, farms, small businesses and large businesses (Niekerk, 2013).

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2.3 PV System Primary Components and Cost

Depending on the type of solar powered PV system that generates power to operate irrigation systems, PV system primary components consist of PV panels, a controller, an inverter, battery storage or a water tank, and control switches. These systems are environmentally friendly, minimal maintenance is needed, they have a long operational lifespan, they require no fuel and the installation of the system is easy (Cuadros *et al.*, 2004). PV solar technology has some restrictions, namely, low efficiency, which ranges between 10 – 23 %, high investment cost and complex electronic requirements when controllers and batteries are utilised. The estimated costs of different PV systems in 2013 are presented in Table 2.1.

Table 2.1 Estimated costs for different types of PV systems (Ahlfeldt and Economics, 2013)

PV System	**Installed Cost (R/W)**
Utility scale fixed tilt	22.47
Utility scale fixed tracking system	24.51
Commercial/industrial scale	20.00
Residential grid-supported	27.50
Residential off-grid	47.00

2.3.1 PV solar panels

PV solar panels are devices that convert solar radiation into electrical energy (Huang *et al.*, 2013). PV solar panels are made up of PV cells. PV solar panels are either linked in series or parallel, forming a PV solar array, to deliver a specific voltage and current under a certain level of irradiance (Helikson *et al.*, 1991). Figure 2.1 illustrates the interconnection of PV solar cells and PV solar modules which lead to the formation of an array. PV solar cells consist of semiconductor material that comes with either two or more layers and produces direct current when exposed to sunlight. The semiconductor layers can be made from two materials which are crystalline or thin film (Morales, 2010). The three common types of PV modules currently used include the following: amorphous, polycrystalline and mono-crystalline.

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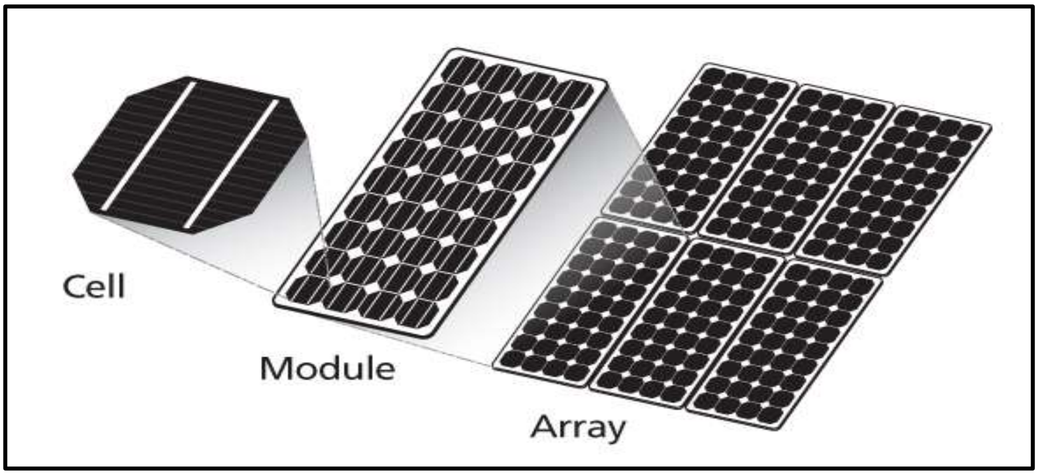

Figure 2.1 Interconnection of a solar cell, module, and array (Solar, 2004)

2.3.1.1 PV technology efficiency

Over the operating life of a PV solar panel, the efficiency will change. The power produced by the PV solar panels will decrease with age over the operating life. What also affects the efficiency of the power produced by the PV solar panels is the ambient temperature of the PV solar panels. Through research, it has been shown that high ambient temperature results in a decline in the energy output of the PV solar panels (Hamrouni *et al.*, 2008; Dubey *et al.*, 2013). The efficiency of the PV solar panels can also be affected by poor maintenance such as the presence of surface contamination on the solar panels and vegetation growth leading to shading of the PV panels thus, reducing the energy output (Hamrouni *et al.*, 2008; Pillay *et al.*, 2016). Crystalline PV solar cells are made out of silicon, while thin-film semiconductors are made out of either cadmium telluride, amorphous silicon or copper indium gallium diselenide. Thin-film cells have an efficiency that ranges between 8 % and 12 % (Niekerk, 2013). Silicon PV solar panels have an efficiency that ranges between 13 % and 18 % (Wasfi, 2011). Calculations indicate that, at best, a mono-crystalline pure silicon solar cell can convert 22% of terrestrial sunlight into electricity, which makes it the most efficient PV solar panel, while the least efficient PV panel is the amorphous silicon type (Stout, 1991; Meah *et al.*, 2008; Saleem et al., 2016).

2.3.1.2 PV technology solar collectors

There are two types of solar collectors for PV systems, namely, flat-plate and concentrator. A flat-plate solar collector has electrically interconnected and packaged PV solar cells in planar panels. Flat-plate collectors are generally non-tracking of the sun, but the inclination tilt can be

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adjusted seasonally, while a concentrator solar collector may be sun tracking on one or two axes. The shape of the solar collector promotes the sunlight to be concentrated and focused on solar cells that are either actively or passively cooled (Stout, 1991). According to Dickensen (1978), there is an issue with concentrator systems only making use of direct solar radiation. Therefore, for areas that experience many cloudy days during the year, the system will not be suitable.

2.3.2 Inverter

It would be ideal if solar powered systems operated directly on DC power. The problem is that there are limited DC devices available, or if available, they are often more expensive than AC devices (Monsour and Burton, 2002). PV solar panels produce DC power and, commonly, motors that are joined with a pump need AC power so, inverters are used to change DC electricity to AC electricity. The conversion efficiency of inverters when converting electricity from DC to AC is 80 – 90 % (Vignola *et al.*, 2008).

2.4 Grid-Connected and Off Grid PV System (Energy Storage)

PV systems can be grid connected, which allows the electricity produced to be fed into the utility mains and using it as a storage volume. The other alternative is the energy can be stored in batteries or excess water stored in elevated water tanks.

2.4.1 Grid-connected PV systems

The concept behind the grid-connected system is to lower the additional cost of installing batteries to the PV system and avoid lost excess electricity that is being produced but unused due to low demand. In solar pumping applications, when the grid is available, some systems are connected to the grid allowing for the two-way exchange of power. The different ways a grid-connected system can be used include the following:

(i) When solar energy is available, and the system needs water, water is directly pumped to the system using solar power.

(ii) When solar energy is available, and water is required by the system, the system does not use all the electricity produced, excess electricity is fed into the grid.

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(iii) When solar energy is available, and water is required by the system, but the system requires more electricity, the remaining amount of electricity required by the system will be obtained from the grid.

(iv) When solar energy is available, and the system does not require any water, electricity is fed into the grid.

(v) When solar energy is not available, and the system requires water, water is directly pumped to the system using grid electricity.

For systems where the utility grid is not available, mainly inaccessible and not electrified regions, the PV system is installed as a stand-alone system or can be connected to a private generator.

The private generator plays roles ((ii)), (iii)), and (v) of the grid, as mentioned above. It provides electricity when needed unless there is a storage system in place. This storage system allows storing electricity or water to offer availability during night times and winter seasons (CSC, 2016).

2.4.2 Battery storage and water tank

Off-grid PV systems are either battery storage or water tank storage. Some solar system applications require storage due to solar energy being available only during the day and can sometimes be absent during the winter season. The most commonly used method for storing electricity is the use of batteries. The use of batteries comes with disadvantages such as increased cost and high maintenance requirements of the system (CSC, 2016).

The excess electrical energy produced by the PV solar panels can be stored in two different ways. When the PV solar panel produces more electrical energy than the pumping system requires, the excess electrical power is stored in the battery. The types of batteries used for PV systems are namely: lead-acid, lithium ion and nickel-iron batteries. The very deep discharge rate, high cost, and environmental concerns limit the PV application of nickel-iron batteries. Lead-acid batteries, on the other hand, are the most commonly used batteries due to the moderate cost, good energy efficiency and ease of recyclability of the lead (Monsour and Burton, 2002; Buschermohle and Burns, 2014).

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2.5 Economics of PV Systems

In terms of the economic feasibility of PV systems; the literature reveals that small systems are economically feasible. A generalised method to determine both technical and economic feasibility that can be applied to a range of sizes has not yet been developed (Kelley *et al.*, 2010). The cost of PV systems is dependent on the power produced by the panels and the storage (batteries or water tanks) components. The cost to run a PV irrigation system is negligible, but high capital costs are required, which is a limitation for the wide-scale adoption (Firatoglu and Yesilata, 2004). There has been a drastic drop in solar panel prices over the past 30 years (Reichelstein and Yorston, 2013). Literature has highlighted methods in which to determine and evaluate the economic feasibility of PV systems as well as comparing it with conventional alternative power sources such as diesel engines and grid electricity (Odeh *et al.*, 2006; Meah *et al.*, 2008; Kelley *et al.*, 2010; Branker *et al.*, 2011).

2.6 PV Irrigation System Configuration

A PV irrigation system uses PV solar cells to capture solar radiation from the sun's radiation to produce electricity for driving the pump. PV irrigation systems commonly consist of an array of solar cells, a power converter, a control unit, a pump and a borehole or reservoir (Yu *et al.*, 2011). The use of PV technology with irrigation systems for pumping requirements offers ease of use, dependability and low maintenance. The use of PV irrigation systems is ideal in remote areas which have no grid electricity connection (Senol, 2012).

There are two main methods for storing energy generated by a photovoltaic water pumping system, namely, the battery-coupled and the directly driven solar water pumping systems.

2.6.1 Battery-coupled system

The components within a battery coupled SPIS consist of PV solar panels, charge controller, batteries, pump controller, pressure switch, storage tank (optional) and a DC water pump (Sontake and Kalamkar, 2016). Lead acid batteries are commonly used for SPIS. One of the drawbacks of the battery is that it lowers the efficiency of the entire system. Charging and discharging the battery results in power being lost, resulting in low efficiency. Designing the batteries to be fully charged and discharged during the operation of the system will make the battery have better efficiency. The typical efficiency of a lead-acid battery is roughly 80 % but can be 75 % in hot climates (Deveci *et al.*, 2015). This system is more reliable than the directly

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driven system because there might be a day where radiation from the sun is too low to produce electricity. To be on the safe side, it is advisable to use batteries in SPIS's to store energy for future use (Abdelkerim *et al.*, 2013). Shown in Figure 2.2 is the set-up of a battery-coupled PV irrigation system.

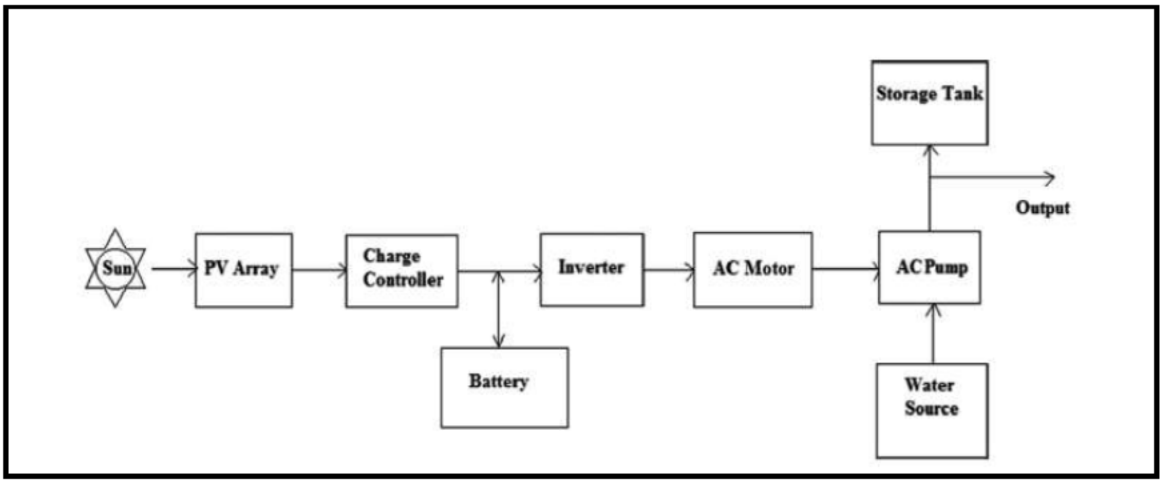

Figure 2.2 Battery-coupled photovoltaic water pump system (Chandel *et al.*, 2015)

2.6.2 Direct driven system

The electricity produced by the PV solar panels in a direct driven SPIS is supplied to the pump. In this system, electricity is used to pump the water and there is no battery to store excess electricity. The system only operates during the day when solar energy is available (Sontake and Kalamkar, 2016). The efficiency of this type of system is typically low, normally not exceeding 30 %. A directly driven system is mostly used for low head irrigation in rural areas (Chandel *et al.*, 2015).

With this type of system, water is pumped when solar radiation is available during the day time. Direct driven systems come in one of two ways. The first one, which is shown in Figure 2.3, is when water is pumped then stored in a water storage tank. This will make water available in the evening and daytime if it is too cloudy (Xu *et al.*, 2013; Deveci *et al.*, 2015). Most operating SPIS make use of water storage tanks instead of the battery (Deveci *et al.*, 2015). The other version of a direct driven system is when water is pump directly to the irrigation system.

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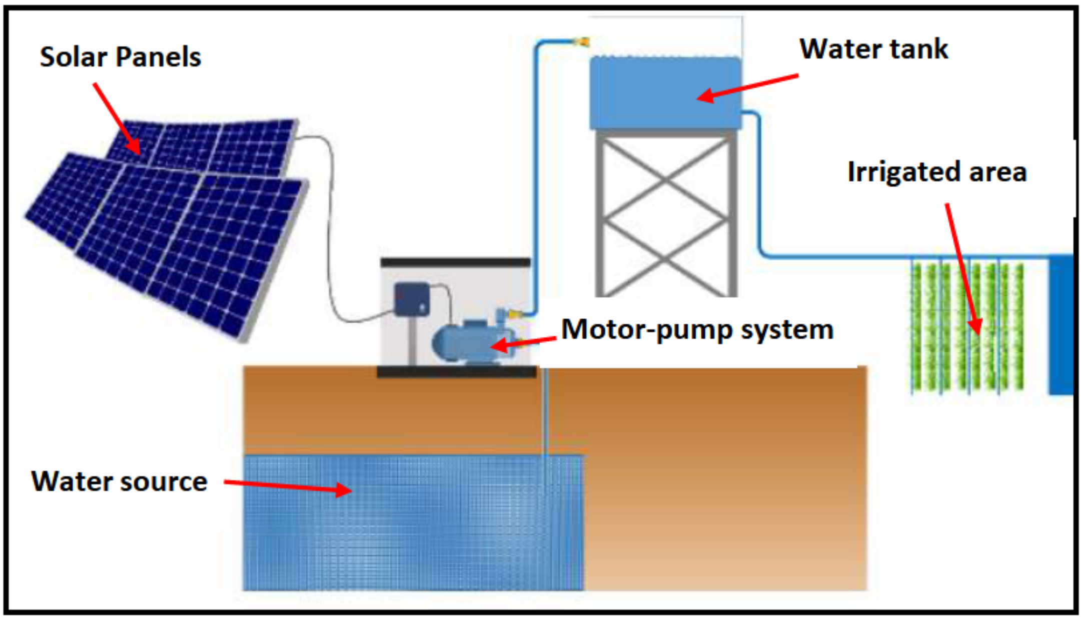

Figure 2.3 Direct driven PV water pump system (Shehadeh, 2015)

2.7 PV Pump Types

For remote areas not connected to the electricity grid, diesel water pumps are used to pump water for irrigation and in some cases, irrigation is performed manually. Diesel water pumps have a high power range, which in turn pumps high volumes of water when required (Senol, 2012). The continued rise in fuel prices and the high maintenance of diesel water pump has resulted in the development of a new type of system, which is PV powered water pumps (Ramos and Ramos, 2009). Since PV powered water pumps have been developed, they have been implemented around the world as an alternative power source for remote locations (Senol, 2012).

These systems are mainly designed to supply water for irrigation to areas that are not connected to the electricity grid. Some of the advantages that come with photovoltaic water pumps (PVWP) are their durability, lack of fuel requirements, they are environmentally friendly and simplicity in the installation process of the system (Deveci *et al.*, 2015). The drawbacks of PVWP are the high investment cost of the system as well as the inconsistent water production during cloudy days and different seasons (Senol, 2012). When it comes to selecting a pump, it is application dependent only. These include water requirement, water head and water quality (Meah *et al.*, 2008).

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There is a range of different water pumps available and PVWP is also included. PVWP can be used in a variety of applications, which result in a wide range of different types of pumps (Monsour and Burton, 2002). The main commercially available PVWP and their application will be discussed in Table 2.2.

Presented in Figure 2.4 is the range of the daily water requirements (m^3) and the total head (m) that different types of pumps can operate under.

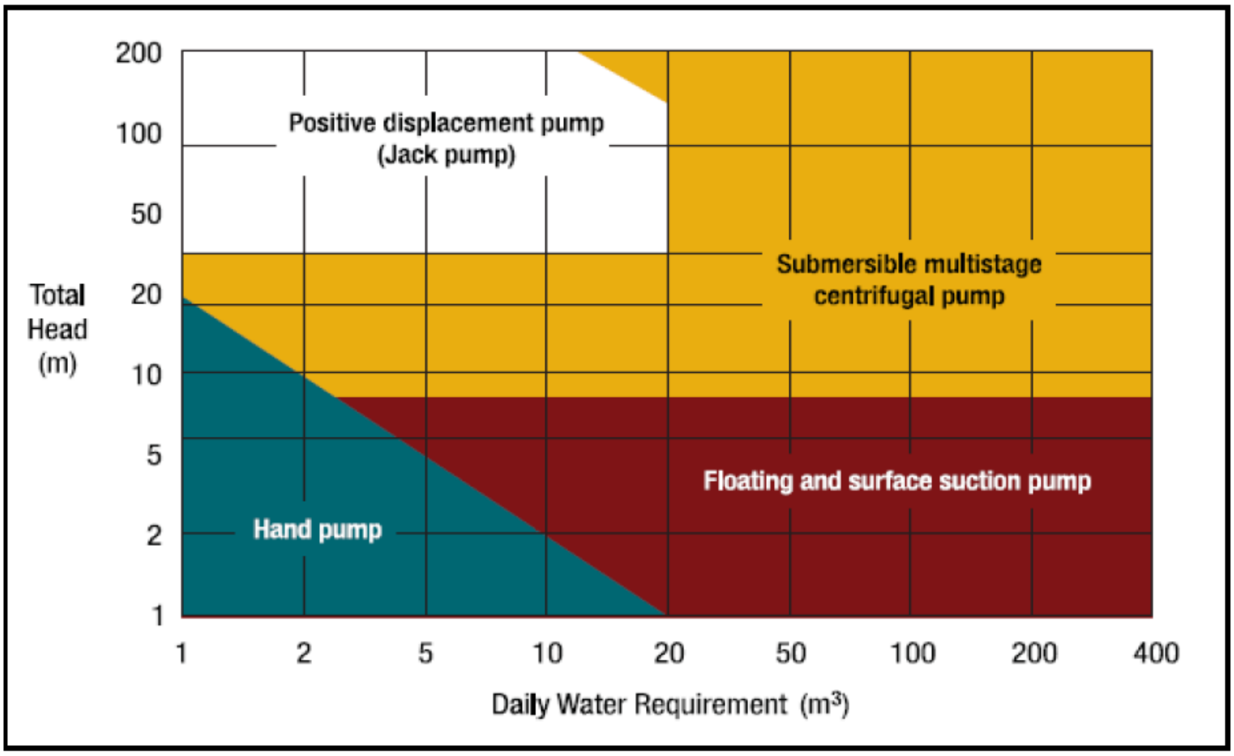

Figure 2.4 Graph of different types of pumps with total head and daily water requirement limitations (RETScreen, 2004)

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Table 2.2 Types of pumps (Monsour and Bonton, 2002).

Pump type	Main characteristics	Advantages	Disadvantages
Submerged three-phase motor	• Primarily used for borehole water extraction • Three-phase motor is directly linked to a multi-stage centrifugal pump, which is submerged in water within a borehole	• Simple installation • Protected from damage and vandalism	
Submerged DC motor pump	• Closed coupled DC motor-pumps are used for some smaller borehole PV pumps • The motor used for this system is a permanent magnet brush type		A brushed motor requires replacement of brushes at least every two years.
Surface mounted motor with submerged pump	• Centrifugal pumps or positive displacement pumps are used for this system • The rod connections are in series, which feed through a rigid galvanised pipe called a riser • One end of the drive rods is connected to the motor and the other to the submerged pump		low efficiency caused by the power losses experienced in the shaft bearings
Floating pump	• A float houses the motor and pump system which rides on the surface of the open wells or channels • the system is very good in pumping irrigation water for canals and wells mainly because of its versatility	PV system can be made portable by incorporating a wheelbarrow type trolley to allow transportation.	Applied to low lift or low head requirement irrigation application systems
Suction lift pump	• The motor-pump system is mounted above the water of an open well • The pump height position above the water is restricted by the atmospheric pressure with the net positive suction head required (NPSHR) • Diaphragm and centrifugal pumps are used for suction lift systems.		• Suitable for low head applications. • The system requires an operator to always be in attendance.

2.8 SPIS internationally and in South Africa

Countries such as Chile, India, and Morocco rely on subsidies from governmental organisations for small-medium scale irrigation schemes. These subsidies range from 30 % - 100 % funding towards SPIS for farmers. The high financial contributions from the government encourage farmers to implement the technology and increase the level of acceptance. The Chilean and Indian government subsidies normally support standardised and limited system kits which seldom meet the requirements of the target farms. Since these countries offer subsidies for SPIS; commercial financing of SPIS via banks does not exist. This is also the result of knowledge and the capacity for the assessment and risk management of these projects being low (Sass and Hahn, 2020).

Infrastructure is the biggest drawback in Africa. Many places do not have access to the electricity grid. Farmers that do not have access to the electricity grid often revert to using diesel power, which is about five times more expensive than grid power per kWh. The initial costs of a diesel-powered irrigation system are a lot less compared to SPIS. The use of diesel-powered irrigation systems could have a negative impact on the farmer’s bottom line over time, due to the operating costs. The Department of Agriculture, land Reform and Rural Development is considering the subsiding of SPIS installations for small-scale more favourably, but severe funding shortages prevent it from being implemented on a meaningful scale (Parker, 2019).

2.9 Water and Energy Consumption in Agriculture in South Africa

The water requirements for irrigation are roughly 60 % of the total water requirements in South Africa, while industrial water requirements are 25 % (GCIS, 2015). Only 1.5 % of the land in South Africa is under irrigation, which produces 30 % of the country’s crops. Irrigation consumes 8 % of the total energy used in agriculture and 28 % of the total electricity used in agriculture (DoE, 2012).

Agriculture in South Africa is dominated by commercial farming, which commonly accesses water from surface water resources. There is a physical scarcity of water in the country, therefore the public is focused on improving the efficiency of irrigation and providing equitable access (Hassan, 2015).

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The electricity produced in South Africa mainly comes from coal, which produces 91.7 % of the total electricity in the country. In the past few years, a need to reduce the reliance on fossil fuels for energy supply has been acknowledged. The need to reduce carbon emissions and advancements in renewable energy sources are contributing factors to the reconsideration of energy supply (Goga and Pegram, 2014).

It is estimated that 2 000 ha of arable land in South Africa is under solar powered irrigation. The factors currently influencing demand for solar powered irrigation in South Africa are as follows (Hassan, 2015):

- The electricity rates for the agricultural sector are still competitive, apart from price increases:
    - Electricity – R 1.30 / kWh
    - Diesel – R 4.00 / kWh
    - RuralFlex (Rural electricity) – R 0.70 / kWh
    - Solar (Commercial) – R 0.85 – 0.90 / kWh
- The business case for solar irrigation technology is lacking as well as the financial benefits amongst farmers.
    - There are expectations that the prices of solar components will continue to fall.
    - There is a perception that there is no available funding.
    - There is a huge investment required for the implementation of solar powered irrigation systems.
- Farmers fear that components will be lost due to theft (du Plessis, Cape Town, South Africa, 2017).
- There are relatively few service providers who are actively involved with SPIS. For the larger irrigation companies who technically service 90 – 95 % of the commercial irrigation farmland, solar is not a viable option yet, although they believe in the concept and that it will have future application (du Plessis, Cape Town, South Africa, 2017).

The main drivers towards the implementation of SPIS are the expectation that there will still be excessive escalations in electricity rates, and concern about Eskom's capacity, both in terms of the adequacy of power and their ability to deliver the power to the user.

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2.10 Irrigation Techniques

Literature reveals that solar powered irrigation is preferable for certain irrigation techniques. Table 2.3 shows the irrigation methods that are suitable for solar powered irrigation.

Table 2.1 The suitability of irrigation techniques with relation to solar pumps (Action, 2012)

Distribution method	**Typical application efficiency (%) (m)**	**Typical head (m)**	**Suitability for use with solar pumps**
Open channels	50 – 60	0.5 – 1.0	Yes
Sprinkler	70	10.0 – 20.0	No
Trickle/Drip	85	1.0 – 2.0	Yes
Flood	40-50	0.5	No

According to Saleem *et al.* (2015), SPIS can be successfully integrated with different irrigation techniques namely, drip, micro-sprinklers and rain guns. So SPIS utilised with drip and several sprinkler irrigation techniques will be discussed in the sections below.

There are different types of sprinkler irrigation systems including set-move irrigation systems, solid-set systems, and continuous-move systems.

2.10.1 Drip irrigation

A drip irrigation is also referred to as trickle irrigation and involves the slow rate of dripping water onto the soil at a flow rate that ranges from 2 – 20 $l.h^{-1}$. The irrigation system consists of pipes with small diameter plastic pipes with emitters or drippers (Brouwer *et al.,* 2016). With drip irrigation, water flows through the emitters and directly into the soil near the root zone of the crops. It may help achieve water conservation through reducing evaporation and deep percolation, if it is designed, installed and managed adequately (Stauffer, 2016). Due to the reduced water contact with leaves, stems, and fruit resulting from drip irrigation, the development of diseases is less common (Shock, 2006).

Compared to sprinkler and flood irrigation, drip irrigation systems have low energy requirements, which are a result of the low water requirement and flow rate (Burger *et al.*,

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2003b). The operating pressure of drip irrigation systems ranges from 0.02 – 0.2 m (Ruffino, 2009). According to Burger *et al.* (2003c), drip irrigation has a water application efficiency that ranges from 90 – 95 %, which is a result of the water being applied directly to the root zone. As a result, countries such as Morocco India and Chile SPIS are preferably integrated with drip irrigation systems for water saving and minimum energy consumption (Sass and Hahn, 2020).

A drip irrigation system comprises many components, with each one playing a vital part in the operation of the system. Drip irrigation systems are recommended for use on soils with a coarse texture where water can be distributed horizontally through capillary action and vertically using gravity. Soils that possess poor ability to distribute water are not recommended to be irrigated with this system (Burger *et al.*, 2003a).

When compared to other irrigation systems such as furrow irrigation, drip irrigation systems are significantly more expensive. The system comes with many components which contribute to the high investment cost of the system such as the pressure regulator, filtration system, controller, backflow preventer, flush valve or cap, valves, pipes and emitters (Christenson, 2006). The system also requires high maintenance due to the emitters having the potential to clog up. This makes the filtration system the most important component of the drip irrigation system as it prevents dirt and debris from clogging emitters (Burger *et al.*, 2003g).

2.10.2 Sprinkler irrigation

Sprinkler irrigation is a method where water is sprayed onto the crops and soil in a manner similar to rainfall. The precipitation is created by ejecting pressurised water through a nozzle called a sprinkler. There is a variety of irrigation capacity available for sprinkler irrigation systems (USAID/Nepal, 2009). The components that a typical sprinkler irrigation system has been namely: the pump unit, mainline and sometimes sub-mainlines, laterals, and sprinklers (Brouwer *et al.*, 1988). Sprinkler irrigation is a high pressure method where one sprinkler can have a wetted diameter that ranges from 10 m to 20 m.

Wind drift has a huge effect on the water application uniformity of a sprinkler irrigation system, which causes water losses that range from 5 to 10 %. High evaporation losses are experienced during high temperature seasons. High water pressure is required to operate the sprinklers (Amend, 2005).

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There are different classifications of sprinkler irrigation systems, depending on the systems' mobility, such as portable, semi-permanent and permanent (James, 1993; Burger *et al.*, 2003e). The most widely used sprinkler distribution systems are portable laterals with sprinklers (moved as a unit), semi-solid set (sprinklers only moved), dragline (sprinklers and hoses moved), big gun (portable supply pipe where gun and supply line are moved), side-roll (entire unit moved) and permanent-solid set (Burger *et al.*, 2003f).

Table 2.4 shows how sprinklers can be divided according to the pressure required. SPIS's are generally suitable for low-pressure irrigation systems (CSC, 2016). This is the result of high-pressure irrigation systems when compared to low-pressure irrigation systems requiring more energy to operate the irrigation system. The higher the energy requirements of the system, the larger the solar panels, making the system more expensive.

Table 2.2 Different sprinkler pressures, flow rates and typical applications (Burger *et al.*, 2003e)

Sprinklers	**Pressure (m)**	**Flow rate ($m^3.h^{-1}$)**	**Typical application**
Low pressure	< 20	< 0.7	Orchards
Medium pressure	25 – 40	< 3.0	Cash crops
High pressure	> 40	< 50.0	Pastures and sugar-cane
High volume	> 45	20.0 – 100.0	Pastures and maize

2.10.2.1 Micro sprinkler irrigation

Micro-sprinkler irrigation systems operate like sprinkler irrigation systems. Compared to sprinkler irrigation systems, the operating pressure and flow rate of micro-sprinkler irrigation systems are low. The components of this type of system are the sprinklers (0.55 mm – 2.20 mm orifice), pipes, valves, connectors, and filters. The water application flow rate of these systems is between 20 $l.h^{-1}$ and 100 $l.h^{-1}$. The diameter of the area wetted by micro-sprinkler is from 1.5 m to 10 m.

The water application efficiency of a micro-sprinkler irrigation system ranges from 80 % to 90 % depending on the level of design and irrigation system management (Godin and Broner, 2013). A filtration system is an important feature for the water application efficiency of the micro-sprinkler irrigation system, even though the clogging of the system rarely occurs.

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When a micro-sprinkler irrigation system is well managed, it can produce increased yields and increase water use efficiency. Water is allowed a chance to penetrate through the soil under low pressure with a micro-sprinkler as water is applied directly to the soil. The irrigation system normally operates at pressures between 14 – 20 m with a low to medium volume of water required. Compared to furrow irrigation, the integration of micro-sprinkler irrigation with solar water pumping systems is ideal due to the low pressure and high water use efficiency of the system, meaning the sizing of the solar panels will not be too large resulting in very high investment costs (Goswami and Zhao, 2009).

2.10.2.2 Centre pivot irrigation

A form of sprinkler irrigation, centre pivot irrigation is a system that applies a small amount at frequent intervals (Ruffino, 2009; Ahmed, 2013). The components that make up a centre pivot irrigation system include a pump, a motor, mainline, wheeled tower with a drive system with laterals attached, emitters (sprinkler and end-guns) and accessories like control switches, pressure gauges, water meter and safety valves. The laterals are fixed at the centre of the field and the system rotates the field at a set fixed speed (Jarrett and Graves, 2010; Ahmed, 2013).

The water loss experienced with centre pivot irrigation is minimal with only drip irrigation having a lower water loss than the centre pivot irrigation system. Compared to other irrigation systems, such as other sprinkler irrigation systems and furrow irrigation, the centre pivot produces more uniform water coverage (James, 1993). Clogging of the nozzles rarely occurs due to their design, which results in the system not requiring a filtration system as advanced as the drip irrigation system. The expected life of the system is 20 years (Burger *et al.*, 2003e).

Centre pivots that operate at low pressures with drop nozzles usually have a water application efficiency of 85 % (Brown, 2008). According to Berne (2015), centre pivot irrigation systems can either have impact-type sprinklers or spray-type sprinklers. Spray-type sprinklers which are also known as spray nozzles have a significantly low-pressure requirement, which leads to a low energy requirement than do impact sprinklers. Centre pivots also need additional power to move the centre pivot tower around the field.

Amend (2005) suggests solar powered centre pivot irrigation system be kept small scale with low pumping requirements due to the high capital investment cost of PV systems. This is due to the system requiring power for irrigation and to move the system around the field. The irrigation system can be very economical to produce high value crops. The centre pivot system

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can also be used to reduce the temperature of the PV panels and be used to keep them clean by positioning the PV panels in the centre of the pivot, which will also reduce operating cost for maintenance (Sedki, 2014).

2.10.3 Furrow irrigation

A type of surface irrigation, furrow irrigation does not irrigate the entire field like basin and border irrigation techniques do. The irrigation technique channels the flow of water along the main direction of the field using furrows (Walker, 1989). The energy requirement of the furrow irrigation system compared to sprinkler irrigation systems is low. The cost to construct a furrow irrigation system is cheaper compared to other irrigation systems such as sprinkler and drip irrigation. This makes the system suitable for cases where the energy requirement and investment costs are limited (Burger *et al.*, 2003f).

The water application efficiency of this system is low ranging from 50 % to 60 %. As a result of this, a substantial amount of water can be lost with this system. The efficiency of this system can be improved by implementing wastewater recovery and reuse techniques, and inlet discharge control (Walker, 1989). The pressure requirements of these systems range between 1 – 3 m (Mahnke, 2010).

Hossain *et al.* (2015) compared the water use and yield production of solar powered drip irrigation and furrow irrigation systems. The drip and furrow irrigation obtain similar yield production. The difference came to the water use, where the drip irrigation system saved 50 % of water when compared to furrow irrigation. The more water the system requires, the higher the pumping requirement, therefore, the number of PV panels required for a furrow irrigation system will be greater than the PV panels required for a drip irrigation system.

2.11 Crop Water Requirements

The crop water requirement is defined as the amount of water required to meet the water loss through evapotranspiration. Evapotranspiration (ET) is the amount of water used by plants through transpiration and water loss through evaporation (Bithell and Smith, 2011). In the process of irrigation, there are potential areas of water loss and these include lateral runoff, deep drainage, and leaks in the delivery system. These are not accounted for in the ET calculations but can be measured and included in the estimates of crop irrigation requirements. There are four main climatic factors that influence crop water requirements and these include

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radiation, temperature, humidity and wind (Crouwer and Heibloem, 1986; Burger *et al.*, 2003c).

There are different methods worldwide that are used to determine crop-evapotranspiration. The ones used in South Africa will be discussed. These methods include the A-pan evaporation with the crop factor, the Penman-Monteith method (short grass reference) and the relation between short grass reference evapotranspiration (ET_o) and A-pan evaporation (E_o). It is advised that irrigation designers start to use the Penman-Monteith method and SAPWAT with the guidance of professionals. Otherwise, tables for A-pan evaporation and amended crop factors (f) can be used to determine crop evapotranspiration. Equation 2.1 shows the A-pan equation and Equation 2.2 shows the Penman-Monteith equation to determine crop evapotranspiration (Burger *et al.*, 2003g).

$$ET_c = E_o \times f \tag{2.1}$$

where,

ET_c = crop evapotranspiration ($mm.day^{-1}$),

E_o = A-pan evaporation ($mm.day^{-1}$), and

f = crop factor (unitless).

$$ET_c = ET_o \times k_c \tag{2.2}$$

where,

ET_o = reference crop evapotranspiration ($mm.day^{-1}$), and

k_c = crop coefficient (unitless).

Drip and micro-sprinkler irrigation systems only irrigate a portion of the ground, as a result of this a ground cover reduction factor is used to account for the reduced evaporation from the soil (Savva and Frekken, 2002). Equation 2.3 shows the crop evapotranspiration with the ground cover reduction factor.

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$$\mathrm{ET_c = ET_o \times k_c \times k_r} \qquad 2.3$$

where,

k_r = ground cover reduction factor (dimensionless).

2.12 Irrigation Water Requirements

When determining the irrigation water requirement, the effective rainfall must be calculated. Long term rainfall data is required to determine the long term monthly average rainfall. Interception, evaporation, runoff and seepage are factors that prevent most of the total rainfall from reaching the plant roots of crops. A large amount of water is removed from the measured rainfall as evaporation losses. Equation 2.4 and Equation 2.5 show how to determine the effective rainfall (Wane and Nagdeve, 2013).

$$\mathrm{P_{eff}} = 0.6 \times \mathrm{P} - \frac{10}{3} \qquad \text{for P} \leq 23 \text{ mm} \qquad 2.4$$

$$\mathrm{P_{eff}} = 0.8 \times \mathrm{P} - \frac{24}{3} \qquad \text{for P} > 23 \text{ mm} \qquad 2.5$$

where,

P_{eff} = effective rainfall (mm), and

P = monthly average rainfall (mm).

The net irrigation requirement per day (NIR_d) is calculated using Equation 2.6. There is a possibility that the NIR_d calculated with the equation can be smaller than the actual maximum NIR_d, which could lead to the system capacity being insufficient during a certain hot period and may lead to losses. To prevent this from occurring, the designer must always compare the average NIR_d with the reported daily values to make the required adjustments (Burger *et al.*, 2003g).

$$\mathrm{NIR_d} = \frac{\mathrm{ET_c - P_e}}{\mathrm{n}} \qquad 2.6$$

where,

NIR_d = net irrigation requirement per day (mm), and

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n = number of calendar days in the relevant month (d).

The groundwater readily available to the crops is determined with Equation 2.7 (Burger *et al.*, 2003g).

$$\mathrm{RAW} = \mathrm{SWHC} \times \mathrm{ERD} \times \alpha \qquad 2.7$$

where,

RAW = readily available water (mm),

SWHC = soil water holding capacity ($mm.m^{-1}$)

ERD = effective soil depth (m), and

α = allowable water depletion (%).

The cycle length is calculated by dividing the crop's daily net irrigation requirement by the total amount of readily available water per cycle. This is presented in Equation 2.8 (Burger *et al.*, 2003g).

$$\mathrm{t_c} = \frac{\mathrm{RAW} \times \mathrm{W}}{\mathrm{NIR_d} \times 100} \qquad 2.8$$

where,

t_c = cycle length (calendar days), and

W = percentage wetted area (%).

The gross irrigation requirement per cycle takes into the irrigation system efficiency in delivering the water required to the plant and this is shown in Equation 2.9 (Burger *et al.*, 2003g).

$$\mathrm{GIR_c} = \mathrm{NIR_d} \times \mathrm{t_c} \times \frac{100}{\eta_s} \qquad 2.9$$

where,

GIR_c = gross irrigation requirement per cycle (mm), and

η_s = system efficiency (%).

`

The system flow rate is determined by Equation 2.10 (Burger *et al.*, 2003g).

$$Q = \frac{GIR_c \times A_T}{t} \times 10 \qquad 2.10$$

where,

Q = flow rate ($m^3.h^{-1}$),

t = operating hours per cycle (h), and

A_T = total system area (ha).

2.13 Irrigation Management

It is vital to implement irrigation management for effective and efficient use of water and energy resources as well as to enhance the farmer's income. The management practices that are utilized to improve water use efficiency are irrigation scheduling, water flow measurements, drainage flow management, conservation tillage, land levelling, nutrient management and reducing evaporative, runoff and deep percolation losses (Aillery, 2006). The most important irrigation management practice is irrigation scheduling, because it avoids the over-application of water while reducing yield losses due to water shortage, therefore optimizing water and energy usage (Evans *et al.*, 1996). According to Wright (2002), irrigation scheduling is the planning of timing and the quantity of water application to crops for optimum and healthy crop growth. To determine the intervals between irrigation and how much water to apply at each interval, the rate at which the crop consumes water and the quantity of water held in the crop root zone needs to be identified. This is done by conducting a soil analysis (where the soil texture, soil infiltration rate and the effective root depth are determined), determining the crop grown and the development stage of crops (McMullen, 2000). The implementation of soil moisture monitoring practices is vital for applying any irrigation management strategy. The techniques that can be used to determine soil moisture are the hand feel method, neutron probe, electrical resistance, soil tension, plant indicators and computerized models (Martine, 2009).

Irrigation management is vital for SPIS's. Having a well-structured distribution system integrated with cautious water use could potentially half the size and the cost of the solar pumping system required. When sizing the solar irrigation system, the system must meet peak

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irrigation demand for a region even though these conditions will not last for a long time, thus resulting in the pump having an excess capacity for the other times of the year. Investment in time and money must be placed in the field towards water storage and the distribution system aimed at improving water use efficiency and utilization application (Halcrow, 1981).

As part of irrigation management for SPIS's, the solar panels of the system require cleaning to remove dirt on them so the system performs at its best. During high temperatures, the efficiency of solar panels is reduced. To prevent this, some systems incorporate a sprinkler in the design that is used to spray the panels to cool and clean them, therefore, maintaining the performance of the solar panels (Halcrow, 1981). It is vital to implement irrigation management for effective and efficient use of water and energy resources as well as to enhance the farmer's income. The management practices that are utilized to improve water use efficiency are irrigation scheduling, water flow measurements, drainage flow management, conservation tillage, land levelling, nutrient management and reducing evaporative, runoff and deep percolation losses (Aillery, 2006). The most important irrigation management practice is irrigation scheduling because it avoids the over-application of water while reducing yield losses due to water shortage, therefore optimising water and energy usage (Evans *et al.*, 1996). According to Wright (2002), irrigation scheduling is the planning of timing and the quantity of water application to crops for optimum and healthy crop growth. To determine the intervals between irrigation and how much water to apply at each interval, the rate at which the crop consumes water and the quantity of water held in the crop root zone need to be identified. This is done by conducting soil analysis (where the soil texture, soil infiltration rate and effective root depth are determined), determining the crop grown and the development stage of crops (McMullen, 2000). The implementation of soil moisture monitoring practices is vital for applying any irrigation management strategy. The techniques that can be used to determine soil moisture are the hand feel method, neutron probe, electrical resistance, soil tension, plant indicators and computerised models (Martine, 2009).

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2.14 Photovoltaic Electrical Output Modelling

The sizing and optimisation of the pumping system, PV accessories and PV solar panels are the most important phase in the design process. This is caused by the complexity of some of the variables required in the design (Hamidat and Benyoucef, 2008; Bouzidi *et al.*, 2009). The high investment cost of PV solar power makes it highly important to make sure the PV system is sized correctly (Cuadros *et al.*, 2004). There are different models available which help determine the maximum power output of the solar panels that are required for the system to operate effectively (Bouzidi *et al.*, 2009). These models have been determined through simulation of the operation of each sub-section of the PV system.

The main stages required to size a PV solar pumping system include the following:

(i) To determine the irrigation requirements of the irrigation system as per the characteristics of the crop, soil and climate.

(ii) Performing a hydraulic analysis of the pumping system as per the depth of the water source and the head needed to stabilise the pressure in the irrigation system.

(iii) To determine the peak PV power required to irrigate the area of land.

To determine the nominal electrical power of the PV solar panels, in referential condition (Standard Test Condition (STC)), according to Kenna and Gillett (1985b) is as shown in Equation 2.11.

$$P_{el} = \frac{1000}{[1 - \alpha_c(T_c - T_o)\eta_{mp}} \times \frac{E_H}{E_T} \qquad 2.11$$

`

where

P_{el} = nominal electric power (W.),

α_c = PV cell temperature coefficient ($^oC^{-1}$),

T_c = PV cell temperature ($^o C^{-1}$),

T_o = referential temperature of the PV array (25 ^{o}C),

η_{mp} = motor pump efficiency,

E_H = hydraulic energy (kWh), and

E_T = mean daily solar irradiance on horizontal plane (kWh.m^{-2}.day^{-1}).

The hydraulic energy of the SPIS is calculated using the amount of water required for irrigation and the total static and dynamic head of the system (Kenna and Gillett, 1985b; Glasnovic and Margeta, 2007; Zegeye *et al.*, 2014). Equation 2.12 shows that the hydraulic head requirement is varying with head and irrigation demand.

$$E_H = \frac{\rho g Q_d H_{TE}}{3.6 \times 10^4 \eta_{mp}} \qquad 2.12$$

where

ρ = density of water (kg.m^{-3}),

g = gravitational acceleration (m.s^{-2}),

η_{mp} = motor-pump efficiency (%),

Q_d = mean daily water volume at the output of the PV pumping system (m^3.day^{-1}), and

H_{TE} = total head (m)

Where T_C is calculated using Equation 2.13 as follows:

$$T_c = T_a + \left(\frac{NOCT - 20}{0.8n}\right) E_T \qquad 2.13$$

where

T_a = air temperature (^{o} C),

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n = monthly average daily hours of bright sunshine, and

NOCT = nominal operating cell temperature (^{o}C).

All variables which include temperature, solar irradiation, monthly average daily hours of bright sunshine and irrigation demand are varying with time and so does the nominal electric power.

2.15 Discussion and Conclusion

Solar radiation is in abundance in South Africa with one of the world's highest solar insolation levels. The implementation of solar energy technology in the country is on the rise due to the prices of solar energy technology being on the declined in recent years, specifically the prices of solar panels. Two thousand hectares of land in South Africa are estimated to operate with SPIS's. Though this may be the case there is little to no literature on the implementation of SPIS's in South Africa.

There are several types of solar panels available in the market. The efficiency of these systems ranges between 8 – 22 % depending on the type of solar panel. The higher the efficiency of the solar panels, the higher the cost. Due to the limited amount of DC powered motors, an inverter is required for the AC system to convert DC power into AC, and this will result in a power loss between 10 – 20 %. There are three ways to store excess energy produced by the SPIS system. These include electricity being delivered to the grid, electricity being stored in batteries and excess water being stored in elevated water tanks, making use of potential energy. The most commonly used method to store excess energy is water tanks.

The two system configurations of the SPIS, which are the battery-coupled system and the direct-coupled system, are available. The battery-coupled system generates electricity and the excess electricity is stored in the battery. Therefore, the system can also operate in the evening. The direct coupled system operates during the day when solar radiation is available. Excess water is then stored in an elevated storage tank. The battery-coupled system is more costly and less efficient because of the cost of the battery and the loss of power experienced by the battery. Direct-coupled systems are mainly implemented in irrigation systems such as drip irrigation, as they require less pressure and the elevated water tank which stores water at specific potential energy, which in turn can supply the dynamic head required by the system.

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There are different solar powered irrigation pumps available for different pumping requirements. For pumping water from a borehole or a well, there are submersible motor and pump systems and submersible pumps with a surface mounted motors available. The most suitable pump for this type of application is the surface mounted pump, as the maintenance of the system is less intense than the submersible motor and pump system. For surface water pumping application, there are suction lift pumps and floating pumps that are available. The better choice between the two pumps is the floating pump, as both pumps are low head high volume pumps. However, the suction lift pump requires security and maintenance while the floating pump does not.

There is a substantial amount of literature available on the implementation of SPIS with drip irrigation and micro-sprinkler irrigation in some parts of the world such as India. There is insufficient literature on the implementation of SPIS with centre pivot irrigation systems and furrow irrigation systems. All of these systems can be low head systems, which can result in the design of SPIS being economically feasible. Through the design of SPIS's, irrigation management is vital in the design process. The most important part of irrigation management is irrigation scheduling, which helps in avoiding over irrigating and optimises water and energy usage.

In conclusion, presently there is inadequate literature on the design and economic feasibility of SPIS's in South Africa. There is also a lack of information on the different irrigation systems that solar energy can be integrated with. The universal models that are accessible only determine the size of the SPIS and do not determine the economic feasibility of a system. The lack of information in literature may lead to farmers who are interested in implementing SPIS, either oversizing their system, resulting in needlessly high investment costs or farmers thinking the technology is too expensive to consider implementing. Therefore, it is essential to design a model that will size a low-cost SPIS for South Africa considering the climatic conditions, soil types and crop types for different irrigation techniques.

The aim of this research is therefore to determine the extent to which SPIS is implemented in South Africa. It is also to develop a model that will size an SPIS in South Africa, with a focus on the climatic conditions, crop type and pattern and the soil type. The model will then be evaluated by testing its ability to size a low cost SPIS and determine whether the system is economically feasible or not.

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3. THE EXTENT AND CHARACTERISTICS OF SOLAR POWERED IRRIGATION SYSTEMS (SPIS) IN SOUTH AFRICA

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Abstract

South Africa has a high potential for solar powered irrigation. However, there has been a lag in the development of solar powered irrigation systems (SPIS) in South Africa, mainly due to the high investment cost associated with solar technology. South Africa has gone through load shedding, which has affected many farmers in the country. The load shedding has triggered an interest in SPIS development. There is, however, not much information available in South Africa on the extent of solar powered irrigation and the systems in use thereof. The work reported in this chapter sought to analyse the prospects for solar powered irrigation in South Africa and the extent and system types in use. The extent of SPIS in South Africa was determined by the use of a questionnaire and categorised in terms of farm size, SPIS configuration (storage of energy), type of irrigation, and the location of the systems. The questionnaires were conducted on SurveyMonkey®, allowing respondents to participate online from October 2017 to April 2018. There were difficulties encountered with finding SPIS users to distribute questionnaires to. The total number of respondents that participated and completed the questionnaires were 18 SPIS engineers, installers and designers and 13 SPIS users (farmers). SPIS engineers, installers and designers' results showed that most SPIS they implemented were in the Western Cape and the Eastern Cape at 33 % for both provinces. SPIS engineers, installers and designers have also integrated SPIS with primarily drip and sprinkler irrigation at 33 % for both irrigation techniques. For the SPIS user results, 54 % of the respondents were commercial farmers. From the results gathered, 39 % of the SPIS users have integrated their systems with drip irrigation and 39 % with sprinkler irrigation. The province that has the most SPIS from the SPIS users is the Western Cape having 31 %. 92 % of the SPIS found in the survey were installed between 2010 and 2016. The total area of SPIS found with the survey is 364.415 ha. The dominant irrigation system from the SPIS users is drip and sprinkler irrigation both being

38 %. The implementation of SPIS reflected from the questionnaire was mainly motivated by load shedding and the rise in electricity tariffs that occurred in South Africa. Most of the SPIS are integrated with irrigation techniques with high water use efficiency. The details of SPIS found in this chapter for South Africa were determined, but more SPIS users in the country need to be confirmed to obtain more information.

Keywords: solar powered irrigation, survey, water use efficiency, load shedding

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3.1 Introduction

South Africa has a high potential for solar powered irrigation, as the country receives high levels of direct normal irradiation. The production of electrical energy through solar photovoltaic (PV) panels is one of the most environmentally friendly, emission free and sustainable sources of energy known to humankind.

The main source of electrical power in South Africa is fossil fuels. The country produces most of its electrical power from coal power stations. In the agricultural sector, irrigation is one of the sectors that consume high levels of electricity (DoE, 2012).

South Africa's electricity costs were possibly rated among the cheapest in the world. This was before 2008 when Eskom, the country's energy supplier, had trouble meeting the country's electricity demands (Jumman and Lecler, 2010). This was a result of the infrastructure, at the time, not matching the maintenance requirements and the growing demands of the country. This resulted in the decline in service and the introduction to "load shedding" and an increase in electricity tariffs. A 25 % tariff increase that would be in effect in the year 2010 and for each of the following three years was approved. The economic state of the country coupled with the tariff increases and load shedding was set to have a negative impact on farm profitability sustainably (Jumman and Lecler, 2010). In 2019, a tariff increase of 13.82 % for 2019/2020 was approved. On the 22nd of January, Agri SA had a meeting with Eskom to discuss possible avenues to reduce the negative impact of load shedding on agriculture. The request was to exclude agriculture from stage 1 load shedding within the context of Food Security. The response from Eskom was it would not be possible since agriculture is not serviced by a dedicated agriculture network and that other stakeholders are similarly affected by load shedding (Liebenberg, 2019).

Most of the irrigation in South Africa is predominantly in commercial farms where the source of water is highly dependent on surface water resources such as rivers and dams. Commercial farmers are driven by energy efficiency and independence, while smallholder farmers are driven by access to energy and the cost of fuel (Hassan, 2015). According to Hassan (2015), the area of arable land that is under solar powered irrigation is estimated to be approximately 2 000 hectares in South Africa.

Apart from the Hassan (2015) report, there is very little information and documentation on the extent of SPIS development in South Africa, and the information available is mainly short

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articles on one SPIS that has been implemented by a company for exposure. As a result, information and characteristics of SPIS in South Africa are lacking. The main objective of the study of this chapter was to determine the extent of solar powered irrigation in South Africa and to determine the characteristics of the SPIS' found. All types of SPIS′ were included in the research.

3.2 Materials and Methods

The study was carried out across the whole of South Africa. The following sections describe the tools and procedures used to develop the questionnaire and to distribute the questionnaire. An ethical clearance application was conducted through the Research Office at the University of Kwa-Zulu Natal (UKZN) and approved under Protocol Reference Number HSS/1039/017M.

3.2.1 Questionnaire

The questionnaire was developed, and it targeted four groups of stakeholders and these were (i) SPIS users, (ii) engineers, installers and suppliers, (iii) potential SPIS users, and (iv) former SPIS users. Initially, the questionnaire was developed on a word document where there were different sections for each stakeholder targeted to participate. The type of questionnaire developed is a semi-structured questionnaire. Due to the issue of stakeholders not participating in the postal questionnaire survey, the questionnaire was changed into an online questionnaire. SurveyMonkey® (SurveyMonkey, 1999) was the tool used to create and run the questionnaire online. Survey Monkey® is an online application that helps users to create and distribute surveys and to collect and analyse the data obtained from the surveys. Two questionnaires were made for each group of targeted stakeholders. A pilot test was not conducted as the sample size was unknown before the questionnaire was distributed.

3.2.2 Data Collection

A few methods were implemented to try and obtain data for the questionnaire.

- Calls were made to practising agricultural engineers and others working in consulting companies and government departments around South Africa.
- Requests were made to South African Irrigation Institute (SABI) and the South African Institute for Agricultural Engineers (SAIAE) to assist in the distribution of the questionnaire by sending out the links to the questionnaires to their members

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- Attended a training programme at Franklin Electric® where companies that sell Franklin Electric® products were in attendance.
- The links to the questionnaires were sent to Farmer's Weekly magazine, where requests for respondents were posted on the Farmer's Weekly Facebook® and Twitter® pages. Some followers on both platforms retweeted and shared the requests, which helped spread the requests to a wider audience.
- Internet searches were conducted to try and find any documentation on systems implemented in South Africa
- A seminar on SPIS was attended ("MASLOWATEN: Large Photovoltaic Irrigation Systems" on the 14th of March, 2018) where networking was done to try and find more participants for the questionnaire.

3.2.3 Analysis

The data was analysed by Survey Monkey® and this data was opened on Microsoft Excel where tables, pie charts and bar graphs with frequencies of the results obtained were produced. Arc GIS was also used to provide a visual presentation of the location of the SPIS systems that were found through the questionnaire.

3.3 Results

3.3.1 SPIS engineers, designers and installers

Eighteen respondents participated in the SPIS engineers, designers and installers questionnaire and the results from SurveyMonkey® are presented below.

3.3.1.1 Basic demographic information

The demographics of the SPIS engineers, designers and installers, such as race, gender and age are presented in Table 3.1. The age range of the respondents is 25 –74 years, and the dominant age range is 45 –54 years (29 %).

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Table 3.1 Demographic profile of respondents

Categories	**Total number of respondents (N=18)**	**Total response rate (%)**
Race		
White	13	81
African	2	13
Indian	1	6
Coloured	0	0
Other	0	0
Skipped	2	-
Gender		
Male	18	100
Female	0	0
Age range (Years)		
18 – 24	0	0
25 – 34	4	24
35 – 44	3	18
45 – 54	5	29
55 – 64	4	24
65 – 74	1	6
>75	0	0
Skipped	1	-

Presented in Figure 3.1 below is a pie chart showing the level of education that the participants have obtained. The highest education levels achieved by the participants range from matric to

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postgraduate degree (honours, masters or PhD), where almost half of the respondents have completed their post-graduate degrees (44 %).

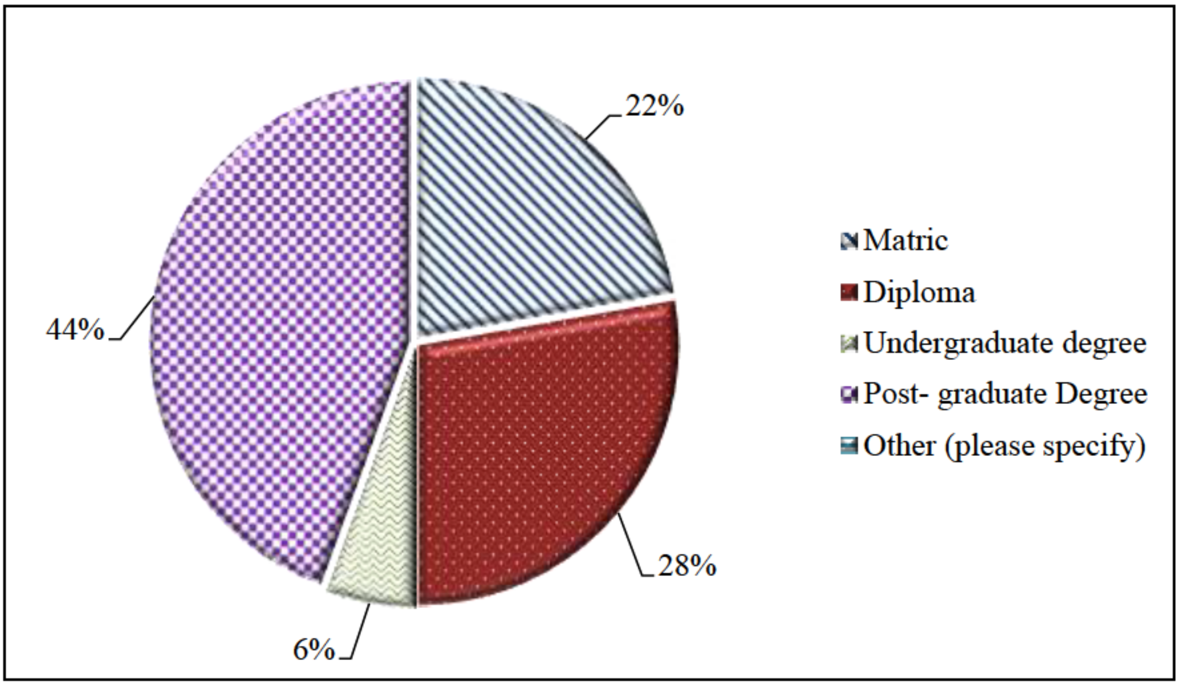

Figure 3.1 The highest education level achieved by the respondents

3.3.1.2 Respondents' involvement with SPIS'The involvement of SPIS engineers, installers and designers with SPIS' and their opinion on the feasibility of SPIS in South Africa is shown in Figure 3.3 to Figure 3.6

The information depicted in Figure 3.3 below shows the range of SPIS's every respondent has been involved with. Most of the respondents are in companies or institutions that have

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implemented in the range of 0 – 5 SPIS (61 %) and a third of the respondents have implemented 17 or more SPIS in South Africa (33 %).

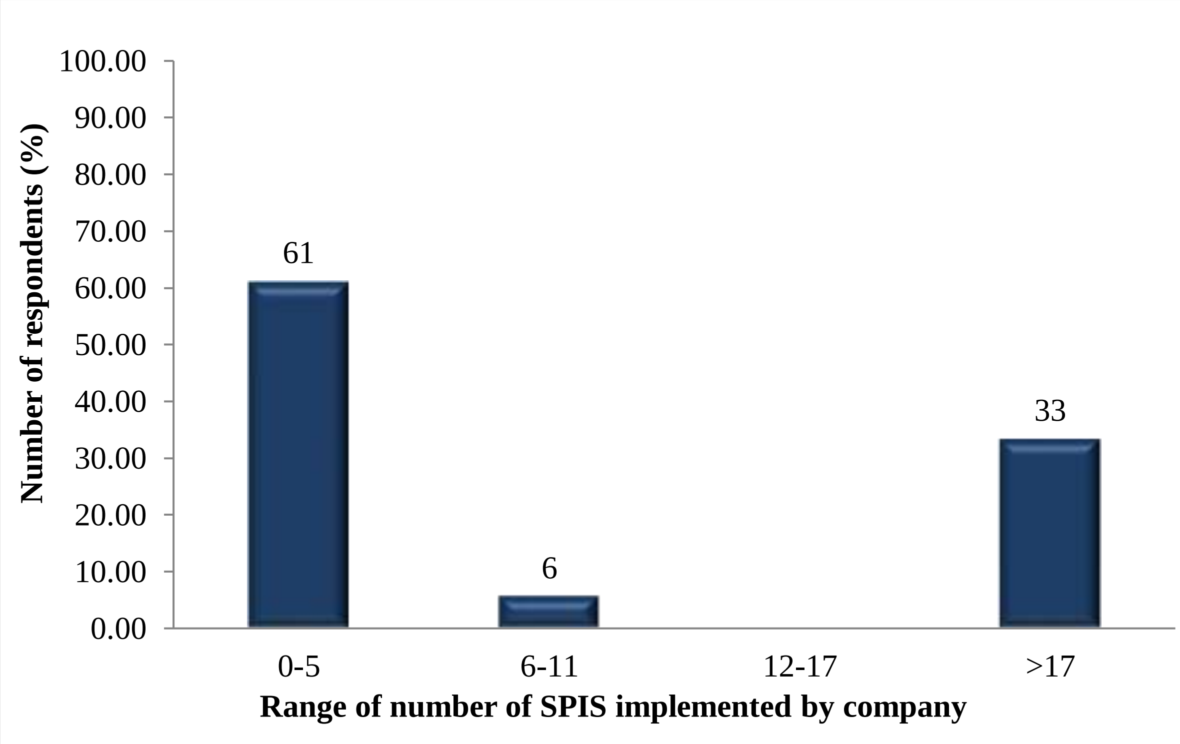

Figure 3.3The involvement of SPIS engineers, installers and designers with SPIS' and their opinion on the feasibility of SPIS in South Africa is shown in Figure 3.3 to Figure 3.6

The information depicted in Figure 3.3 below shows the range of SPIS’s every respondent has been involved with. Most of the respondents are in companies or institutions that have implemented in the range of 0 – 5 SPIS (61 %) and a third of the respondents have implemented 17 or more SPIS in South Africa (33 %).

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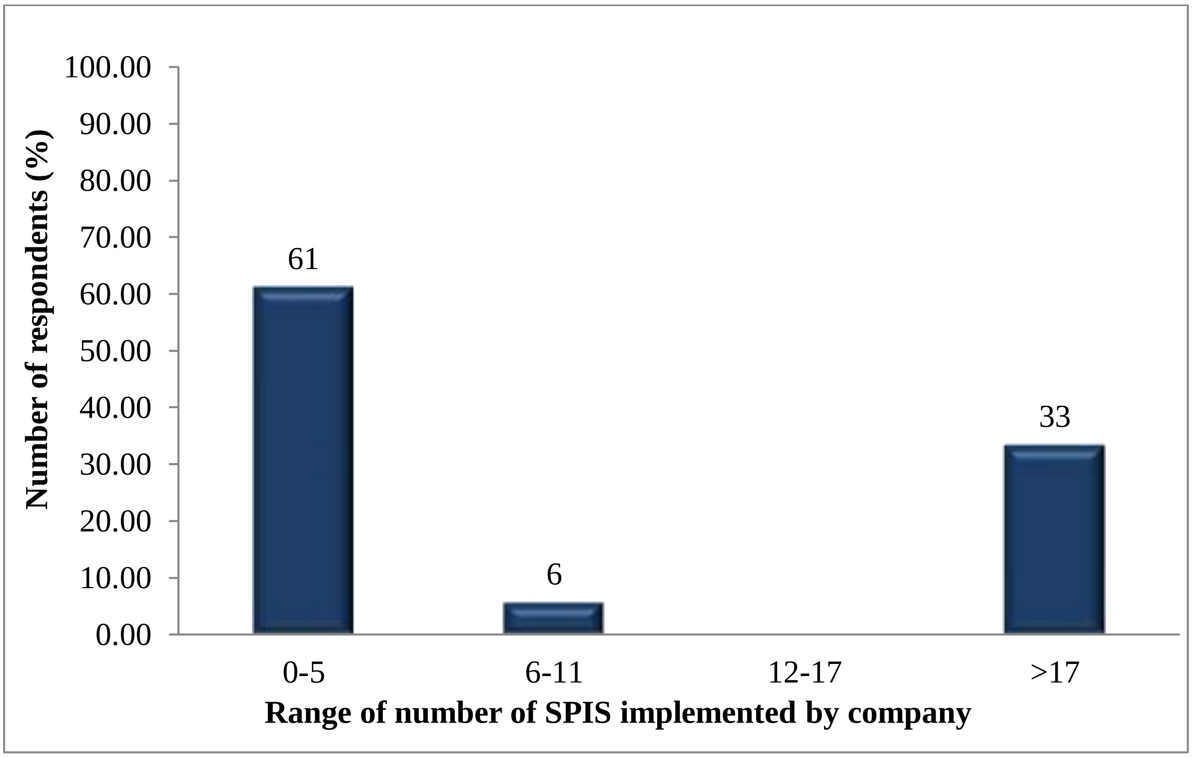

Figure 3.3 The range of SPIS implemented by the respondents' company or institution

Shown in Figure 3.4 is the percentage of the type of farming SPIS that has been implemented by the respondent. The type of farm refers to either commercial farming, smallholder farming or subsistence farming. Almost half (44 %) of the respondents were involved with the implementation of SPIS for smallholder farming.

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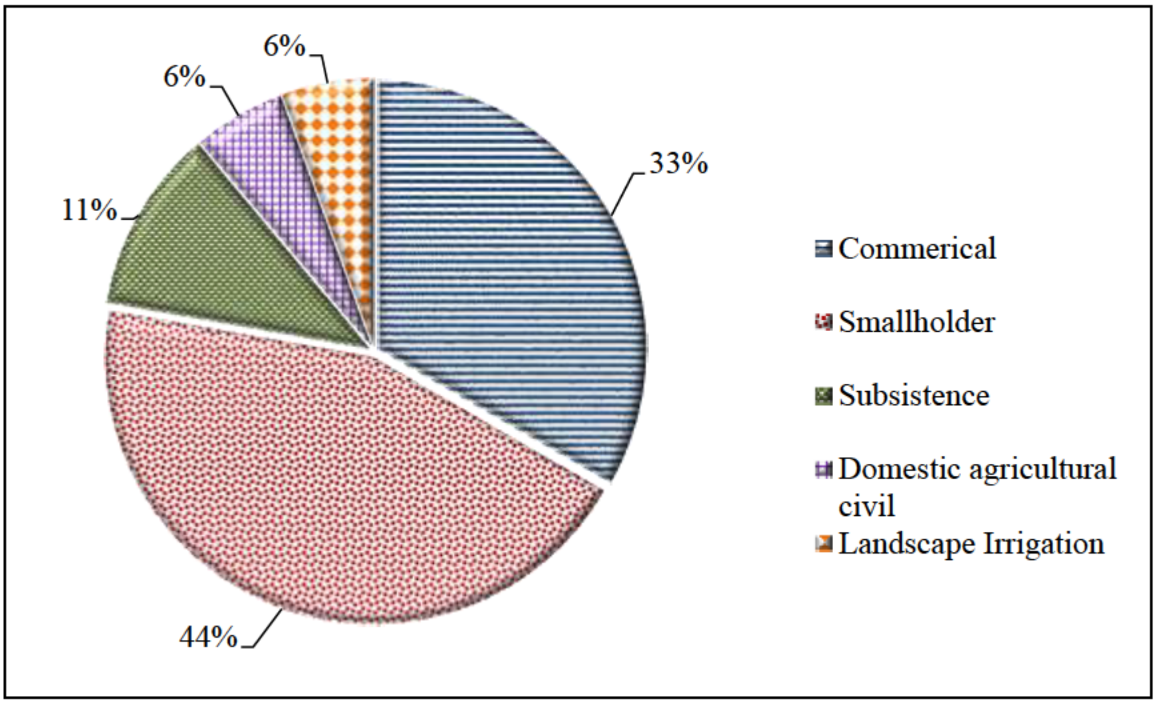

Figure 3.4 The main type of farming the respondent's company implements SPIS for

Illustrated in Figure 3.5 is the response to which provinces each respondent had implemented SPIS in South Africa. Some respondents implemented SPIS in multiple provinces in the Country which resulted in the sum of the percentages adding up to 100 %. The Eastern Cape and the Western Cape both have the top SPIS implementation (33 %).

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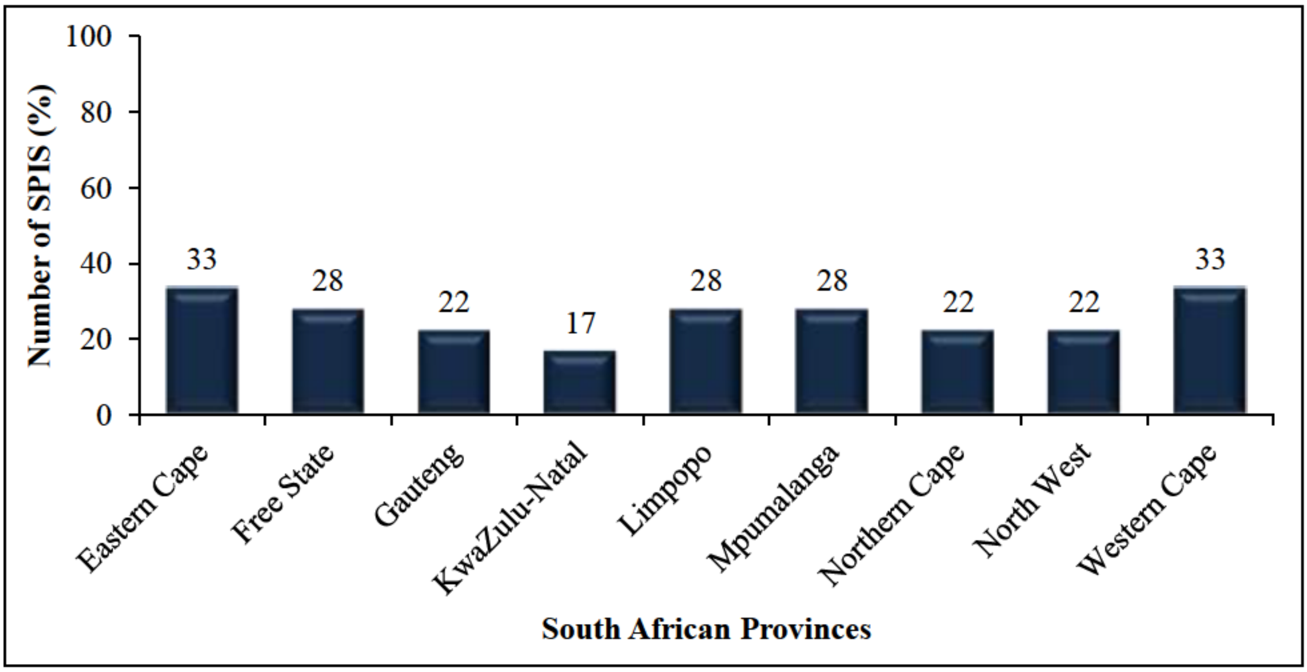

Figure 3.5 The provinces the respondents have implemented SPIS

Shown in Figure 3.6 is the percentage of irrigation systems that the engineers, installers and designers have mainly integrated with SPIS. Sprinkler and drip irrigation had the most integration with SPIS at 33 % each.

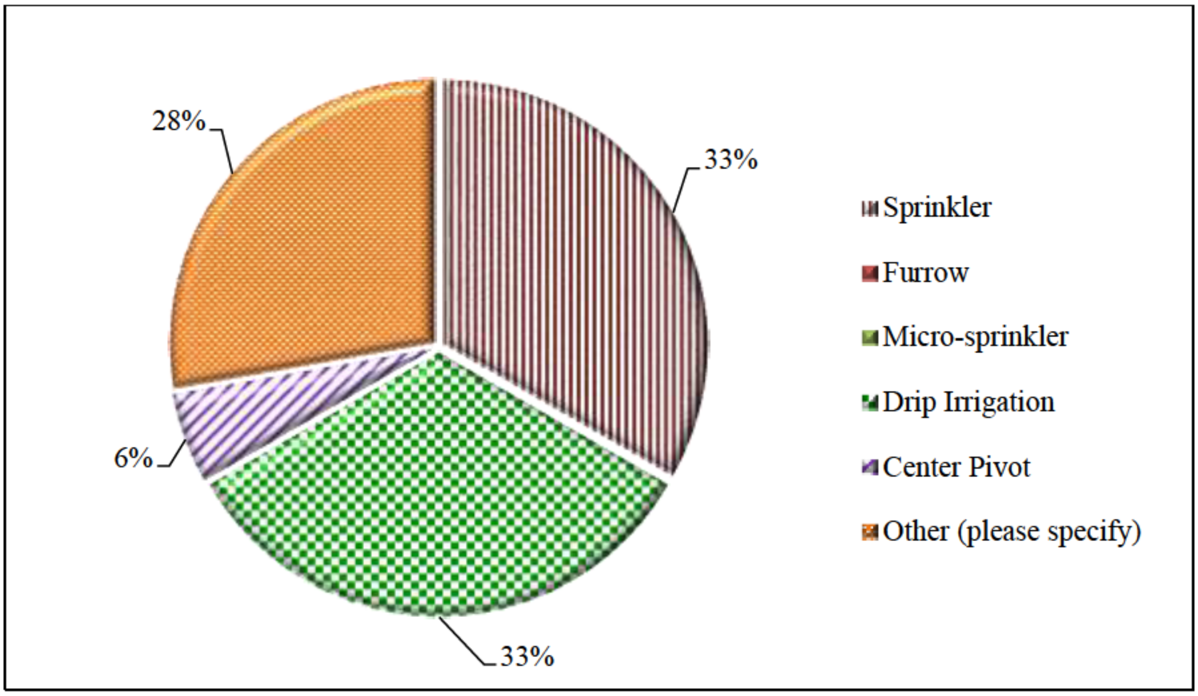

Figure 3.6 Types of irrigation systems a company mainly implemented

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When asked whether the SPIS they implemented had been vandalised or not, 78 % of the respondents replied that this had not happened and 22 % replied that some of the SPIS had been vandalised.

In response to the question as to whether they believe SPIS is feasible in South Africa, the majority of the respondents (89 %) answered that they did with the remaining 11 % believing that SPIS is not feasible in South Africa.

3.3.2 SPIS users (farmers)

This section of the questionnaire was designed for SPIS users who are mainly farmers in South Africa.

3.3.2.1 Basic SPIS user information

The demographics of the SPIS users such as their race, gender and age are presented in Table 3.2. The majority of the respondents were Whites (77 %), followed by Africans (23 %), and all of them were males (100 %). The respondents' ages ranged between 25 and 74 years, and the dominant age range was 45 – 54 years (55 %).

Table 3.2 The demographics of the respondents (SPIS users)

Categories	Total number of respondents (N = 13)	Total response rate (%)
Race		
White	10	77
African	3	23
Indian	0	0
Coloured	0	0
Other	0	0
Gender		
Male	13	100
Female	0	0
Age		
18 – 24	0	0
25 – 34	1	9
35 – 44	2	18
45 – 54	8	55
55 – 64	1	9

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65 – 74	1	9
>75	0	0

Illustrated in Figure 3.7 is the highest education level obtained by each participant. Many of the respondents (38 %) have obtained a diploma.

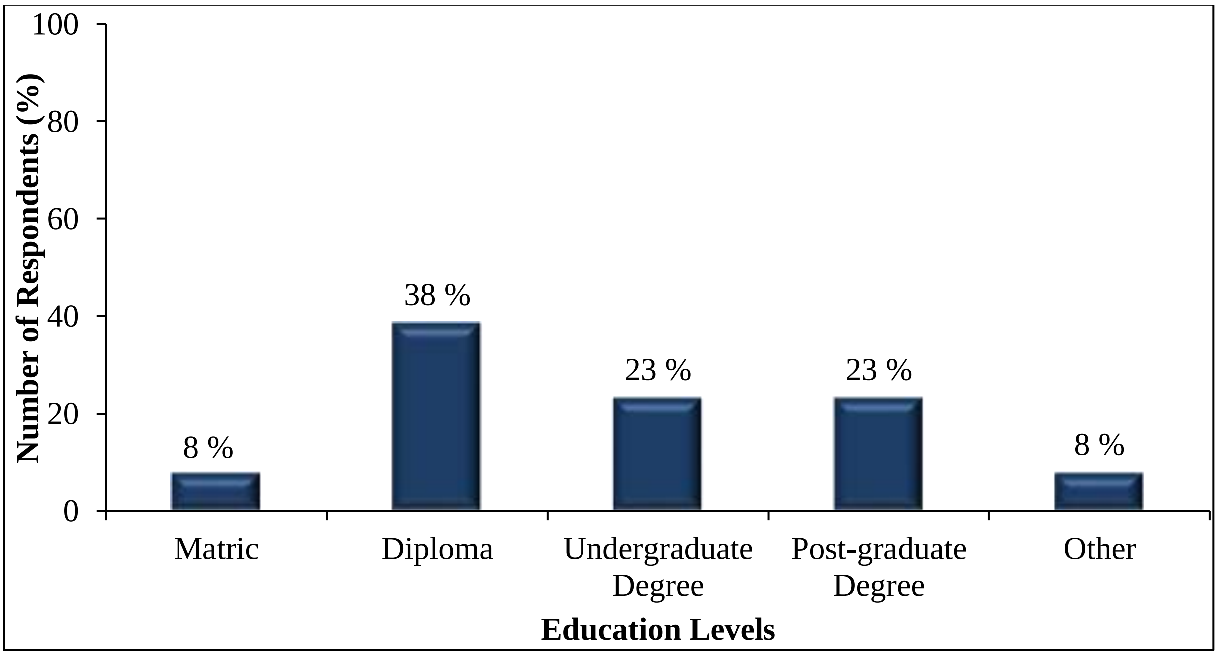

Figure 3.7 The level of education of the respondents

3.3.2.2 Location information of SPIS'

The location of the SPIS users such as the province and district municipality, in which the farm was located in and the area of the farm, is presented in Figure 3.8 and Table 3.3.

The Western Cape province dominated the other provinces such as Gauteng, Eastern Cape, Limpopo, Free State and KwaZulu-Natal, by having the highest number of SPIS (31 %) (see Figure 3.8).

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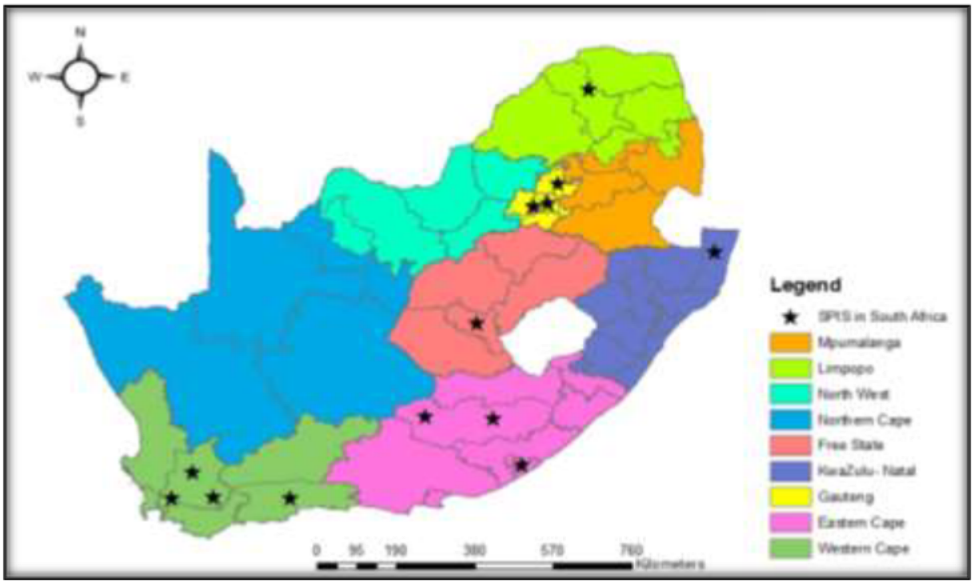

Figure 3.8 South African map showing the location of SPIS identified.

Table 3.3 shows the province, the district municipalities and metropolitans and the farm sizes of each farm. The largest SPIS system was in the Western Cape, in the Cape Winelands district municipality with a farm size of 140 ha. The smallest SPIS system was in Limpopo, in the Capricorn district municipality with a farm size of 0.135 ha. The total size of all farms combined was 364.415 ha.

Table 3.3 The province, municipalities and the farm sizes of the SPIS systems

Number of SPIS	**Province**	**Municipality/ Metropolitan**	**Farm Size (ha)**
1	Free State	Mangaung Metropolitan	4.28
2	Limpopo	Capricorn District	0.135
3	Western Cape	Eden District	41
4	Western Cape	Eden District	60
5	Western Cape	Cape Winelands District	140
6	Western Cape	Cape Winelands District	35
7	Western Cape	Cape Winelands District	48
8	Eastern Cape	Buffalo City Metropolitan	12
9	Eastern Cape	Chris Hani District	10
10	Gauteng	Ekurhuleni Metropolitan	2
11	Gauteng	City of Tshwane Metropolitan	4
12	Gauteng	City of Johannesburg Metropolitan	Not Specified
13	KwaZulu-Natal	Zululand District	8
Total Area			**364.415**

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3.3.2.3 Characteristics and components of the SPIS

The characteristics of each SPIS were checked to determine whether a trend existed for the SPIS users. Figure 3.9-Figure 3.13 illustrates the characteristics of the farmers' (users') SPIS.

Figure 3.9 presents commercial farms as the type of farm mostly integrated with SPIS (54 %).

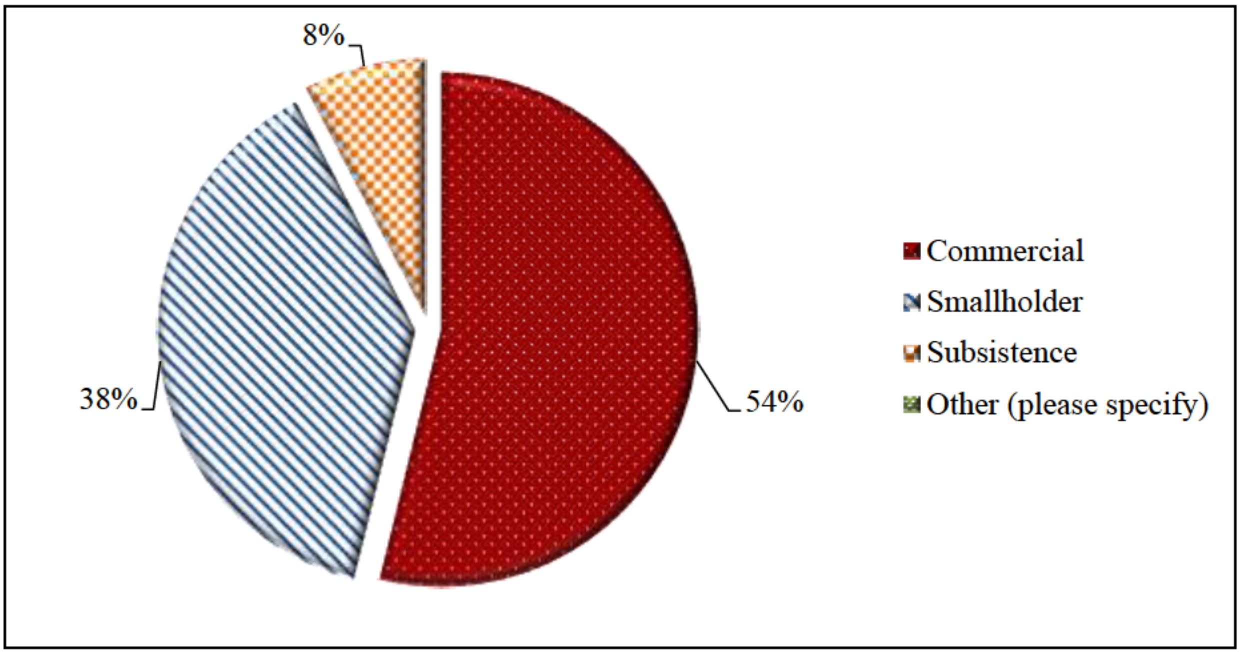

Figure 3.9 The type of farm the respondents' SPIS are integrated with

Figure 3.10 shows the water source that is mostly used with SPIS by percentage is a borehole (61 %), followed by river or dam (31 %).

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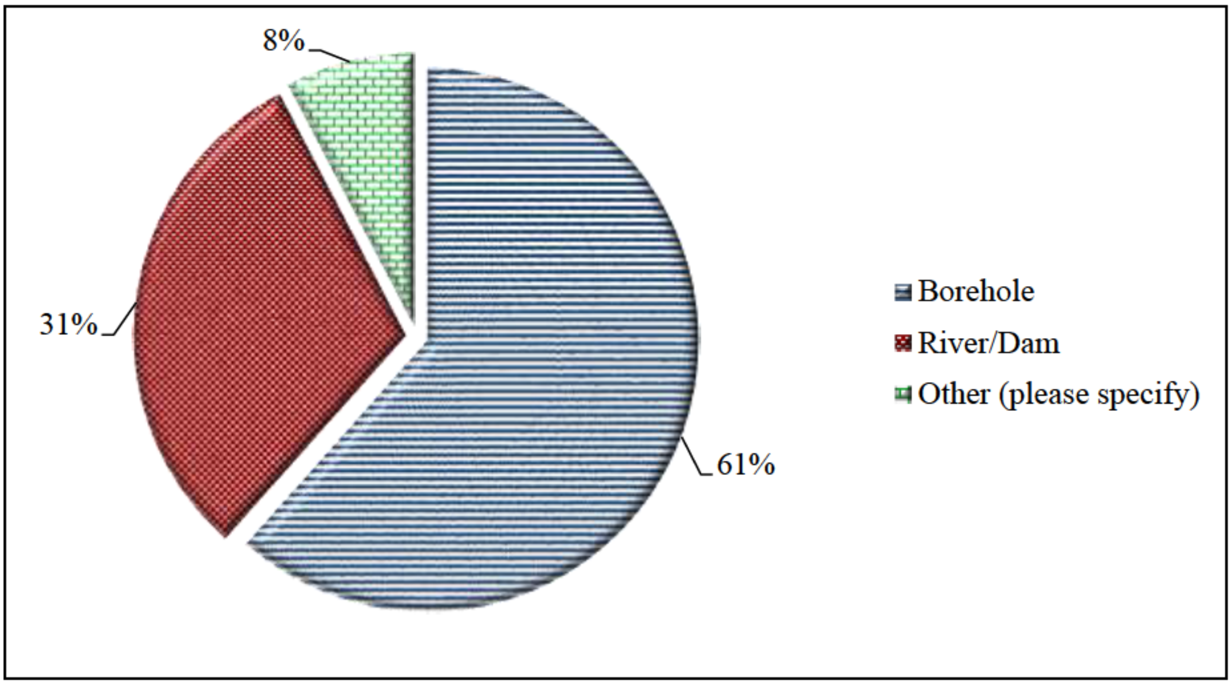

Figure 3.10 The type of water source for irrigation

Shown in Figure 3.11 is that drip irrigation and sprinkler irrigation are equally the most integrated with SPIS (38 %).

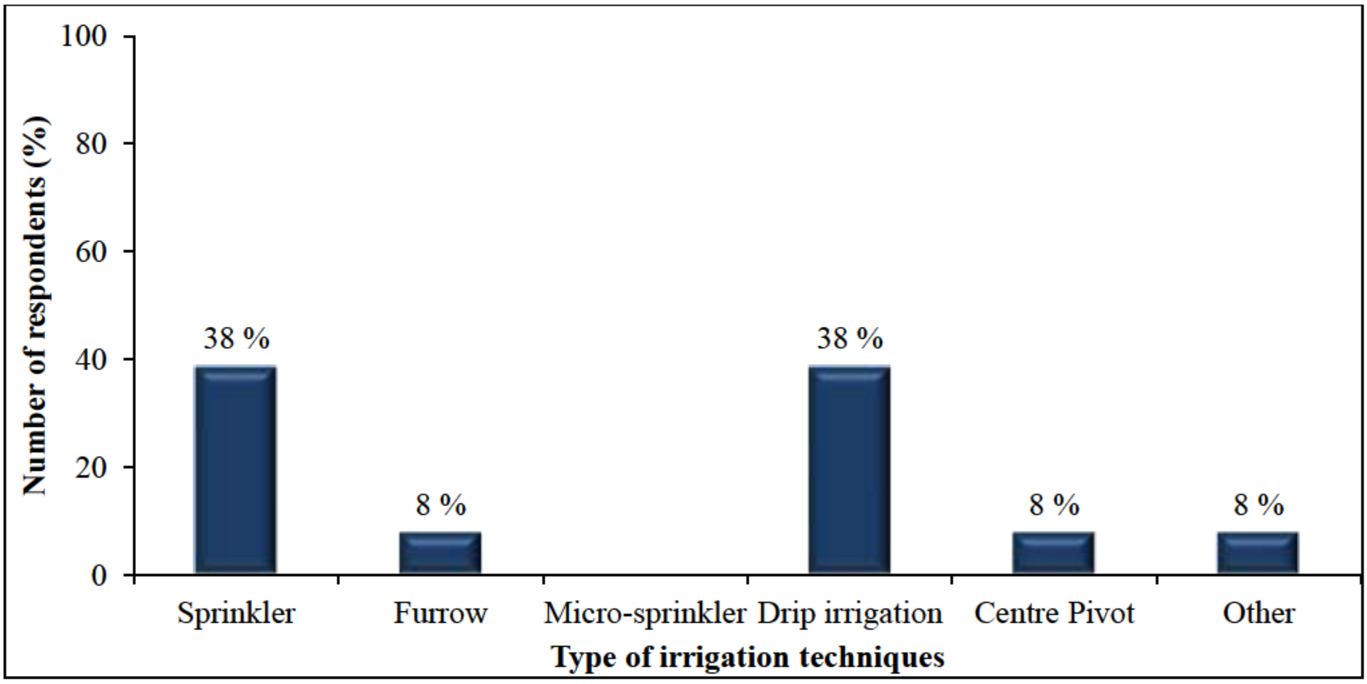

Figure 3.11 The type of irrigation technique SPIS is integrated with

Presented in Figure 3.12, the type of solar panels that are used for SPIS by the respondents is mainly poly-crystalline solar panels (77 %).

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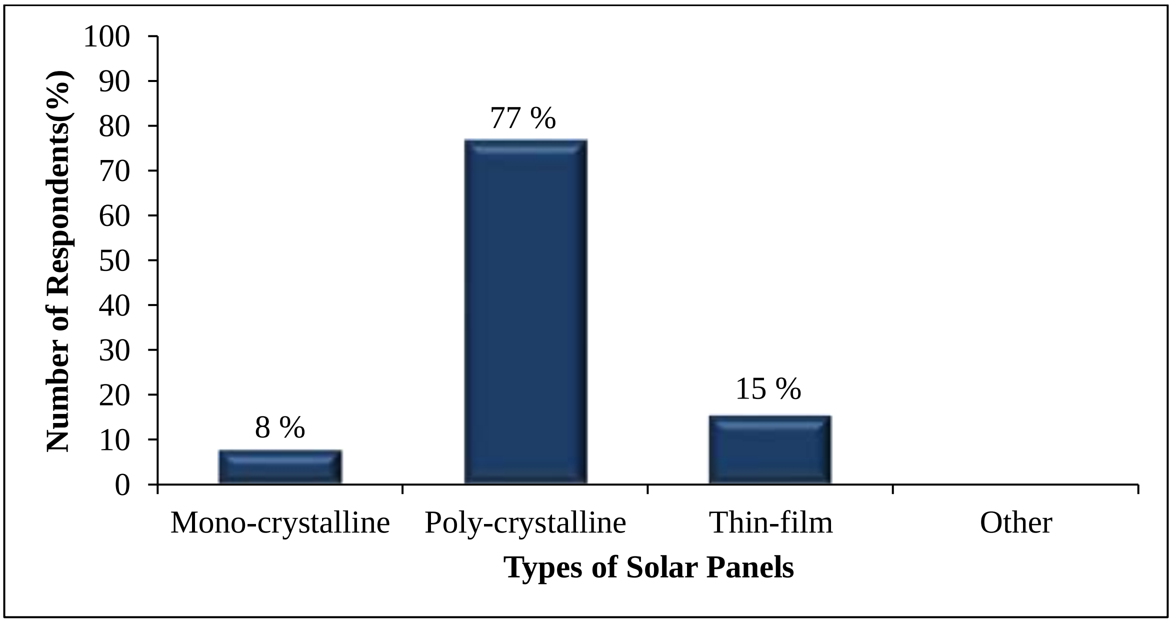

Figure 3.12 The type of solar panels used in the respondents SPIS

Presented in Figure 3.13, the results show that most of the respondents (62 %) have submersible multistage centrifugal motor pump set pumping water.

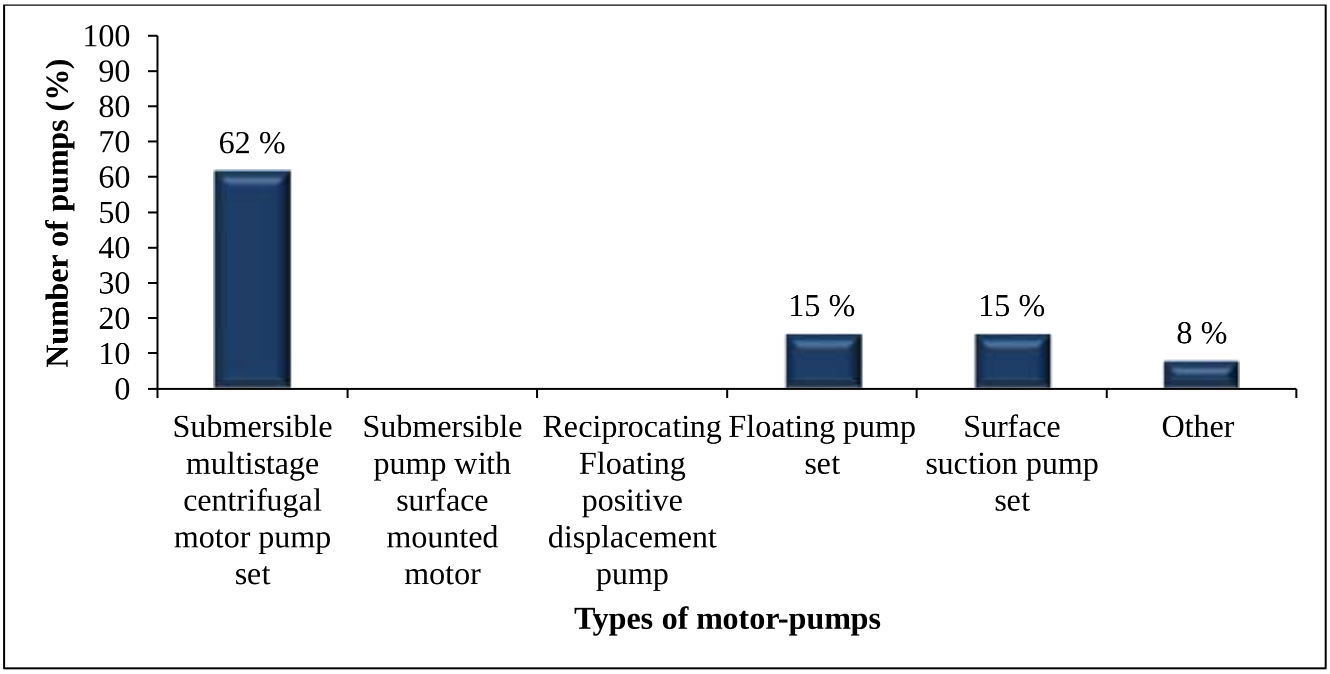

Figure 3.13 The type of pump-motor set used for the SPIS

3.3.2.4 Storage options (energy and water)

The use of solar energy in water pumping may need some sort of water or energy storage options depending on the demands of the farm. Two alternatives are available for the storage of

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electrical power. These alternatives include a battery storage package and the use of the electrical grid. These two alternatives save excess electricity that is produced from the solar panels. A storage water tank is used in an SPIS to store water that is pumped for days when there is not enough solar radiation to power the motor pump set. Another alternative for back up energy is a generator, where farmers can use this when there is not enough solar radiation available to pump water for irrigation.

Table 3.4 shows the responses the respondents provided concerning five questions that required answers of yes or no.

Table 3.4 Energy and potential energy storage of SPIS

	Yes		No		Skipped		Total Respondents
	No. of respondents	Percentage (%)	No. of respondents	Percentage (%)	No. of respondents	Percentage (%)	
Does the system have batteries?	1	8	12	92	0	0	13
Is the system connected to the grid?	4	31	9	69	0	0	13
Does the system make use of a generator for backup power?	3	23	9	69	1	8	13
Does the system have a water tank to store excess water pumped?	4	31	9	69	0	0	13
Do you ever have pressure and or flow rate problems?	4	31	9	69	0	0	13

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3.3.2.5 Additional information on the SPIS'

Additional information about the SPIS's of the respondents is captured from Figure 3.14-Figure 3.16.

Displayed in Figure 3.14 is the years in which the respondents installed their SPIS. The years 2013 and 2016 had the highest installation of SPIS (31 % each). One respondent did not mention which year they implemented their SPIS.

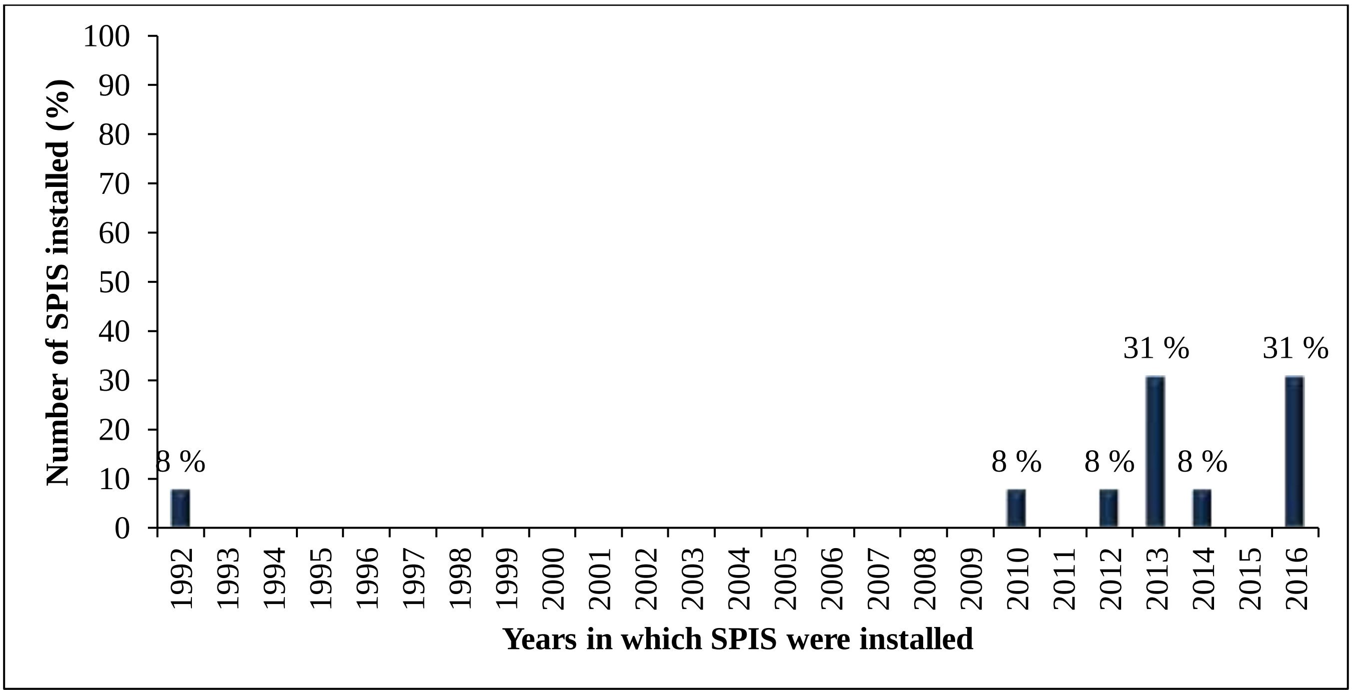

Figure 3.14 The year in which the SPIS was implemented

In Figure 3.14 the respondents were asked what changes they would implement to their SPIS. Most of the respondents replied that they would increase the security of their SPIS (46 %).

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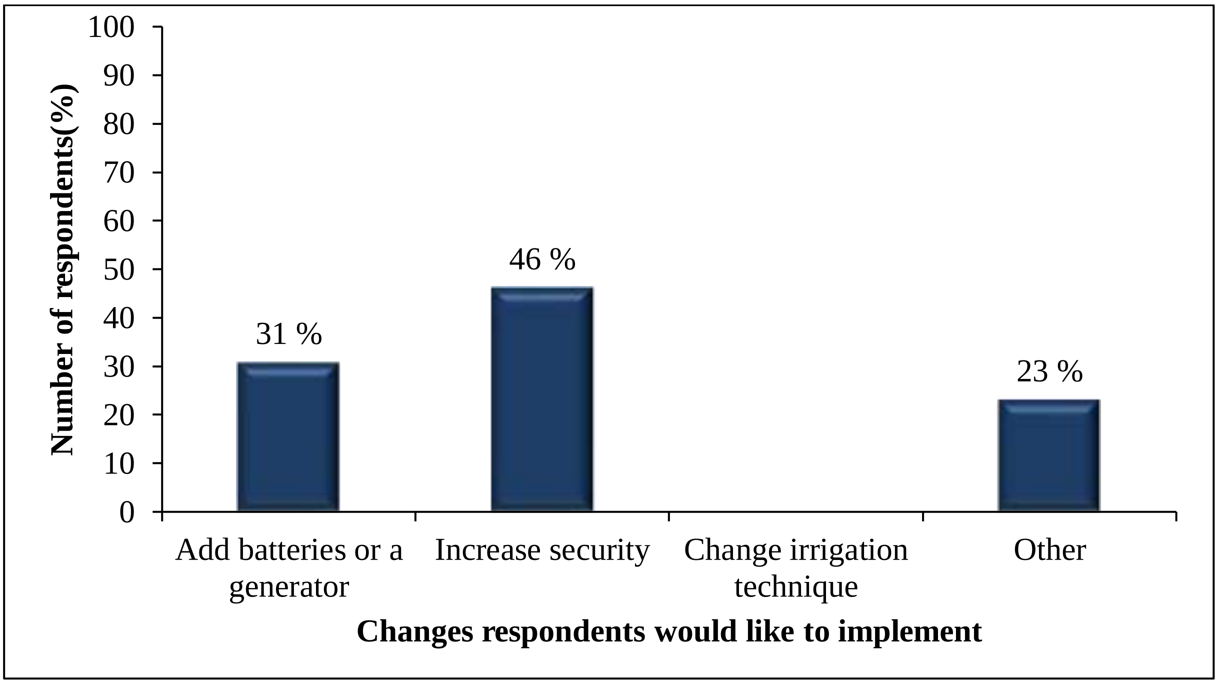

Figure 3.14 Improvements the respondents would implement to their SPIS

Presented in Figure 3.16 is a bar graph showing the results for the power source the respondents were using before they installed the SPIS. Most of the respondents were using grid electricity (70 %).

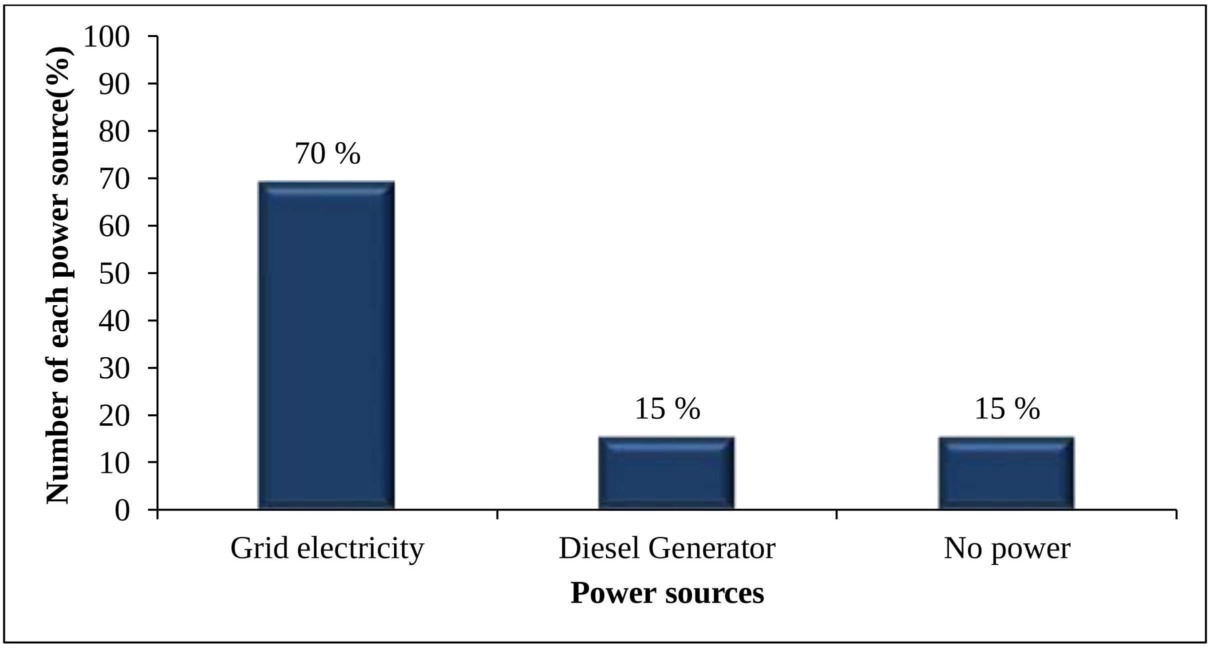

Figure 3.16 The power source each respondent used before the SPIS

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3.4 Discussion

This section discusses the results obtained from the two questionnaires that were distributed to SPIS engineers, designers and installers and SPIS users.

3.4.1 SPIS engineers, designers and installers

The discussion on the results is split into two in this sub-section. The respondents' basic information includes the demographics and the education level and the respondents' involvement with SPIS'.

3.4.1.1 Respondents' basic information

The race results correspond to the Engineering Council of South Africa (ECSA)'s proportions of the total number of registered engineers in 2016, where they stated that registration statistics by the race of engineers for White, African, Coloured and Indian are 71 %, 18 %, 9 % and 2 %, respectively. The reason for the low percentage registration rates of non-white engineers is related to individuals migrating to other economic sectors or they are creating their business opportunities outside engineering (ECSA, 2016). The results for gender also correspond to ECSA's 2016 annual report, which states that 10 % of the registered engineers were women (ECSA, 2016; Padayachee, 2017). Gender bias is one of the main reasons stated by Padayachee (2017). This means that fewer women than men become professional engineers. Another reason is gender imbalance, which means that the fields of science, technology, engineering and mathematics (STEM) in 2016 had 23 % of women globally. Padayachee (2017) stresses that the gap needs to be addressed and prioritised so that more women can join the fields of STEM.

The education level of the SPIS engineers, installers and designers results does not correspond to the 2012 findings of the Council on Higher Education of South Africa, which state there are 41 % of engineering graduates with certificates and diplomas and 44 % of engineering graduates with undergraduate degrees (CHESA, 2012). The results from the survey show that many of the respondents have a post-graduate degree. In South Africa, the University of South Africa and the University of Pretoria offer engineering honours degrees, which are considered post graduate degree in South Africa.

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3.4.1.2 Respondents' involvement with SPIS'

There may be an overlap of the results, as some of the respondents may have come from the same company. This cannot be confirmed because the respondents answered the questionnaire anonymously.

The small number of SPIS implementation around the country is caused by the high investment cost that comes with SPIS, as well as the perception of theft and security risk associated with SPIS. There is also limited understanding of technology by banks for financing and the possibility of land reform in South Africa (Hassan, 2015). In other countries, governments are promoting the use of SPIS in the framework of their national action plan regarding climate change as a way to reduce emissions in the agricultural sector (Hartung and Pluschke, 2018). South Africa has not done this yet.

According to a study done by Hassan (2015), there are more than 225 thousand smallholder farmers in South Africa occupying an estimated 10 million ha, over 40 thousand commercial farmers are occupying an estimated 82 million ha and roughly 3 million households with subsistence farmers occupying 4 million ha of land. Commercial farms are generally large and would require many solar panels which will require large areas of land to provide power for irrigation systems and very high investment costs for the solar technology required. This explains the high number of SPIS that are implemented for smallholder irrigation systems. The high investment costs that come with SPIS would prevent subsistence farmers from implementing SPIS. Subsistence farmers grow crops for their use to feed their families only. This would support the result of the low implementation of SPIS for subsistence farms due to the farmers not selling their crops for profit to be able to afford SPIS. Smallholder farmers own small plots of land on which subsistence crops are grown and one or two cash crops that are sold for profit. Since the plot areas are small, the number of solar panels would be small compared to large commercial farms. Though the investment cost of SPIS is high, smallholder farmers would be able to save profit from their cash crops and or apply for a loan to assist in purchasing an SPIS.

Singh (2016) states that the north and north west regions of South Africa receive more solar radiation than the south and south east. Shortwave flux (SW_{flux}) is a measure of solar radiation per square area and between the years of 1980 – 2009, the Northern Cape received the highest mean SW_{flux}, followed by North West, Free State, Limpopo, Gauteng, Mpumalanga, Western

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Cape, Eastern Cape and Kwa-Zulu Natal has the lowest SW_{flux}. Niekerk *et al.* (2018) identified the irrigated area in South African provinces, and the Western Cape (269 476 ha) has the highest irrigated area, followed by Limpopo (218 302 ha), Eastern Cape (152 866 ha), Northern Cape (144 579 ha), Mpumalanga (125 595ha), Kwa-Zulu Natal (177 341 ha), North West (97 211 ha), Free State (129 077 ha) and Gauteng (20 115 ha). This information shows why the Western Cape and the Eastern Cape are receiving the highest implementation of SPIS from engineers, installers and designers of SPIS.

The Department of Water and Sanitation in 2014 had 32 % of their registered water users using sprinkler irrigation systems, followed by 29 % using moving irrigation systems, then 26 % using micro-irrigation system and 14 % using flood irrigation systems (Schulze, 2016). This explains why the respondents have mostly integrated SPIS with sprinkler and drip irrigation. According to Zegeye *et al.* (2014), photovoltaic energy has been widely used in low power applications in the world. A drip irrigation requires a low head compared to other irrigation systems making their power requirements low.

South Africa receives high levels of solar energy that can be converted into electrical power (DoE and GIZ, 2015). Hassan (2015) states that solar energy is already competitive with diesel when the grid connection is not available. Many of the respondents feel that SPIS is feasible in South Africa and they mentioned the following reasons why:

- SPIS saves energy and has better returns if the system is subsidised on the capital investment of the system.
- Grid electricity from Eskom is rising in price and is likely to become expensive and unreliable in the future, and the economy is volatile.
- The prices of technology are decreasing and will continue to make it more affordable
- With small scale irrigation systems, SPIS is feasible.
- South Africa receives a significant amount of solar energy which can be increased when using low pressure drip irrigation systems.
- SPIS's save a lot of money in the long run.
- South Africa receives high levels of sunshine and many areas are off the grid.

The remaining respondents that felt SPIS's are not feasible in South Africa gave the following reasons, which include the following:

- The cost of infrastructure requirements is too high, and it is not economically viable.

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- Solar is not suitable for irrigation because of the varying 8 hours of sunlight received in South Africa on average.

3.4.2 SPIS users (farmers)

The discussion on the results is split into five in this sub-section. The respondents', information which includes demographics and the education level, the location information of the SPIS, characteristics and components of SPIS', storage options and additional information of the SPIS are all discussed in this sub-section.

3.4.2.1 Basic SPIS user information

These results are presented in Table 3.2 respectively. According to Reform (2017), 72 % of the total farms and agricultural holdings are owned by white people in South Africa. Males own 72 % of the total farmland and agricultural holdings in the country while females own 13 % (Reform, 2017). The results obtained in Table 3.2 reflect this reality of white males dominating the ownership of farms in South Africa.

3.4.2.2 Location information of SPIS'

According to Hassan (2015), the estimated area of land in South Africa that is under solar irrigation is 2000 ha. The total area of the SPIS systems that were found through the questionnaire was 364.42 ha. Communication was made with Hassan (2015) to request more information on the project that was funded by the International Finance Corporation and he stated he could not share the information. Table 3.3 and Figure 3.7 show that four out of the 13 SPIS are in the Western Cape, followed by 3 system both in the Eastern Cape and in Gauteng. Limpopo, KwaZulu-Natal and the Free State have one SPIS system. Figure 3.4 shows that engineers, installers and designers have implemented SPIS's in all the provinces in South Africa. The survey for SPIS users did not reach users in Mpumalanga, Northern Cape and North West. The data collected from the SPIS users and SPIS engineers, designer and installers do not correlate due to the survey not being distributed effectively.

Hassan (2015) states that commercial farmers in South Africa are driven towards SPIS because of energy independence and efficiency. This shows why most of the SPIS users are commercial farmers.

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3.4.2.3 Characteristics and components of the SPIS

The (DWF, 2004; WWF, 2016) stated that South Africa primarily uses surface water for most of its urban, industrial and irrigation requirements. Groundwater is also used, but it's mainly used in rural areas and more arid areas. Groundwater use is limited to a few places in the country due to the geology which is hard rock. This information does not correspond to the results obtained in the survey as most of the SPIS use boreholes as a water source.

Most of the respondents have sprinkler and drip irrigation systems. One of the benefits of having these two irrigation techniques integrated with solar are, compared to furrow and centre pivot irrigation, the power requirements of these systems are low head, which resulted in the cost of the solar pumping system being low cost (Basalike, 2015).

The most commonly used type of solar panel for SPIS is poly-crystalline solar panels. These results correspond to literature where the cost factor of mono-crystalline solar panels overrules its advantage with its efficiency, which ranges between 15 – 20 %, while the efficiency of polycrystalline solar panels ranges between 13 – 16 % (Bharam, 2012; Davies, 2013). The cost of poly-crystalline solar panels is lower than the cost of mono-crystalline solar panels (Davies, 2013). Thin-film solar panels are the cheapest type of solar panel, but the reason why this type of solar panel is seldom used is that their efficiency is low at 7 – 13 % compared to monocrystalline and polycrystalline solar panels, which leads to them requiring a lot of space (Davies, 2013; Sendy, 2017).

3.4.2.4 Storage options (energy and water)

The submersible centrifugal pump has high reliability for pumping water especially for boreholes with medium depth (60 m) (Argaw, 2003). The submersible multistage centrifugal pump can provide high head pumping requirements (Volk, 2005). Most of the respondents are pumping water from a borehole and most of the respondents are using submersible multistage centrifugal pumps with their SPIS.

There are disadvantages to using a battery pack in an SPIS, and these include, reducing the efficiency of the overall system because the operating voltage is dictated by the batteries and not the solar panels. Batteries are usually not recommended because of the additional cost for maintenance and the initial cost of the system (Eker, 2005). This explains why only a few SPIS users have SPIS with a battery pack. The reason there are few grid connected SPIS is because

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Eskom does not allow the connection of small scale generator connections to their low voltage networks because this places the safety of the public and Eskom operating staff at risk (Eskom, 2014). Biswas and Iqbal (2018) state that the use of a diesel engine provides lower costs for hybrid systems, but they are a bad solution for longer periods due to the increasing fuel prices and the cause of pollution to the environment. According to Abdelfattah (2017), a stand-alone system with an elevated storage water tank is the most popular. This is not reflected in the results as only 36 % of the respondents have storage water tanks integrated with their SPIS.

The design of SPIS needs to be fit-for-purpose and need regular services to advise farmers on the most suitable system, but these are often not in place (Hartung and Pluschke, 2018). This is the cause of some systems having pressure and flow rate issues at times.

3.4.2.5 Additional information on the SPIS'

"Eskom resorted to national 'load shedding' from late 2007 to protect the power system from a total blackout, and a national emergency was declared in January 2008. Load shedding continued until the end of March 2008, while Eskom initiated a recovery plan, with the support of the government and business" (Joffe, 2012; Goldberg, 2015) This would explain the high implementation of SPIS during the year 2010 and 2016 as most of the respondents switched from Eskom grid electricity to solar power.

SPIS are vulnerable to theft and vandalism in some areas in South Africa (Palmer, 2005; Hartung and Pluschke, 2018). The problem of theft and vandalism is why many of the SPIS users specified to increase the security of their SPIS. This also explains why some SPIS engineers, designers and installers have had some of the SPIS they been involved with being vandalised.

3.5 Conclusion

This study concludes that there are SPIS' in South Africa, and a significant number is mainly located in the Western Cape and the Eastern Cape. All the remaining provinces do have SPIS as SPIS engineers, installers and designers have implemented them. The main reason most of the SPIS users opted to use solar as a power source for their water pumping needs was to get off the electrical grid and have some energy independence. This was due to the increase in electrical power costs and unreliable electricity during the years South Africa experienced load shedding. This can also be seen by the fact that a majority of the SPIS users installed their SPIS

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from the year 2010 to 2016. It was also found during this study that solar powered irrigation is feasible in South Africa as most of the SPIS users that participated in the questionnaire are commercial farmers.

The solar panel type that is predominately used is poly-crystalline solar panels, mainly due to its high efficiency (13 – 16 %) compared to thin-film solar panels (7 – 13 %) and its low cost compared to mono-crystalline solar panels (Laswell, 2018). Sprinkler and drip irrigation are irrigation techniques that are mainly integrated with solar powered irrigation with the SPIS users that participated in the questionnaire. The motor-pump set that is primarily used by the SPIS users is the submersible multistage centrifugal motor-pump set. These types of pumps are high head low flow types of pumps, where they can be used to pump water from deep surface water and boreholes. Most of the SPIS users pump their water from boreholes.

Overall the information acquired gave an idea of the extent of SPIS in South Africa and the main characteristics of SPIS in South Africa. The use of solar in irrigation will continue to rise as the price of solar components continues to decrease and more information on SPIS is available.

The recommendations going forward with this study are to find a better way to obtain responses from the SPIS users that were not identified. This can be done by visiting SPIS engineers, installers and designers directly and requesting them for the details of the SPIS they implemented and possibly also giving the contact information of the SPIS users. Some companies are restricted from doing this though.

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3.6 References

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4. DESIGN AND DEVELOPMENT OF A SOLAR POWERED IRRIGATION SYSTEM MODEL FOR SOUTH AFRICA

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Abstract

Irrigation is important in South African agriculture. Since 2008, the country has been experiencing electricity load shedding and increasing tariffs. This has been affecting the agricultural sector, specifically farms that rely on irrigation systems. There is a lack of information in South Africa on the design and application of solar powered irrigation systems (SPIS). There are also limitations with the design of an SPIS for different configurations. There is a need to develop a model or tool that can assist in designing low-cost SPIS in South Africa. The work reported in this chapter lays out the design and development of an SPIS model, using Microsoft Excel and Visual Basic Application (VBA), to determine the most suitable or optimal low-cost SPIS for given conditions of climate, crops, soils and topography in South Africa. CLIMWAT and CropWAT models were used to determine the crop water requirements which are used in the SPIS model. Solar irradiation data were obtained from the NASA Predication of Worldwide Energy Resources (POWER) and this information was accessed by the model through hypertext mark-up language (Html) coding on VBA. The equations used to design an SPIS were placed in MS Excel and VBA was used to make the model user friendly. The hydraulic power requirement for the pump was determined wherein the model then selects an appropriate pump type and size. The electrical power requirements are also determined by the model, which then selects the suitable size and number of photovoltaic solar panels required. The model offers sizing of the battery package system for the battery-coupled configuration and offers a sizing of the storage water tank for the direct-coupled system. A model to size for South Africa has been designed and developed. A centre pivot irrigation system in the Durban region was used in the model to size the SPIS to irrigate sugarcane. The components sized were for two out of the three SPIS configurations and these were the direct coupled system and the battery-coupled system. The performance of the battery pack and PV solar array was then

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simulated using the Photovoltaic Geographical Information System (PVGIS) tool. The simulated average energy output per day of the PV solar array was 0.11 % less than the average power requirement per day. The percentage of days when the battery is fully charged was simulated to be 61 % for the critical month of June.

Keywords: SPIS, NASA, irrigation system configuration, model

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4.1 Introduction

Solar energy is a renewable energy source that has gained popularity due to its low operational costs and long life cycle costs (Deveci *et al.*, 2015). South Africa has had a huge dependence on electricity generated from coal, which accounts for 90 % of the electricity consumed. South Africa has access to high levels of solar radiation, where the country receives an average solar radiation that is between 4.5 and 6.5 $kWh.m^{-2}.day^{-1}$ (Chang *et al.*, 2011; FAO, 2015).

In 2008, South Africa started going through electricity load-shedding and one of the causes of this was the dangerously low coal deposits at power stations (Daniel, 2019). Load-shedding recently occurred again in 2019 and the reason stated that it was Eskom's infrastructural problems. The power utility revealed that it has been struggling to maintain the high demands of electricity because of repair work done to boiler tubes (Sicetsha, 2019). Eskom has also been granted by the National Energy Regulator of South Africa (NERSA), permission to increase electricity tariffs for the next three years (2020 – 2022) by 22 % (Head, 2019). Serious concerns have been expressed by agricultural organisations that any further load-shedding could negatively impact the profitability of farmers during important periods, particularly irrigation dependent farmers (Dean, 2019). As a result, the old biological objective of applying irrigation for sustaining maximum production paradigm is now required to be replaced with the new paradigm of water being used to be optimised and to increase profitability (WRC, 2017). With the rise in electricity tariffs, the dependence of commercial agriculture on electricity as a source to pump water will likely continue (WRC, 2017). Some smallholder farmers in South Africa do not have access to the electricity grid. These farmers only have access to diesel powered pumps, which have high operating costs (Parker, 2019). Countries such as India and China have implemented large scale government investments in solar powered irrigation systems (SPIS) subsidy projects for small scale farmers, which has the advantage of having almost no operating costs (Parker, 2019).

There are three main different SPIS configurations and these include the direct-coupled SPIS, where water is pumped during the day when solar irradiation is available, and pumped water is delivered straight to the irrigation system. The next SPIS configuration is the direct-coupled SPIS with a water storage tank. For this type of configuration, water is pumped during the day when solar irradiation is available, and water is delivered to the elevated water storage tanks. This results in water being available all day independent of weather conditions (Xu *et al.*, 2013; Deveci *et al.*, 2015). The last type of SPIS configuration is the battery-coupled SPIS, where

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electricity is produced by the PV solar array and is delivered to the battery pack. This system allows for excess energy not used by the system to be stored in the batteries (Deveci *et al.*, 2015). South Africa does not have documentation on installed SPIS in the country and the performance of these systems is not analysed or documented. In Chapter 3 of this study, 13 SPIS were identified around the country and it was determined that most of the systems were direct-coupled SPIS.

There are software programs and online tools available for download and use, which simulate and estimate the photovoltaic system performance. PVGIS is a Photovoltaic Geographical Information System that is free to use online. PVGIS can be used to simulate and estimate the performance of off grid PV systems that have a battery pack (Huld, 2011). PVSyst is a PC software tool that can be used for the study, sizing and data analysis for complete PV systems. It deals with a range of systems such as grid connected, stand alone, pumping and DC-grid PV systems. The software includes extensive meteorological data and PV system component database, as well as general solar energy tools (PVSyst, 2019).

However, there is limited research on SPIS in South Africa. There have been reports on the suitability of the country to implement SPIS, but there is no information available on the sizing of SPIS in South Africa and the performance of implemented SPIS in the country. The objective of the work reported herein was to develop a model that can assist to design and size differently configured SPISs for South Africa considering climatic conditions of the region, soil properties, crop type, irrigation technique and farm size. The hypothesis for this study is that an SPIS model that can size the components of an SPIS for drip and centre pivot irrigation system can be developed for South Africa.

4.2 Materials and Methods

4.2.1 Study area

The model was designed to size SPIS components for South Africa. The country is located on the southern tip of the African continent. Latitudinally the country stretches from 22° S to 35° S and longitudinally from 17° E to 33° E. The country is relatively dry and receives an average annual rainfall of about 450 mm (Communication, 2016). Most of the country has warm, sunny days with cool nights. On the west, the country is bounded by the Atlantic Ocean and the Indian Ocean is on the east side of the country. The country has six main climatic zones, the cold interior, temperate interior, hot interior, temperate coastal, the sub-tropical coastal and arid interior. South Africa has approximately 14 million ha of cultivated land, which is 13 % of the total land in the country. It has been estimated that 1.3 million ha of the cultivated land is under irrigation (Matthew, 2017; Niekerk *et al.*, 2018), which comprises 10 % of the cultivated land in South Africa. In 2014, the Department of Water and Sanitation registered areas, which showed that an estimated 32 % of the irrigation land was under sprinkler irrigation, 29 % was under moving irrigation systems, 26 % was under micro irrigation and 14 % was under flood irrigation (van der Stoepand Tylcoat, 2014).

4.2.2 Solar radiation data

NASA Prediction of Worldwide Energy Resources (POWER) online website was used to obtain the horizontal solar irradiation of an area with the input of coordinates required from the user. The website creators requested that the following be stated with the use of their work as follows: *"These data were obtained from the NASA Langley Research Center (LaRC) POWER Project funded through the NASA Earth Science/Applied Science Program"* (Stackhouse *et al.*, 2016). Figure 4.1 shows the map of South Africa with the range in global horizontal irradiation that is received annually.

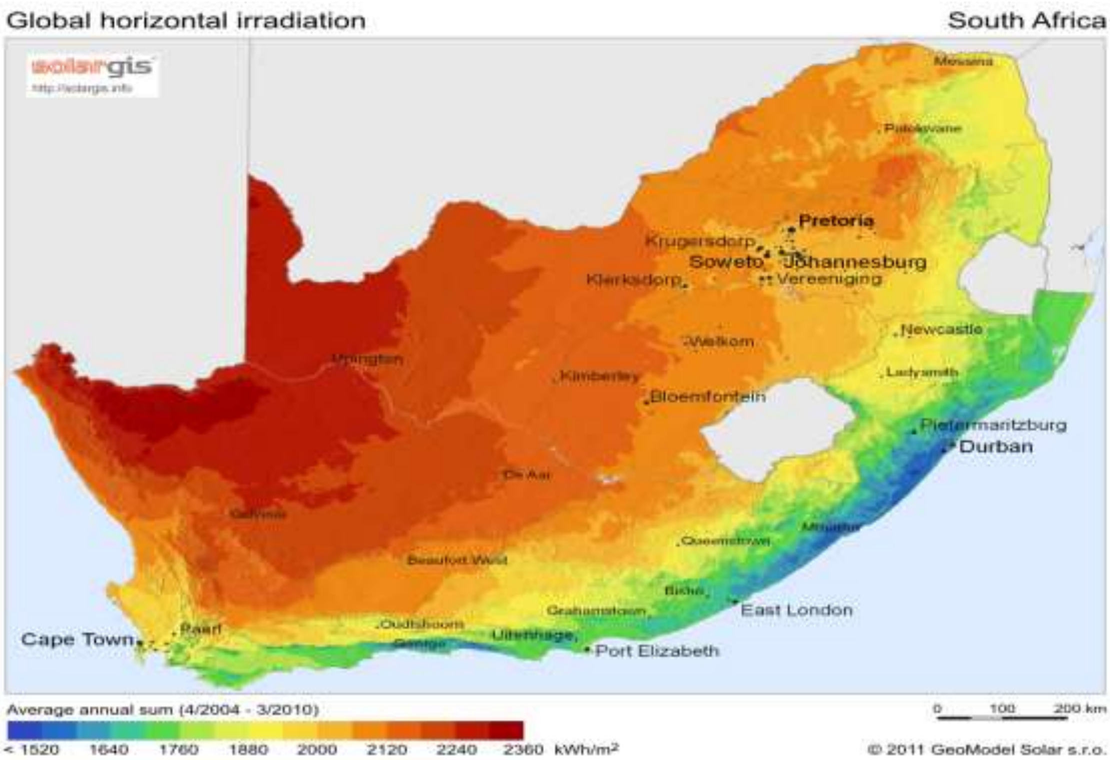

Figure 4.1 Map of the average annual global horizontal irradiation of South Africa

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4.3 Model Design and Development

Three types of SPIS configurations were considered for the development of the model. These configurations include the direct-coupled SPIS system, the battery-coupled SPIS system and the direct-coupled SPIS system with a water storage tank. The model flow diagram is presented in Appendix B and C. The newly developed model is from hereon named the SPISyst model.

4.3.1 Solar radiation data

MS Excel along with its Visual Basic Application (VBA), was used to design, develop and operate the model. MS Excel spreadsheets were used to conduct calculations, while MS Excel VBA was used to make the model user friendly through having the use of command boxes and user-forms which will prompt the user to insert the required input variables. MS Excel and VBA were selected because most users with a PC have access to MS Excel and VBA comes with MS Excel so it all comes in one package. Figure 4.2 shows the user form that is used to obtain the monthly average daily (MAD) horizontal solar irradiation from the NASA POWER website. The user is required to enter the top right and bottom left coordinates of the area of interest.

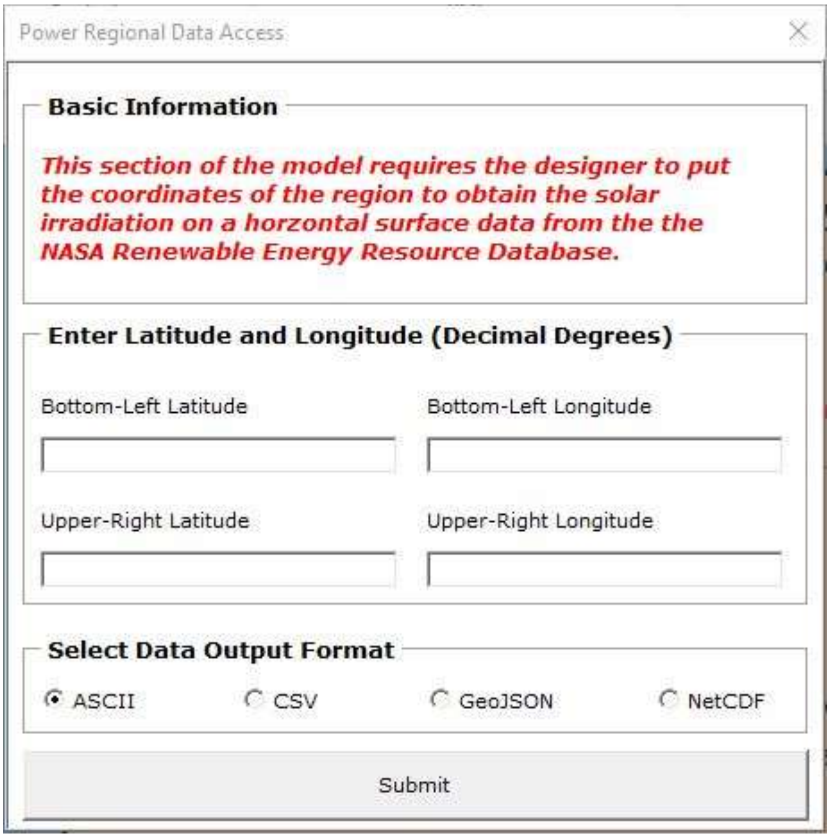

Figure 4.2 NASA POWER regional data access user form

4.3.2 General user and area information

Figure 4.3 shows the second user form that was created to appear after the user has completed the NASA POWER regional data access user form. The purpose of this user form is to obtain details of the user, such as the user's name, email address, name of the farm, the size of the farm, the location of the farm, the irrigation system in use, the type of water source and the static pumping head of the irrigation system. The user form has tabs on the left, when clicked, illustrations of the three different types of SPIS configurations appear.

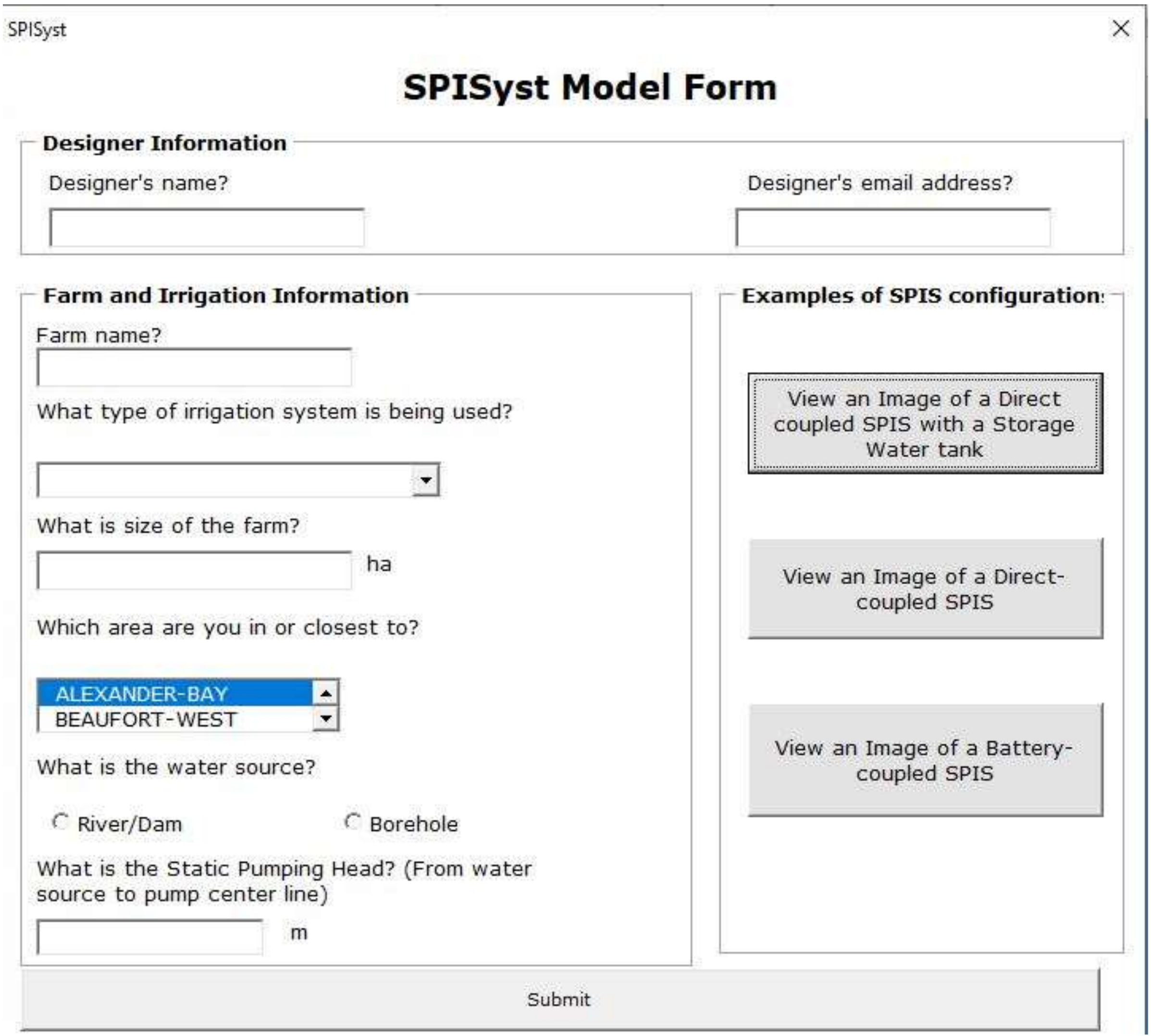

Figure 4.3 First SPISyst user form to establish which irrigation system the designer is working with

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4.3.3 Crop water requirements

To determine the crop water requirements, the models CLIMWAT and CropWAT were used. The reason for this software being chosen for this model was firstly the CropWAT programme is free and secondly, it is user friendly. To determine the crop water requirements CLIMWAT was used to obtain the climatic and rainfall data required by CropWAT. The majority of the data collected in the software covers the period from 1971 – 2000. The least number of years of collected data is 15 years. The mean daily maximum temperature (°C) and mean daily minimum temperature (°C) (FAO, 2019) are weather parameters that were collected for each location in South Africa available on CLIMWAT as MS Excel outputs.

4.3.4 Irrigation water requirements

The irrigation water requirements were determined with the use of CLIMWAT and CropWAT. The approach used for CropWAT to determine crop water requirements starts with determining the crop reference evapotranspiration. The FAO Penman-Monteith method (Burger *et al.*, 2003c) is used for the computation of evapotranspiration from meteorological data. Equation 4.1 presents the FAO Penman-Monteith equation.

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad 4.1$$

where,

ET_o = reference crop evapotranspiration (mm day^{-1}),
R_n = net radiation at the crop surface (MJ m^{-2} day^{-1}),
G = soil heat flux density (MJ m^{-2} day^{-1}),
T = air temperature at 2 m height (°C),
u_2 = wind speed at 2 m height (m s^{-1}),
e_s = saturation vapour pressure (kPa),
e_a = actual vapour pressure (kPa),
$e_s - e_a$ = saturation vapour pressure deficit (kPa),
Δ = slope of the vapour pressure curve (kPa $°C^{-1}$), and
γ = psychrometric constant (kPa $°C^{-1}$).

The crop evapotranspiration is different from the reference evapotranspiration because the ground cover, the properties of the canopy, and aerodynamic resistance of the crop are different

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from grass. The crop coefficient integrates the characteristics that are different between field crops and reference grass. Equation .2 shows how to calculate crop evapotranspiration with the use of the crop coefficient.

$$ET_c = k_c ET_o \qquad 4.2$$

where,

ET_c = crop evapotranspiration (mm d^{-1}), and

k_c = crop coefficient (dimensionless).

Equation 4.3 and 4.4 were available as the dependable rain method for determining the effective rainfall on CropWAT. The empirical formula was developed based on analysis that was done on different arid and sub-humid climates by the Water Service of FAO. Equation 4.3 and 4.4 determine the monthly effective rainfall by using long-term average rainfall figures (Wane and Nagdeve, 2013).

$$P_{eff} = 0.6 \times P - \frac{10}{3} \qquad \text{for } P \leq 23 \text{ mm} \qquad 4.3$$

$$P_{eff} = 0.8 \times P - \frac{24}{3} \qquad \text{for } P > 23 \text{ mm} \qquad 4.4$$

where,

P_{eff} = effective rainfall (mm), and

P = monthly average rainfall (mm).

To determine the nett irrigation requirement Equation 4.5 is used.

$$NIR = ET_c - P_{eff} \qquad 4.5$$

where,

NIR= nett irrigation requirement (mm/month).

When the nett irrigation requirement is determined the gross irrigation requirement is determined, which depends on the type of irrigation technique or system used as shown in Equation 4.6.

$$GIR = \frac{NIR}{\eta_s} \qquad 4.6$$

where,

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GIR= gross irrigation requirement (mm/month), and

η_s = irrigation system water application efficiency (decimal).

4.3.5 Irrigation system total dynamic and friction head

To size an SPIS appropriately, the total dynamic head of the irrigation system is required to be calculated accurately to avoid oversizing or under-sizing the SPIS (Chandel *et al.*, 2015). Drip and centre pivot irrigation systems were selected for the development of the model for the following reasons; wide application in South Africa, high water use efficiency, low labour requirements and low energy requirements (Burger *et al.*, 2003a). With lower energy requirements, this leads to less power required from solar panels, which will result in sizing less solar panels for the irrigation system.

To make sure the irrigation systems are sized appropriately, the frictional head losses in the pipe network of the irrigation systems will be calculated in the model using General Exponential Equation, Equation 4.1 (Burger *et al.*, 2003d). The secondary losses from valves and bends in the system will be assumed to be 10 % of the total frictional head (Burger *et al.*, 2003d).

$$h_f = \frac{FblQ^p}{{d_i}^r} \qquad 4.7$$

where:

h_f = frictional head (m),

p, b, r = constants for General Exponential Equation,

l = length of pipe (m),

Q = flow rate ($m^3.hr^{-1}$ or $m^3.s^{-1}$),

d_i = internal diameter of pipe (m), and

F = Jensen-Fratini constant.

4.3.5.1 Centre pivot irrigation system total dynamic head

The model will calculate the total dynamic head for a centre pivot irrigation system with the following sprinkler spacing and sprinkler discharge scenarios:

- Scenario 1-Constant sprinkler spacing (L_e,) variable sprinkler flow rate (q_e)
- Scenario 2-Variable sprinkler spacing (L_e), constant sprinkler flow rate (q_e)

Figure 4.4 is the user form that appears when the user selects the irrigation system type as a centre pivot irrigation system on the previous user form in Figure 4.3. It should be stressed that the design of the irrigation system is required to be completed before the SPISyst model is used. Irrimaker model can be used to develop the design of the irrigation system (Model Maker Systems, 2018). The user form is set up to accommodate the varying frictional head losses through the centre pivot structure as shown in Figure 4.4 using Equation 4.3.

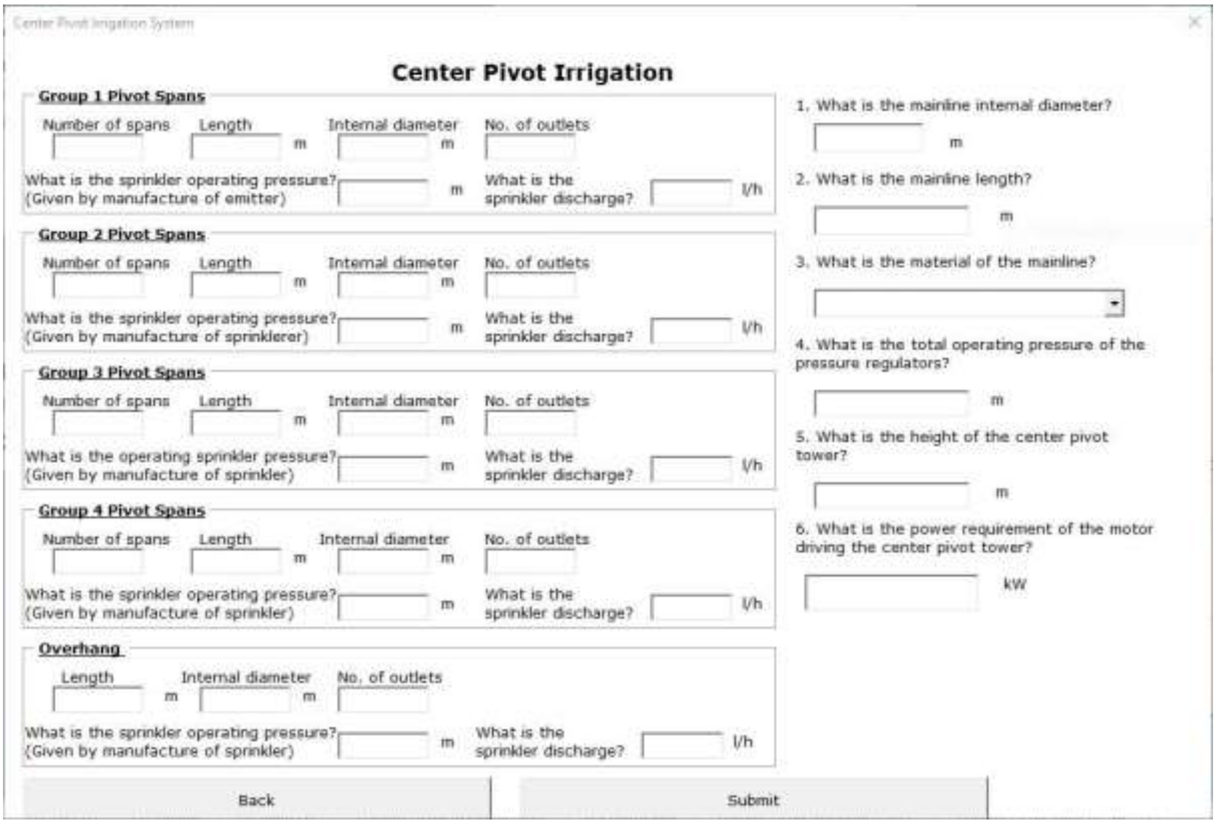

Figure 4.4 The centre pivot user form for the SPISyst model

When the total frictional and secondary frictional losses are calculated with the use of the user form in Figure 4.4, the total head of the centre pivot irrigation system needed for the pump will be calculated using Equation 4.8.

$$H_p = h_{stat} + h_{tower} + h_{op} + h_f + h_{pr} + h_{sec} \qquad 4.8$$

where:

H_p = total pump head requirement (m),

h_{stat} = static head (m),

h_{tower} = height of tower (m),

h_{op} = operating pressure of end sprinkler (m),

h_f = frictional head of the system (m),

h_{pr} = pressure regulator pressure (m), and

h_{sec} = secondary frictional losses (m).

4.3.5.2 Drip irrigation total dynamic head

The conventional drip irrigation system concept was considered for the model. The model calculates the total frictional head for a drip irrigation system with the same sized blocks and different sized blocks. To do this, the user is required to complete the design for the drip irrigation system and this can be done on the Irrrimaker model or other methods. Figure 4.5 shows the first user form that appeared after the user had selected their irrigation system like drip irrigation from the user form shown in Figure 4.3.

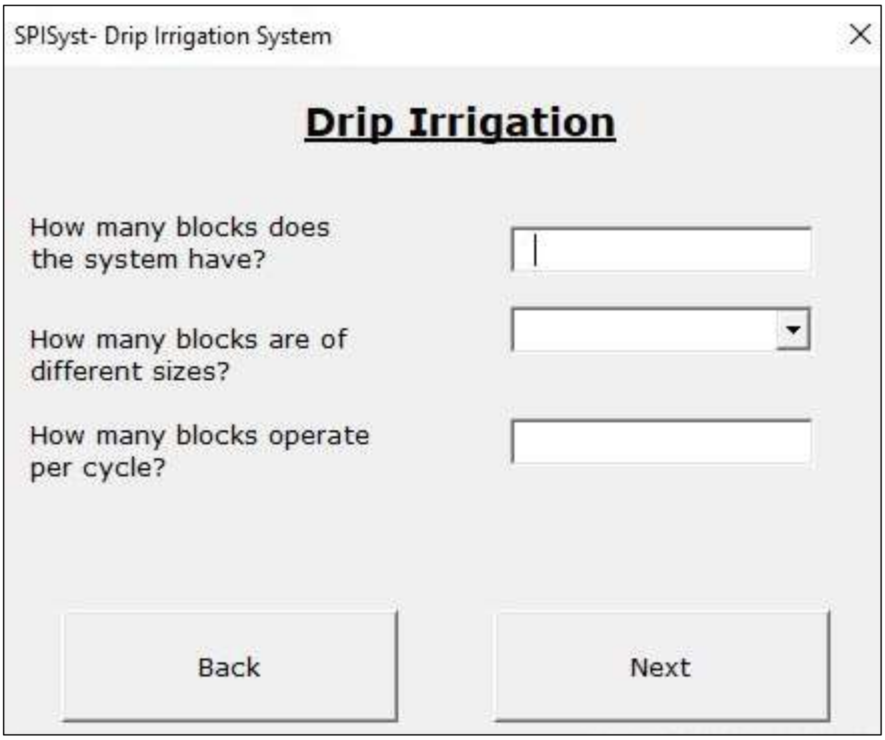

Figure 4.5 Drip irrigation user form

The user form in Figure 4.5 gathers information from the user about the number of blocks the system has. The model then determines the total frictional head for the same sized blocks and

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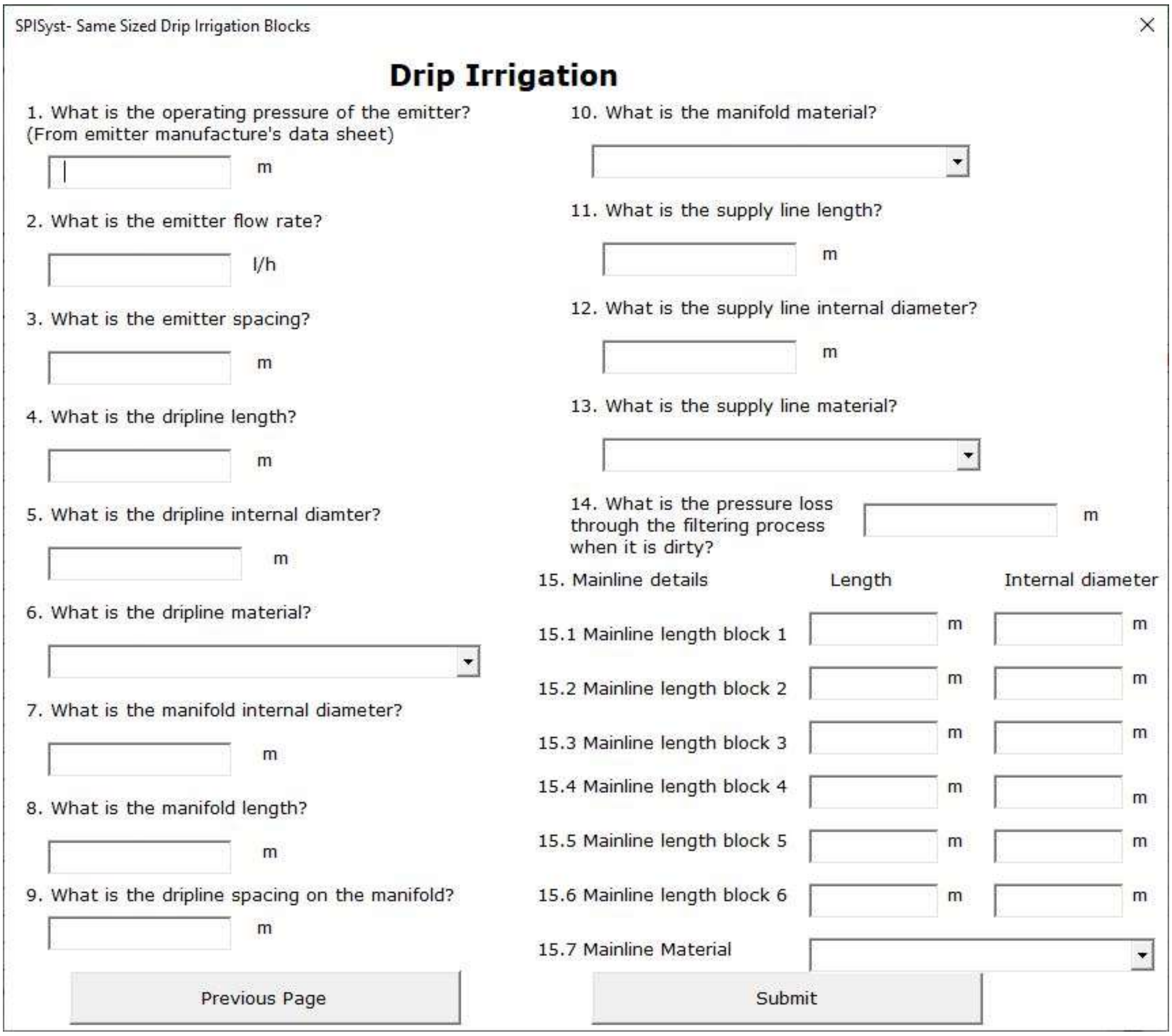
unequal sized blocks. What is meant by the same sized blocks is, the blocks are equal in size and spacing of emitters, lateral lines, and manifolds.

The user form in Figure 4.6 will appear first so the user will enter the information on blocks that are the same size if they specified there are two or more blocks of the same size. When the user form is completed by the user, the user form in Figure 4.7 for the unequally sized blocks will appear that the user input into the model. The number of blocks that are not the same size is limited to six blocks for the model. Figure 4.7 shows the page that will appear when the user has clicked “Submit” on the user form in Figure 4.6. The user will input information about the supply line from the water source. Figure 4.8 shows the user form that appears for the user to insert details related to the critical supply line length for unequal sized drip irrigation blocks.Drip irrigation systems have a filtration process to remove clogging components such as sand, silt, clay and organic matter, which can be detrimental to the components of the system (Burger *et al.*, 2003i). This has been accounted for in the SPIS model.



SPISyst- Same Sized Drip Irrigation Blocks

Drip Irrigation

1. What is the operating pressure of the emitter? (From emitter manufacture's data sheet) m
2. What is the emitter flow rate? l/h
3. What is the emitter spacing? m
4. What is the dripline length? m
5. What is the dripline internal diamter? m
6. What is the dripline material?
7. What is the manifold internal diameter? m
8. What is the manifold length? m
9. What is the dripline spacing on the manifold? m
10. What is the manifold material?
11. What is the supply line length? m
12. What is the supply line internal diameter? m
13. What is the supply line material?
14. What is the pressure loss through the filtering process when it is dirty? m

15. Mainline details	Length		Internal diameter	
15.1 Mainline length block 1		m		m
15.2 Mainline length block 2		m		m
15.3 Mainline length block 3		m		m
15.4 Mainline length block 4		m		m
15.5 Mainline length block 5		m		m
15.6 Mainline length block 6		m		m
15.7 Mainline Material				

Previous Page

Submit

Figure 4.6 Drip irrigation user form to obtained data from user for equal sized blocks to determine frictional head of irrigation system

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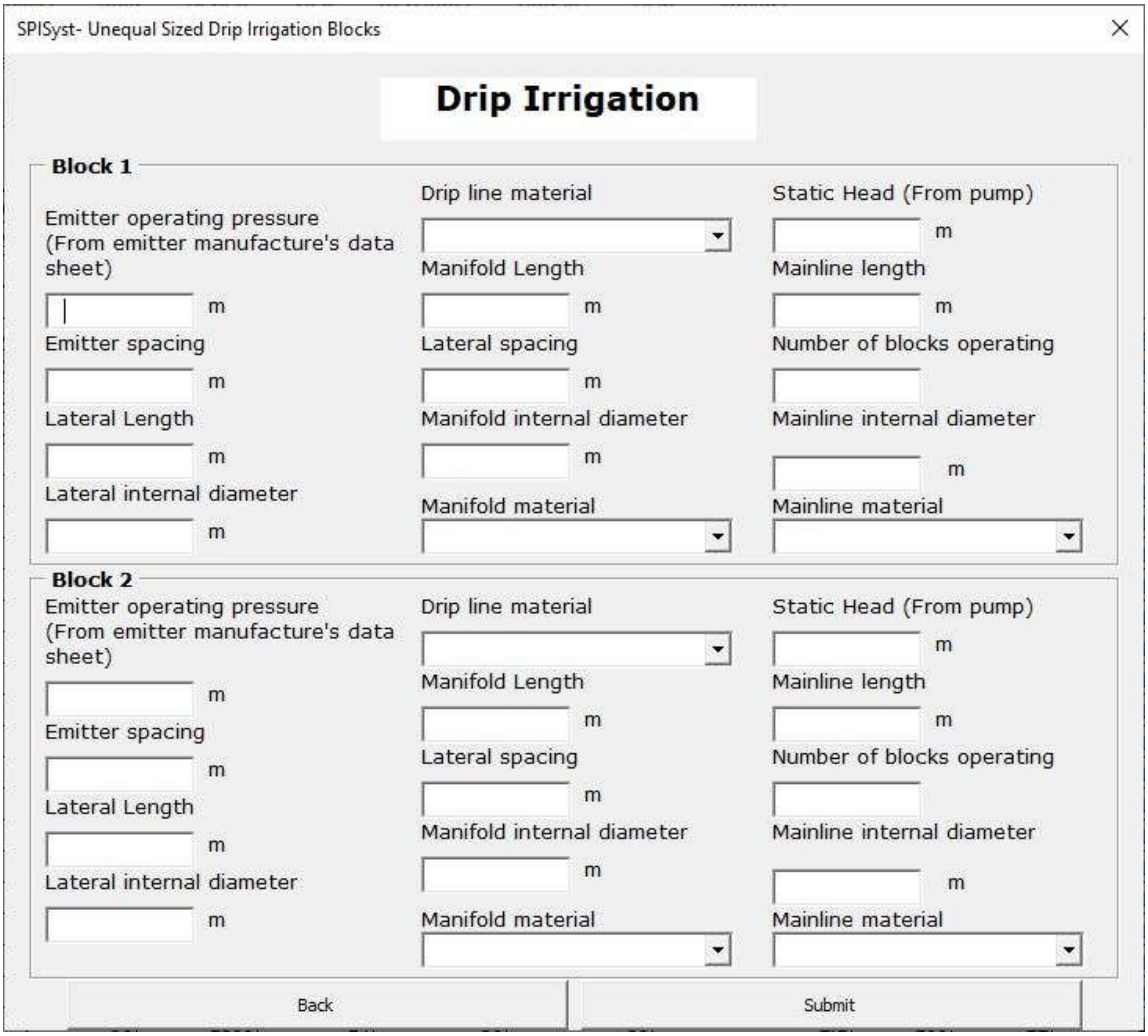

Figure 4.7 Drip irrigation user form to obtain data from user of unequally sized number of blocks for frictional head calculation.

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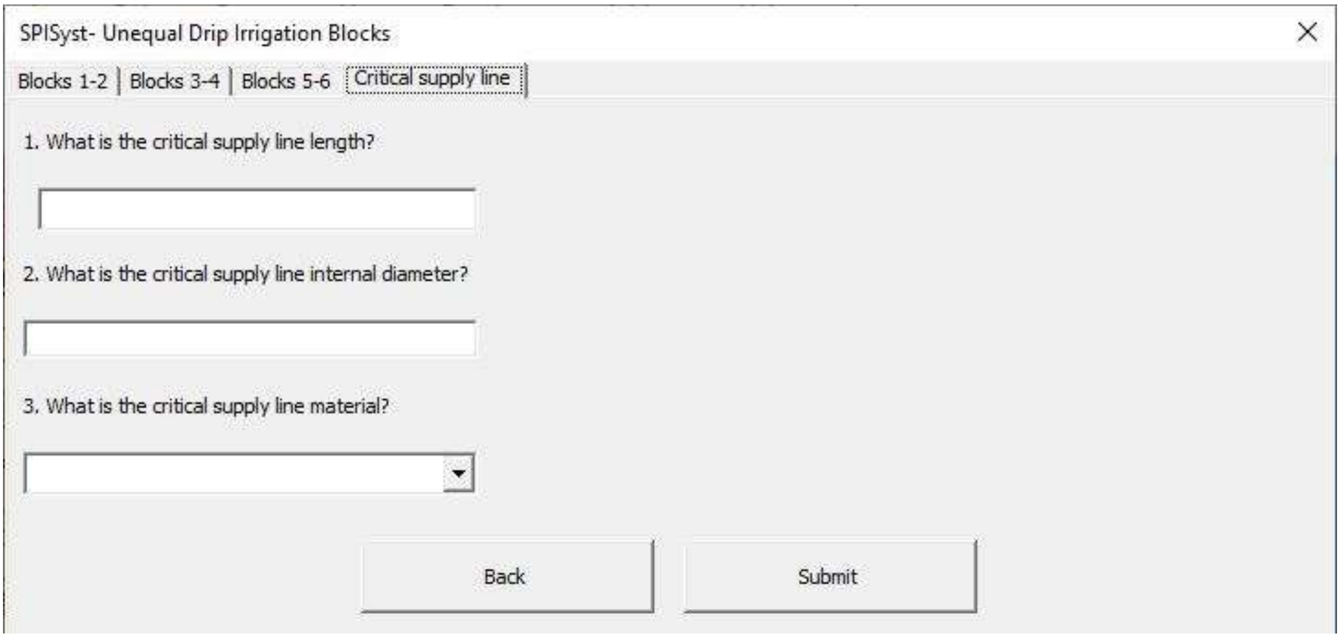

Figure 4.8 Supply line user form for drip irrigation

Equation 4.9 is used to determine the pumping head required for the irrigation system.

$$H_p = h_{stat} + h_f + h_{sec} + h_{fil} + h_{op} \qquad 4.9$$

where:

h_{fil} = fictional head losses due to filtration (m).

4.3.6 Energy required

The hydraulic energy demand of the system will be calculated from the total dynamic head and the flow rate (Cuadros *et al.*, 2004; Gajić *et al.*, 2013; Zegeye *et al.*, 2014) using Equation 4.10. The linear graphs in Figure 4.9 were used to obtain the linear equations to size the pump and the SPIS in the SPISyst model using the system efficiency for a drip irrigation system and a centre pivot irrigation system. The density of water was assumed to be 1000 $kg.m^{-3}$, and the gravitational force was assumed to be 9.81 $m.s^{-2}$. The irrigation system efficiency was varied from 65 – 100 % as shown in Figure 4.9. The total dynamic head and the flow rate were varied to develop the graph.

$$E_H = \frac{\rho g Q H_p}{3600 n_{mp}} \quad 4.10$$

where,

E_H = hydraulic energy (kW),

ρ = density of water ($kg.m^{-3}$),

g = gravitational acceleration ($m.s^{-2}$),

n_{mp} = pump motor efficiency (%),

Q = flow rate obtained from CropWAT ($m^3.h^{-1}$), and

H_p = total irrigation system head (m).

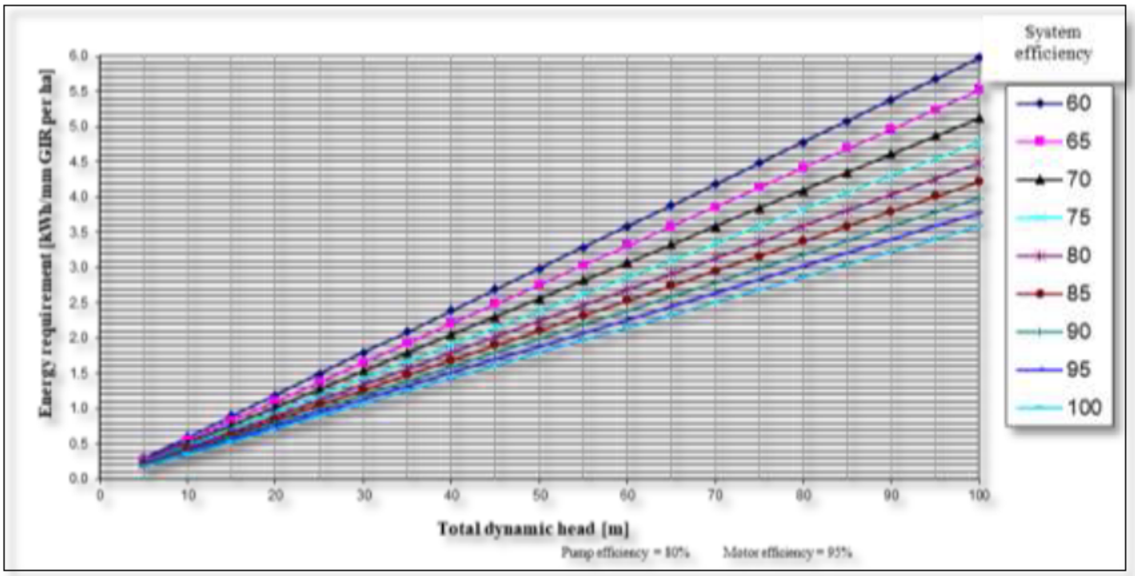

Figure 4.9 The energy requirement versus total dynamic head graph for varying system efficiency (after Burger et al, 2003e)

4.3.7 Power requirements from solar panels

This section will go through the steps and calculations taken to determine the number and size of solar panels to meet the power requirements of the irrigation system.

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The data obtained from the NASA POWER website are the monthly average daily (MAD) horizontal solar irradiation. The MAD horizontal solar irradiation has to be converted to MAD tilted surface solar irradiation (Axaopoulos, 2016b).

For numerous locations around the world, the MAD irradiation on a horizontal surface can be looked up online. To accurately determine how much energy is falling on an inclined solar panel, at an angle from the horizontal, a series of calculations have to be conducted (ITACA, 2016).

Axaopoulos (2016b) states that R_b is the conversion factor for the direct solar irradiation received on the inclined solar panel. The conversion factor is a ratio of the MAD irradiation on an inclined surface (H_t) to that MAD on a horizontal surface (H). Equation 4.11 is used to calculate the conversion factor (R_b) for the MAD direct solar irradiation, which is presented below (Axaopoulos, 2016a).

$$R_b = \frac{\cos(\phi - \beta)\cos\delta\sin\omega'_s + \left(\frac{\pi}{180}\right)\omega'_s\sin(\phi - \beta)\sin\delta}{\cos\phi\cos\delta\sin\omega_s + \left(\frac{\pi}{180}\right)\omega_s\sin\phi\sin\delta} \quad 4.11$$

where:

ϕ = latitude coordinate of the location in decimal format (°),

δ = declination angle (°),

$\omega_{s'}$ = sunset hour angle (°), and

β = solar panel array slope to the horizontal (°).

According to Axaopoulos (2016a), solar declination is the angle between the sun’s rays and the plane of the equator on earth. The declination angle varies between -23.45° to +23.45°. This variation is responsible for the changing seasons, with their unequal periods of daylight and darkness. The sunset hour angle is the angular distance between the hour circle of the sun and the local’s meridian. Equation 4.12 presented below calculates the declination angle (Axaopoulos, 2016b) and Equation 4.13 calculates the solar hour angle (Axaopoulos, 2016b).

$$\delta = -23.45.\sin\left(\frac{284 + n}{365}\right) \quad 4.12$$

where,

`

n = the day of the year (unitless).

$$\omega_s = \cos^{-1}(-\tan\phi.\tan\delta) \quad 4.13$$

The MAD extraterrestrial irradiation (H_o) is calculated using Equation 4.14. This equation can only be used for latitudes ranging from -60 º to +60 º (Axaopoulos, 2016b).

$$H_o = \frac{24 \times 3600 \times G_{sc}}{\pi}\left(1 + 0.033\cos\frac{360n}{365}\right)\left(\cos\phi\cos\delta\sin\omega_s + \frac{\pi\omega_s}{180}\sin\phi\sin\delta\right) \quad 4.14$$

where:

G_{sc} = solar constant = 1.367 kW.m^{-2} (Axaopoulos, 2016c).

The clearness index (K) is the ratio of MAD horizontal irradiation and the MAD horizontal extraterrestrial irradiation. Thus, K is an indication of solar radiation from the sun that is lost in the earth's atmosphere as a result of scattering and absorption. Equation 4.15 presented below is used to determine K (Axaopoulos, 2016b).

$$K = \left(\frac{H}{H_o}\right) \quad 4.15$$

where,

H = total MAD solar irradiation on a horizontal surface (kW.m^{-2}).

Several researchers, some of them, which include, Choudhury (1963); Ruth and Chant (1976); Tuller (1976); Collares-Pereira and Rabl (1979); Erbs *et al.* (1982), have proposed different methods for determining the ratio H_d/H_o where H_d is the MAD horizontal diffuse irradiation. According to Liu and Jordan (1960) and Axaopoulos (2016b) the ratio H_d/H_o is calculated using Equation 4.16 presented below.

$$\frac{H_d}{H_o} = 1.446 - 2.965K + 1.727K^2 \quad 4.16$$

Equation 4.17 will then calculate the total solar irradiance received by the inclined solar panel array. The reflectance of the ground (ρ) will be assumed to be 0.2 (Axaopoulos, 2016b).

$$\frac{H_T}{H} = \left(1 - \frac{H_d}{H_o}\right)R_b + \frac{H_d}{H_o}\left(\frac{1+\cos\beta}{2}\right) + \mu\left(\frac{1-\cos\beta}{2}\right) \quad 4.17$$

where:

μ = reflectance of the ground (unitless)

H_T = MAD titled surface irradiation (kW.m^{-2}).

`

When the irrigation water requirements were determined through CropWAT and the tilted solar radiation determined, a ratio between irrigation water requirements and tilted solar radiation is derived to determine the critical month which requires the most power. Equation 4.18 which is used to calculate the critical month value is presented below (Cuadros *et al.*, 2004). The units of the critical ratio are presented below with Equation 4.14. The ratio can be made unitless by multiplying by the density of water, the gravitational acceleration and the total head of the irrigation system. All these values will be fixed from January to December so the highest value of the ratio will be the critical month.

$$M_{CR} = \frac{Q}{E_T} \tag{4.18}$$

Units: $\frac{m^3}{kg} \times \frac{s^2}{m} \times \frac{m}{1}$

The month that yields the highest value ratio is taken as the critical month, i.e, the month in which the irrigation system will be designed (Kelley *et al.*, 2010; Zegeye *et al.*, 2014).

4.3.8 Photovoltaic (PV) array sizing

Equation 4.19 is used to determine the temperature of the cells in the PV module. The higher the PV cell temperature of the module the lower the efficiency of the PV module (Dubey *et al.*, 2013). These weather parameters from CLIMWAT were used in the development of the SPIS model for the calculation of the nominal solar power output to operate the SPIS. This was done because of the effect of temperature on the efficiency of solar panels. Equation 4.19 is selected due to its application being among the best and being the simplest amongst a large number of other equations present in literature (Araneo *et al.*, 2014).

$$T_c = T_a + \frac{N_{OCT} - 20}{0.8n} H_T \tag{4.19}$$

where,

T_c = temperature of the cells in the module (°C),

T_a = air temperature (°C),

N_{OCT} = nominal operating cell temperature (°C), and

n = number of sunshine hours.

`

Kenna and Gillett (1985a) developed the equation used to determine the nominal electric power output of the PV solar panels which is presented below with Equation 4.20.

$$P_{el} = \frac{1000}{[1 - \alpha_c(T_c - T_{a)})]\eta_{mp}} \times \frac{E_H}{H_T} \quad 4.20$$

where,

P_{el} = nominal electrical power of solar panels (kW),

α_c = PV cell temperature coefficient ($^oC^{-1}$),

H_T = intensity of MAD tilted solar irradiance on a surface ($kWh.m^{-2}.day^{-1}$), and

η_{mp} = solar powered motor-pump efficiency (unitless).

To determine the minimum number of solar panels the system requires, the nominal power requirement of the solar panels determined with Equation 4.20 is divided by the power rating of each solar panel (McCluskey, 2018).

The model has a list of polycrystalline solar panels, which is presented in Appendix B, with power ratings ranging between 100 – 330 W. The model will determine the solar panels which gives the lowest cost.

4.3.9 Water storage tank

The storage water tank SPIS is only suitable for drip irrigation systems. This is due to the irrigation system having low pressure head requirements and flow rate. To size, the storage water tank for an SPIS, the flow rate and the pressure head requirements of the system are required. The pump and storage water tank must be designed to provide water for days of autonomy (DoA), which is an estimated number of days that would be cloudy and not provide enough power to pump the daily water requirement. Equation 4.21 was required for the maximum height of the storage water tank of the SPIS. The height of the available water tank stands available in the market is limited to a height of 9 m (RainHarvest, 2017).

$$H_p \leq 9m \quad 4.21$$

`

If this equation is not satisfied, then the configuration with a storage water tank is not suitable for the drip irrigation system. When satisfied then the sizing of the water tank will be determined from Equation 4.22.

where,

$$V_r = Q \times DoA \times h_{op} \quad 4.22$$

V_r = volume of water required for storage ($m^3.day^{-1}$),

Q = flow rate of irrigation system ($m^3.h^{-1}$),

DoA = number of days of autonomy (days), and

h_{op} = number of hours the irrigation system operates in a day (hours).

The capacity of water storage tanks available in the market range from 260 – 10 000 litres. A system with a volume of 20 000 litres is the allowable limit for the system where two storage water tanks can be used for a storage water tank SPIS.

4.3.10 Battery sizing analysis

To size the battery bank for a battery-coupled SPIS, the average daily load needs to be converted to amp-hours per day (McCluskey, 2018). The number of days of autonomy (DoA) and the depth of discharge (DoD) will be accounted for in the overall actual sizing of the battery bank. The depth of discharge of a battery pack is a fraction amount of the battery capacity that is set to be discharged to protect the battery pack and maintain the battery life span (Andoh-Appaiah, 2018). A 2 – 3 DoA is commonly used for off-grid solar systems (Teitelbaum, 2016; McCluskey, 2018). A 50 % DoD is mainly used for lead acid batteries, which helps protect the battery lifespan since they are used almost every day (Teitelbaum, 2016; McCluskey, 2018). Batteries are sensitive to extremely low temperatures because less energy can be obtained from cold batteries compared to warm batteries. So, a temperature multiplier that corresponds to the winter average ambient temperature of the region must be selected from the manufacturers' catalogues. Equation 4.23 was used to size the required battery capacity of the irrigation system (McCluskey, 2018).

$$B_C = \frac{E_H \times DoA \times T_{BM}}{V_{DC} \times DoD} \quad 4.23$$

where,

`

B_C = required battery capacity (Ah),

V_{DC} = system voltage (V), and

T_{BM} = battery temperature multiplier ($^{o}C^{-1}$).

The total number of parallel battery strings needs to be limited to three or less for lead acid batteries (Teitelbaum, 2016). So, the battery capacities that form three strings or less will be selected for the sizing of the system in the model. Equation 4.24 is used to determine the number of batteries per string (McCluskey, 2018).

$$B_{||} = \frac{B_C}{b_C} \quad 4.24$$

where,

$B_{||}$ = total parallel battery strings (unitless), and

b_C = unit battery capacity (Ah).

To determine the total number of battery cells per string Equation 4.25 is used (McCluskey, 2018).

$$B_S = \frac{V_B}{v_b} \quad 4.25$$

where,

B_S = number of batteries per string (unitless),

V_B = battery bank voltage (V), and

v_b = unit battery voltage (V).

Equation 4.26 is used to determine the total battery cells (McCluskey, 2018).

$$B_{TOT} = B_S \times B_{||} \quad 4.26$$

where,

B_{TOT} = total number of battery cells (unitless).

The number of strings in a battery bank is limited to a maximum of three strings for common lead-acid batteries. A list of the lead-acid deep cycle batteries used in the SPISyst model is shown in Appendix D (Current Automation, 2018b).

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4.3.11 Solar powered motor-pump selection

The energy requirements and flow rate will help in selecting the appropriate solar powered pump from a list of pumps within the model. Lorentz® submersible centrifugal solar water pumps were selected for the model and the list of the pumps is presented in Appendix D (Bundu Power, 2018)

From the survey conducted for this study in Chapter 3, it was revealed that the most common type of pump used in the SPIS was a three-phase submersible pump. For this model, information and details on three-phase motor-pumps were loaded in the model where the wattage of the pumps range 200 – 40000 W.

4.3.12 Charge controller selection

For the sizing of an appropriate charge controller, the power supply of the voltage of the charge controller needs to correlate to the solar panels open circuit voltage (V_{oc}) or maximum power voltage (V_{mp}) (Bane, 2017). Equation 4.27 and 4.28 were used to select a suitable charge controller for the SPIS system.

$$I_C = I_{sc} \times N_{||} \times 1.25 \qquad 4.27$$

where,

I_C = charge controller current (A),

I_{sc} = solar panel string charge (A), and

$N_{||}$ = number of panels connected in parallel (unitless).

and

$$V_{Ci} = V_{oc} \times N_{sr} \qquad 4.28$$

where,

V_{Ci} = maximum allowable input voltage from solar panels to charge controller (V),

V_{oc} = solar panel array open circuit voltage (V), and

N_{sr} = number of solar panels connects in series (unitless).

`

A charge controller is only required for battery-coupled systems. Calculations require the battery selected capacity and voltage and the systems current requirements. A list of the charge controllers used in the SPISyst model is presented in Appendix E (Sustainable.co.za, 2018a).

4.3.13 SPISyst model check with PVGIS model

Photovoltaic Geographical Information System (PVGIS) is a simulation model that was used to check the results obtained with the SPISyst model, by estimating the potential energy generation of the sized SPIS. The model is a free online based PV energy simulation model for stand-alone, grid-connected and off-grid PV systems in Europe, Africa and Asia. The model works by estimating the solar energy production of a system with a PV solar array. It is a PV Geographical Information System (GIS) so it uses Google Maps application that makes it easy to use to find the area of interest. The online model calculates the monthly and yearly potential energy production of a PV system with defined solar array orientation and tilt angle.

4.4 Results and Discussion

This section contains the results of the calculation methods described in the sections above in the form of tables and graphs. The crop water requirements and the irrigation water requirements that were determined by CropWAT are presented in Appendix H and the design of the irrigation system is presented in Appendix J.

4.4.1 Calculation of inclined surfaces solar irradiation

The monthly average daily (MAD) horizontal irradiation obtained through the NASA POWER website for a region in Durban with the coordinates 29.859° South, 30.022° East was obtained through the first user form of the model. The data obtained from the website through the model are presented in Table 4.1as H_o from January to December. The orientation of the inclined surface is 180° facing the northern direction. The incline angle is fixed for the whole year at 30° to maximise the potential solar irradiation available to be captured by the solar array area. For January, the MAD horizontal surface solar irradiation is 5.53 $kWh.m^{-2}.day^{-1}$ and MAD inclined surface irradiation was estimated to be 5.74 $kWh.m^{-2}.day^{-1}$.

From the MAD horizontal solar irradiation obtained from the NASA POWER website, this data was used as shown in Table 4.1 to obtain the monthly average daily solar irradiation on an

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inclined surface. Table 4.1shows some of the variables used to calculate the MAD tilted surface solar irradiation which was done in the SPISyst model.

Table 4.1 Estimation of MAD tilted solar irradiation on an inclined surface for Durban (coordinates), RSA.

Month	MAD horizontal surface solar irradiation (H) ($kWh.m^{-2}day^{-1}$)	MAD horizontal surface extraterrestrial irradiation (H_o) ($kWh.m^{-2}day^{-1}$)	Ratio (H_d/H)	Conversion factor (R_b)	MAD tilted surface solar irradiation (H_T) ($kWh.m^{-2}day^{-1}$)
January	5.53	7.40	0.19	0.92	5.74
February	5.26	8.32	0.26	0.99	5.71
March	4.8	8.87	0.35	1.11	5.58
April	4.05	9.46	0.49	1.37	5.14
May	3.39	9.22	0.59	1.78	4.73
June	2.96	9.33	0.68	2.13	4.23
July	3.17	9.05	0.62	1.95	4.55
August	3.78	9.66	0.55	1.51	4.94
September	4.36	8.87	0.41	1.20	5.24
October	4.56	8.76	0.37	1.02	5.02
November	4.87	7.42	0.24	0.94	5.11
December	5.44	7.44	0.20	0.91	5.58

The MAD tilted surface solar irradiation is higher compared to the MAD horizontal surface solar irradiation. This means that having the solar panels at an incline angle of 30 ^{o} will absorb more solar energy compared to the solar panels at an incline angle of 0 ^{o}. So, sizing solar panels using the MAD titled surface solar irradiation is advisable.

4.4.2 Comparison of MAD horizontal and inclined solar irradiation

Illustrated below in Figure 4.10 is the comparison of MAD horizontal surface solar irradiation and MAD titled surface solar irradiation with the monthly required flow rate of the irrigation system. The crop of interest for this centre pivot irrigation system is sugarcane. The flow rate of the system was obtained from CropWAT. The CropWAT output with the irrigation water

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requirements is available in Appendix F. This was then used to determine the flow rate for each month which is shown in Figure 4.10 and The procedure that follows the MAD tilted surface solar irradiation, is the determination of the critical month. The critical month value obtained is shown in Table 4.2.

Table 4.2.

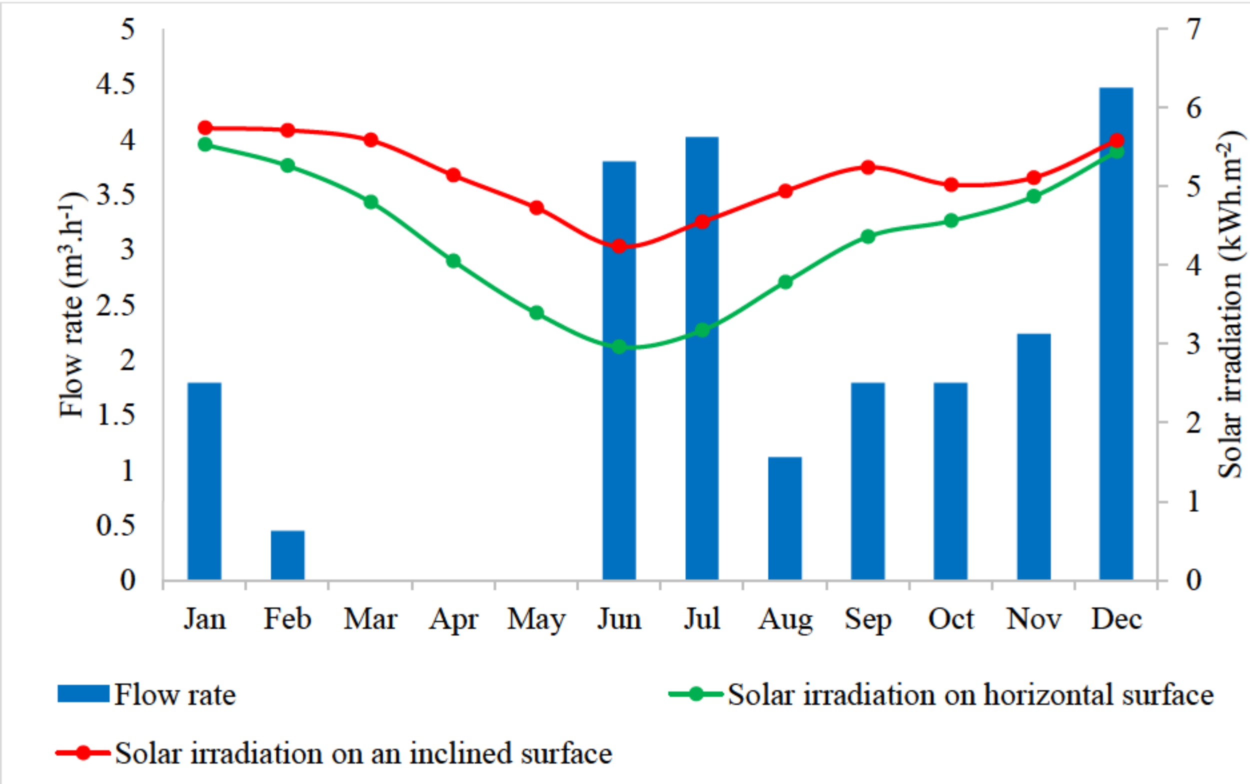

Figure 4.10 Flow rate requirements and available MAD horizontal and tilted surface solar irradiation

Figure 4.10 shows the graphical comparison of MAD horizontal irradiation, MAD inclined surface irradiation and the average daily flow rate requirements for each month for the sugarcane crop. From the graph, the month with the highest average daily flow rate of 4.46 $m^3.h^{-1}$ in December, followed by June and July, which have an average daily flow rate of 3.79 $m^3.h^{-1}$ and 4.02 $m^3.h^{-1}$ respectively. The months with the lowest MAD horizontal irradiation were June and July, which were 2.96 kWh.m^{-2}.day^{-1} and 3.17 kWh.m^{-2}.day^{-1} respectively. The MAD 30° inclined surface irradiation for June and July were estimated to be 4.23 kWh.m^{-2}.day^{-1} and 4.55 kWh.m^{-2}.day^{-1} respectively. From this graph, it can be seen that the incline angle of 30 ° helps increase the solar irradiation the solar panels will be exposed to mainly during the

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winter period. For this scenario, the winter period had high flow rates for June and July, which means these months had the potential of being the critical month for the design of the SPIS.

4.4.3 SPIS sizing and component selection

The procedure that follows the MAD tilted surface solar irradiation, is the determination of the critical month. The critical month value obtained is shown in Table 4.2.

Table 4.2 Shows the critical month of the system

Month	MAD horizontal surface solar irradiation (H) ($kWh.m^{-2}$)	Flow rate (Q) ($m^3.hr^{-1}$)	Critical month ratio (M_{CR}) (Eqtn 4.18)
January	5.53	1.7856	0.323
February	5.26	0.4464	0.085
March	4.80	0	0
April	4.05	0	0
May	3.39	0	0
June	2.96	3.7944	1.282
July	3.17	4.0176	1.267
August	3.78	1.116	0.295
September	4.36	1.7856	0.409
October	4.56	1.7856	0.08
November	4.87	2.232	0.458
December	5.44	4.464	0.821

To size an appropriate solar PV array, the critical month ratio of the system needs to be determined to find which month will require the most power from PV solar array. The month of June has a critical month ratio of 1.282. The procedures that followed were the sizing of the SPIS components using variables from June. This helped in making sure the design of the solar panel array meets most, if not all, of the demand during the year.

After all the input values were entered in the model by the user, the spreadsheet presented in Figure 4.11 appears on the screen showing the user the components of each type of configuration that were required. The direct-coupled SPIS configuration is Option 1. The components along with their details are listed. The components sized and selected by the model for the SPIS configuration were the solar panels and the pump-motor size. The battery-coupled system was Option 2 in the model output. The components that were sized for this SPIS configuration were solar panels, charge controller, battery pack and the pump-motor. The third option was the storage water tank configuration. For this SPIS configuration, the components sized were the solar panels, the pump-motor and the storage water tank.

RESULTS					
Irrigation System Type:	Center Pivot	Designer's Name	Piwe Piliso	Designer's email address	Piwevp@gmail.com
Crop type:	Sugarcane	Location:	Durban		
Direct-Coupled System - OPTION 1		Battery-Coupled System - OPTION 2		Storage Water Tank System - OPTION 3	
Solar Panels		Solar Panels		Solar Panels	Null
Number	8	Number	5	Number	Null
Area required (m2)	6.8536	Area required (m)	5.0688	Area required (m)	Null
Brand	Renewsys Solar	Brand	Renewsys Solar	Brand	Null
Type andSize	SP-RENE-125W	Type and Size	SP-RENE-140W	Type and Size	Null
Pump		Charge Controller		Pump	
Size	PS600-C-SJ5-8	Size	MPPT 100V/50A	Size	Null
Brand	Lorentz	Brand	Victron Blue Solar		
Single/3 phase	Single phase	Quantity	1	Brand	Null
Power(W)	600	Battery Pack		Single/3 phase	Null
Voltage (V)	48	Number of cells	12		
Amps (A)	13	Brand	Enertec (Discover)	Storage water tank	
		Voltage (V)	12	Quantity	Null
		Amp Hours (Ah)	100	Capacity	Null
		Number of strings	3	Brand	Null
		Pump			
		Size	PS600-C-SJ5-8		
		Brand	Lorentz		
		Single/3 phase	Single		
		Power	600		
		Volatge	48		
		Max Amps	13		

Figure 4.11 The output spreadsheet of the SPISyt model

For the irrigation system example used for this chapter, the sized components are presented in Table 4.3.

Table 4.3 Sized components for the direct-coupled and battery-coupled system options

Direct-Coupled System		
Item	Rating and units	Brand
Solar Panels	125 W x 8	Renewsys®
Solar motor pump	Single-phase 600 W (48 V 13 A)	Lorentz®
Battery-Coupled System		

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Solar Panels	140 W x 5	Renewsys®
Solar motor pump	Single-phase 600 W (48 V 13 A)	Lorentz®
Battery cells	100 Ah x 12	Enertec(Discovery)®
Charge Controller	1 x MPPT 100 V/ 50 A	Victron Blue Solar®

Since the design example used was a centre pivot irrigation system, the direct-coupled SPIS with a storage water tank configuration does not get designed for this scenario because the pressure requirements of the irrigation will be too high to be supplied through gravity. The direct-coupled and battery-coupled systems had the same pump size since they were both designed for an operation time of 6 hours. The nominal power of the solar array of the battery-coupled system was 700 Wp, and the direct-coupled system had a nominal power of 1000 Wp. The battery-coupled system required less power compared to the direct-coupled system because of the stored energy in the battery pack. The direct-coupled system required fewer major components compared to the battery-coupled system and the installation of the system is less complex compared to the battery-coupled system (Sontake and Kalamkar, 2016).

4.4.4 Model checking with PVGIS

With the use of PVGIS, the results obtained from Figure 4.11 for the battery-coupled system were used in the validation of the results. Table 4.3 shows the input information provided to the PVGIS website as well as the simulation outputs. Figure 4.12, Figure 4.13 and Figure 4.14 present graphically the results of PV performance, battery performance and the battery state of charge, respectively.

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Table 4.4 Required input information and simulation results from PVGIS model (European Commission Joint Research Centre, 2017)

Provided inputs:	
Location [Lat/Lon]:	-29.858
Horizon:	Calculated
Database used:	PVGIS-CMSAF
PV installed [Wp]:	700
Battery capacity [Wh]:	1440
Discharge cutoff limit [%]:	50
Consumption per day [Wh]:	1960
Slope angle [Â°]:	30
Azimuth angle [Â°]:	180
PVGIS Simulation outputs:	
Percentage of days with full battery [%]:	70
Percentage of days with empty battery [%]:	0
Average energy not captured [Wh]:	754.45
Average energy missing [Wh]:	0

The SPIS configuration that is simulated using the PVGIS tool is the battery-coupled SPIS. The simulation output summary in Table 4.4 shows that the potential of the percentage of days with full battery is 70 % and the potential of the percentage of days with empty battery is 0 %. Table 4.4 also shows that an average of 1080 Wh of potential energy is not captured by the SPIS, and an average of 0 Wh of potential energy is missing. The average energy not captured of 754.45 Wh is due to solar panels being fixed at an incline angle of 30 ^{o}. If the solar designed to have single or dual axis rotation lower average energy not captured would be obtained. The simulation results for the design for the battery pack show the battery capacity will be full at 14400 Ah for 70 % of the days and being empty for 0 % of the days. This shows that the battery pack will be reliable and potentially provide power for the demands of the irrigation system.

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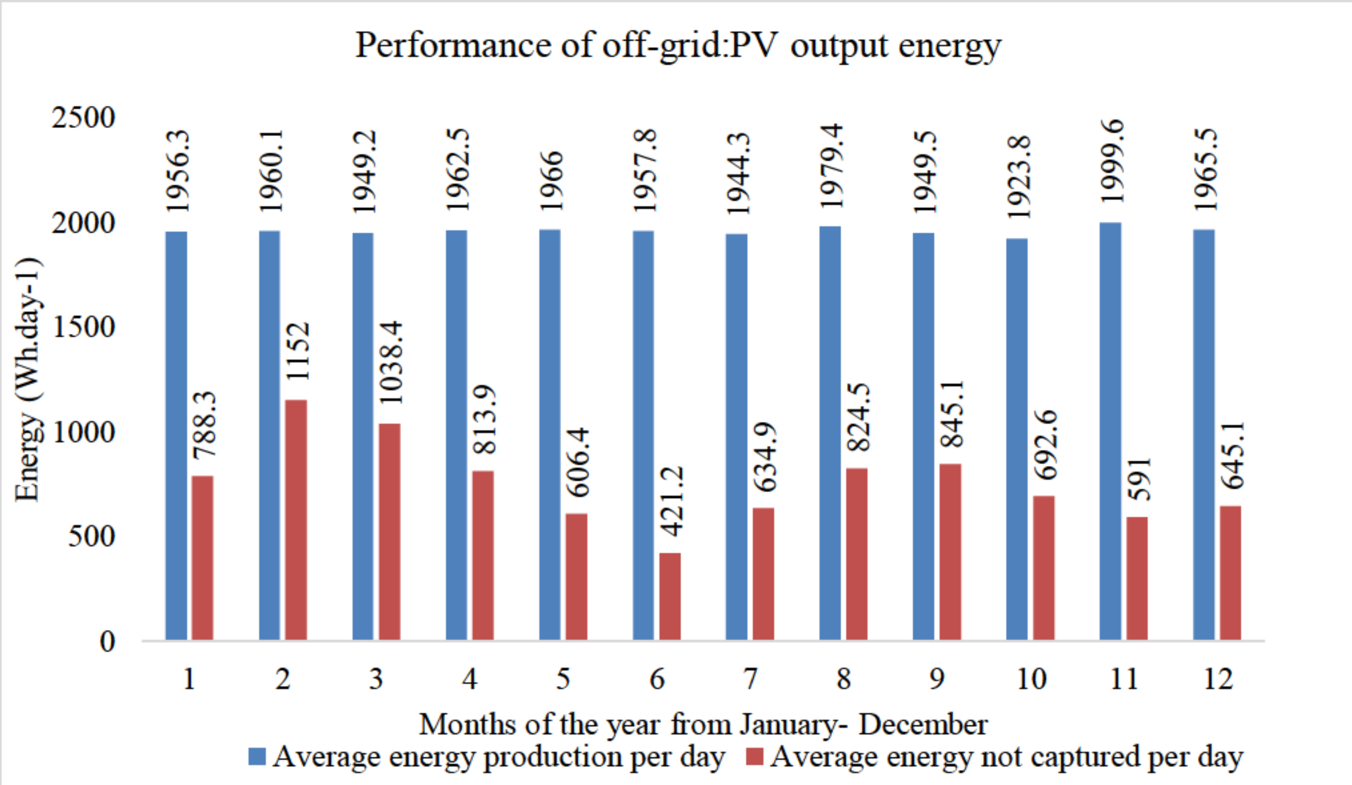

Figure 4.12 Energy output of the PV system from PVGIS model (European Commission Joint Research Centre, 2017)

Figure 4.12 shows more details of the simulation summary output in Table 4.4 for the average energy production per day. The critical month for the centre pivot irrigation system example was determined to be June and the consumption per day for this month is 1960 Wh. Figure 4.12 shows that June had a potential of 1957.8 $Wh.day^{-1}$ of energy produced. Even though the simulated average energy produced by the PV solar array is less than the consumption per day by 0.11 %, most of the requirements for June will be met by the PV solar array. The average energy not captured by the PV array for the critical month of June is the lowest at 421.2 Wh, which is expected since the PV array was designed to capture the most energy possible for the critical month of June. The month with the highest average energy not captured by the PV array was the month of February with 1152 Wh and this is due to the incline angle being fixed at 30 °. The simulation shows that the solar panels would still be able to provide an average output energy of 1960.1 Wh.

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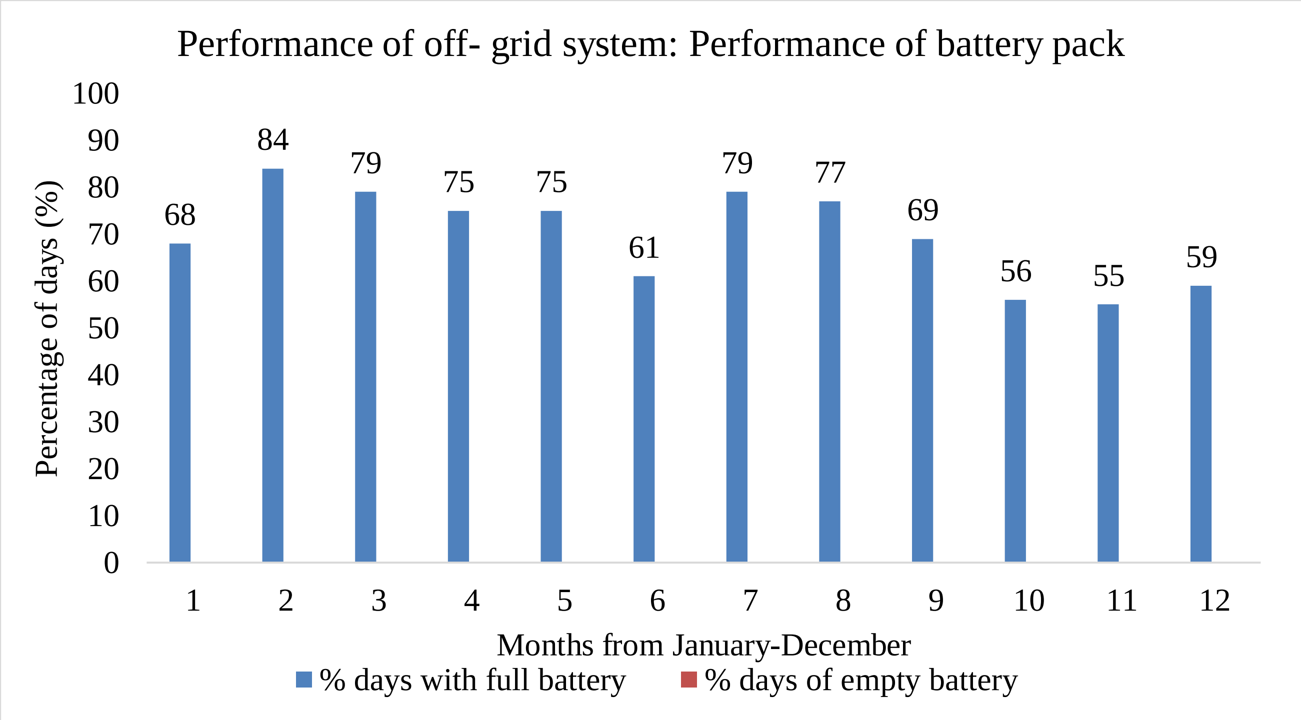

Figure 4.13 Performance of battery pack of the system from PVGIS model (European Commission Joint Research Centre, 2017)

The performance of the battery pack sized is shown in Figure 4.13. For the critical month of June, the percentage of days when the battery becomes full is 61 %. The percentage of days when the battery becomes empty is simulated to be 0 % for all the months of the year. The battery is fully charged before being discharged and the battery having the potential of not going empty makes the life span of the battery long.

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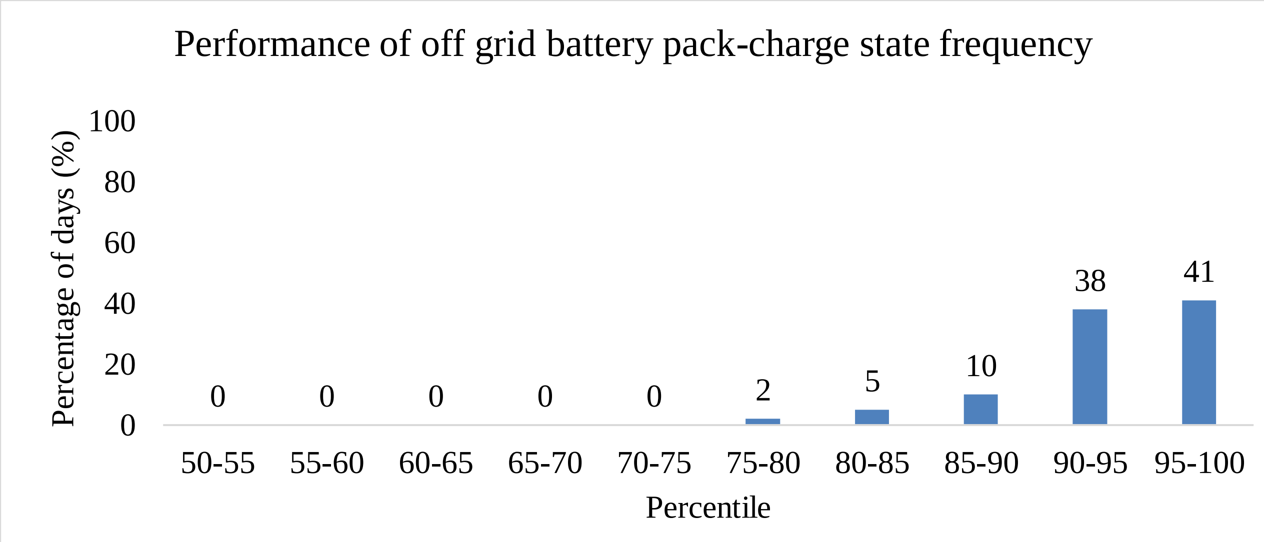

Figure 4.14 Charge state frequency of battery pack from PVGIS model (European Commission Joint Research Centre, 2017)

Figure 4.14 shows the state of charge of the battery, and for a percentage of days of 41 %, the stage of charge of the battery is between 95 – 100 % for the whole year. The results show that the sized battery would have a high potential of not discharging in a state of charge below 50 – 55 % which means that the life span of the battery would not be negatively affected. The system would be able to charge the battery for the two days of autonomy it was designed to supply power for.

4.5 Conclusion

The model was designed and developed using MS excel and VBA where three SPIS configurations were options for selection. The performance of the PV solar panel array, with a nominal power of 700 Wh for the critical month of June, was found to have an average daily energy output of 1957.8 Wh. The irrigation system had a daily consumption requirement of 1960 Wh. The results from the PVGIS tool showed that the sized PV solar array will meet most of the power requirements of the centre pivot irrigation system. The performance of the battery pack sized in the model for the critical month was predicted by the PVGIS tool to have 63 % percentage days of the battery being full and the battery state of charge having 35 % percentage days of the battery having a state of charge in the range 95 – 100 %. These results show that the model can size SPIS components that will be able to meet the power requirements of the drip and centre pivot irrigation systems.

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It is recommended that the SPISsyt model is used to design an SPIS that will be implemented, and the performance of the system is evaluated to further confirm that the model can size the major components of an SPIS. The SPISyst model should also include the design of surface water pumps in the database for component selection. The cost of the components can also be incorporated to then develop a bill of quantities with the output of the components required for the SPIS.

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4.6 References

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5. TESTING OF THE SOLAR POWERED IRRIGATION SYSTEM ($SPIS_{YST}$) MODEL UNDER SIX OF SOUTH AFRICA'S MAJOR CLIMATIC ZONES

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Abstract

Solar energy has huge potential in South Africa due to the country receiving high levels of solar irradiation. The integration of photovoltaic technology and irrigation can help South African farmers eliminate the negative effects of possible electricity load shedding and increasing electricity tariffs. South Africa has a few solar powered irrigation systems and there is no literature on the design and implementation of these systems in the country, resulting in a need for an SPIS model. The objective of this study was to test the solar powered irrigation system (SPISyst) model for the six major climatic zones in South Africa and determine the quantity and size of the main solar powered irrigation systems (SPIS) components. The SPIS configurations that were sized for comprised the direct-coupled system, a battery-coupled system with a 5-hour operation time for both the centre pivot and drip irrigation systems and a battery-coupled system with a 10-hour operation time for the drip irrigation systems only. The electrical power required to pump irrigation water for the six climatic zone scenarios were determined and the temperate coastal climatic zone, which had a drip irrigation system for grapes obtained the highest electrical power requirement for the direct-coupled system of 0.01809 $kW.mm^{-1}.ha^{-1}.m^{-1}$. The direct-coupled system required few components compared to the battery-coupled system, but the latter offers back up electrical power to operate the motor-pump and the SPIS have less solar panels than the direct-coupled system. A linear generic equation between pump power requirements and the number of solar panels was developed for the nine South African provinces. Of the nine provinces, the Western Cape province showed that it required the highest electrical solar power for an irrigation system with a critical month in the winter season with a gradient of the linear graph being 0.5366 and the least number of solar panels when designed for the summer season with a gradient of the linear graph being

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0.2581. The SPISyst model was able to size SPIS components for both direct-coupled and battery-coupled system scenarios and a rule of thumb to estimate the number of solar panels was determined.

Keywords: Solar powered irrigation system, climatic zone, renewable energy, photovoltaic technology

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5.1 Introduction

The use of conventional energy sources, such as fossil fuels, has been identified to have negative impacts on the environment and there has also been an increase in the costs of these energy sources which have become barriers to the expansion of irrigated agriculture (Dekker *et al.*, 2012). Renewable energy sources such as wind, biofuels and solar are alternatives that can be considered for the sustainable growth of irrigated agriculture. The integration of solar energy with irrigation is favoured more compared to other renewable energy source alternatives due to the correlation between crop water requirements and power production from solar irradiation converted to electrical power by photovoltaic technology (Ahmed, 2013; Zegeye *et al.*, 2014).

South Africa has encountered electricity load shedding since 2008 and the latest episode occurred at the beginning of the year 2019. Load shedding has had a direct negative impact on irrigation activities of farmers who cannot use their electric pumps during their access window of water (Bulbulia, 2019). The National Energy Regulator of South Africa (NERSA) had approved several high increases in annual tariffs between 2008 – 2013, which resulted in electricity costs more than doubling, raising prices by cumulative 114 % which have increased production costs for farmers (Deloitte, 2017). Alternative energy sources such as solar energy can be used in irrigation with the use of photovoltaic (PV) solar panels to create a solar powered irrigation system (SPIS). SPIS can be an off-grid, grid-tied or hybrid system. There are three different off-grid SPIS configurations which are the direct-coupled system, the battery-coupled system and the direct-coupled system with a storage water tank. The battery-coupled system and the direct-coupled system with storage water tank system are designed to store electrical power and water at an elevated height, respectively, to account for days of autonomy. Days of autonomy are the number of days the system will be able to irrigate without the PV panels providing power to the system due to low solar irradiation. This results in farmers favouring energy independence and one way to obtain this is the use of PV technology as a source to produce energy for irrigation purposes (Dekker *et al.*, 2012).

Deveci *et al.* (2015) developed a low cost solar powered drip irrigation model using System Modelling Language. There are also software programs available for download, such as HOMER®, PVSyst® and Retscreen® which size and simulate solar systems for a cost (HOMER Energy, 2018; Natural Resources Canda, 2018; PVSyst, 2019). SISIFO® is an online site that sizes and simulate SPIS components for the direct-coupled system and the direct-coupled system with a storage water tank or reservoir. The solar powered irrigation system

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model was designed to size SPIS components for three different irrigation systems configurations which are the direct-coupled system, the direct-coupled with storage water tank and a battery-coupled system. The developed SPIS model was named the SPISyst model.

South Africa has six major climatic zones which have dominant crops that are grown in each zone, in a range of specific soil types with the use of different irrigation techniques. Investigations of SPIS sizing with varying crop types, climatic conditions, soil types and irrigation techniques, namely, drip irrigation and centre pivot irrigation, in South Africa are missing in the literature. An investigation of this nature may be beneficial for obtaining the quantity and size of SPIS components required for the different SPIS configurations for South Africa and then compare the results. The objective of the study was to test the SPISsyst model under different climatic zones, crops, soil types and irrigation techniques in South Africa. The model is tested by inputting different scenarios of designs based on the 6 climatic zones and recording the results of the model. To show the influence or impact of climate on the sizing of SPIS specifically, the climate a rule of thumb (RoT) can be developed for nine areas of the provinces in South Africa to compare the differences in the size of the solar panels required.

5.2 Materials and Methods

This section will be detailing the procedures taken and the tools used along with the SPISyst model to determine a RoT for the sizing of SPIS in South Africa.

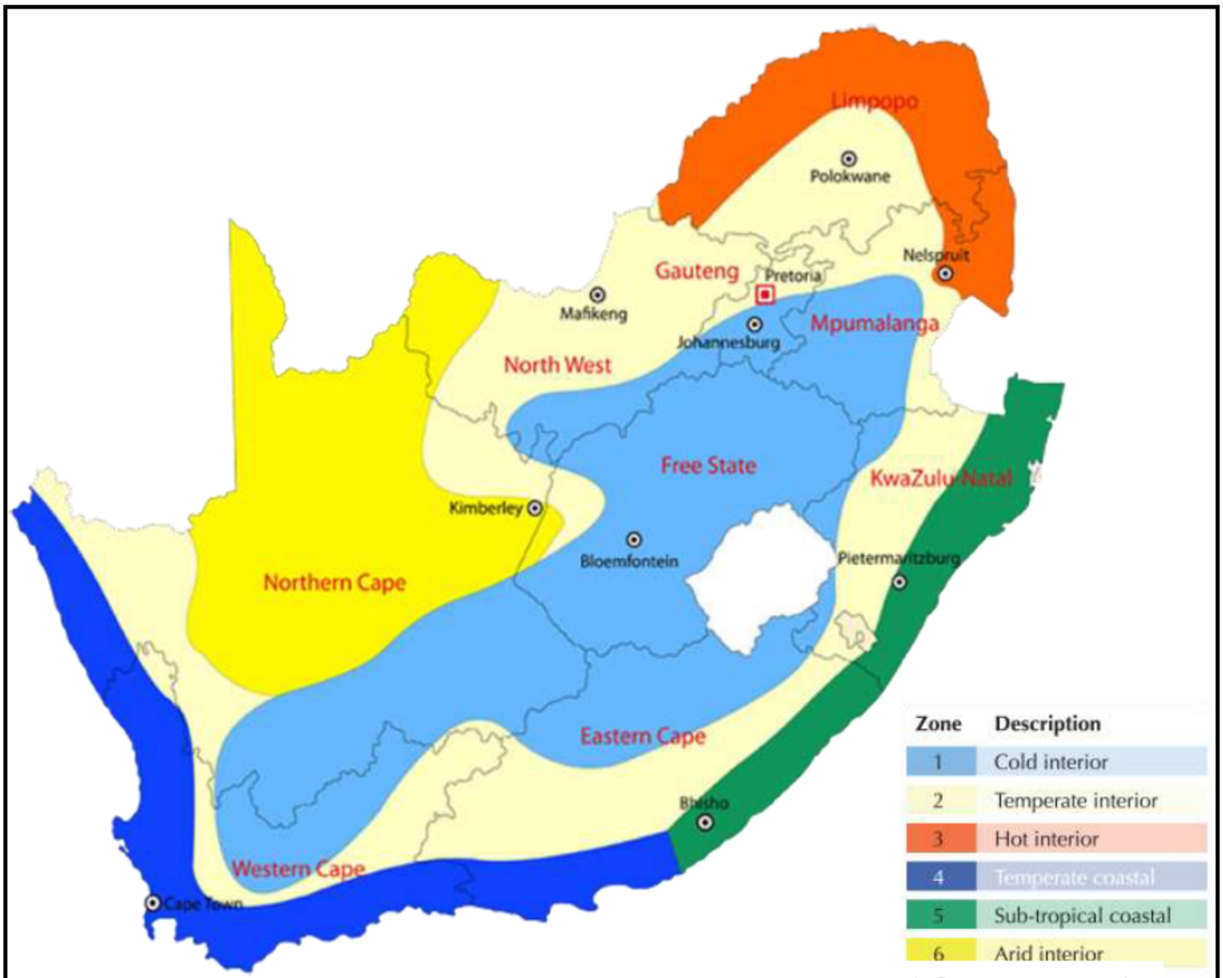
5.2.1 SPISyst model

The SPISyst model (developed as outlined in Chapter 5) sizes the components required for an SPIS considering the three configurations which are the direct-coupled system, the battery-coupled system and the direct-coupled system with a water storage tank. The model output is the components required for a designed irrigation system (drip or centre pivot). In the previous chapter, the model output was checked through a PVGIS simulation to observe if the output components were suitable for the irrigation design. The results showed that SPISsyst outputs were suitable for the irrigation system example given.

5.2.2 Study area

The study area was South Africa, specifically the six climatic zones and the nine provinces. The six major climatic zones and the nine provinces in South Africa are presented in Figure 5.1.

Latitudinally the country stretches from 22° S to 35° S and longitudinally from 17° E to 33° E.



(after SEA, 2017).

Figure 5.1 Map of South Africa's six major climatic zones (Africa, 2017)

5.2.3 Climatic zones and crop selection

To test for the different climatic zones, crops, soil type and irrigation systems (drip and centre pivot irrigation systems), literature was used to determine the dominant crops in each climatic zone. The crops selected had to be mainly irrigated with either drip or centre pivot irrigation systems. The soil type that each crop is mainly grown in was also selected from the literature. The information obtained is presented in Table 5.1.

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Table 5.1 Combination of South African climatic zones, crop type, soil types and irrigation systems for perennial crops for SPISyst model evaluation or testing.

No.	Climatic Zones	Crops	Soil type	Irrigation system	Site selec
1	Temperate interior	Potato	Sandy loam	Centre pivot	Potchefstroo North West
2	Hot interior	Mango	Sandy	Drip	Punda-Milia Limpopo
3	Temperate coastal	Grapes	Loam	Drip	Cape Town Western Ca
4	Sub-tropical coastal	Sugarcane	Sandy loam	Centre pivot	Cape St Luc KZN
5	Arid interior	Lemon	Sandy loam	Drip	Upington – North West
6	Cold interior	Summer – Maize Winter – Wheat	Loam	Centre pivot	Bloemfontei Free State

The crops for each climatic zone were selected based on the dominant irrigated crops in terms of yield. In South Africa, potatoes can be produced all year round. The Sandveld area in the North West province lies in the temperate interior climatic zone and is one of the major regions for potato production in South Africa at 15 % of the country's potato production (Kotze, 2016). The Western Cape region, which is mainly in the temperate coastal climatic zone, produces more than 80 % of South Africa's table grapes (Department of Agriculture, 2012). Sugarcane is primarily grown in tropical regions and favours the sub-tropical coastal climatic zone in South Africa, which is mainly on the coast of the KwaZulu-Natal province (Department of Agriculture, 2014). The areas that are key for the production of mangoes are located in the north eastern parts of the country and the Limpopo province is the largest producer of mangoes (Department of Agriculture, 2015). The area that produces the largest amount of maize is the Free State according to Lehohla (2002). The Free State is also an area that produces the most wheat in South Africa (ARC, 2017). The Northern Cape province is highlighted as one of the

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provinces which grow citrus, which is grown along the Orange River (Department of Agriculture, 2017). The Orange River in the Northern Cape lies within the arid interior climatic zone.

5.2.4 Crop water requirements

To determine the crop water requirements of each crop in the climatic zones, FAO CLIMWAT 2.0 and CropWAT 8.0 were used (FAO, 2009). CLIMWAT 2.0 was used to obtain the weather data for each location within each climatic zone. These climatic data were selected as it was available for free on CLIMWAT and it extracted from CLIMWAT in MS Excel spreadsheets, which made it easy to integrate with the SPISyst model. The climatic data that were required for the model were the monthly average temperature and the sunshine hours for the whole of South Africa. The research was informed that its request for data was too large and only institutions that have a Memorandum of Understanding (MoU) with South African Weather Services (SAWS) could access the data. SAPWAT also had data in the software, but the data could not be extracted from the software unless done manually. CLIMWAT was used in CropWAT 8.0 to determine the crop water requirements. SAPWAT 4 was not used in this study as problems were encountered by installing the programme.

Equations 5.1 and 5.2, the dependable rain method, was applied in determining the monthly effective rainfall in CropWAT 8.0 using long-term average rainfall data (FAO, 2009).

$$P_{eff} = 0.6 \times P - \frac{10}{3} \qquad \text{for } P \leq 23 \text{ mm} \qquad 5.29$$

$$P_{eff} = 0.8 \times P - \frac{24}{3} \qquad \text{for } P > 23 \text{ mm} \qquad 5.30$$

where,

P_{eff} = monthly effective rainfall (mm), and

P = monthly average rainfall (mm).

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5.2.5 Weather data

The average daily solar irradiation on a horizontal plane per month was obtained through the NASA Prediction of Worldwide Energy Resources (POWER) online website (Stackhouse *et al.*, 2016) with the input of coordinates of an area. The average temperature data required for the SPISyst model calculations to determine the power requirements of the solar panels are obtained from CLIMWAT 2.0. SAPWAT4 was not used for this study due to the problems encountered in installing the software, and in any case, SAPWAT4 and CropWAT 8.0 give comparable results since SAPWAT4 is based on CropWAT 8.0.

5.2.6 Design of irrigation systems

The SPISyst model was created to size SPIS components for drip irrigation and centre pivot irrigation systems. From the two irrigation systems and the crops selected for each climatic zone, a suitable irrigation system was chosen as shown in Table 5.1. The Irrigation Design Manual (Agricultural Research Council, 2003) was used in the irrigation systems design processes. Google Earth Pro® was used to obtain the area data for each site, such as the coordinates, and elevations. The coordinate and elevation data needed to be converted to be used on AutoCAD® 2020 to draw the irrigation design of each system. GPS Visualizer®, which is an online website, was used to obtain the elevations from Google Earth Pro® data and was saved as a comma separated value (csv) file. The csv file of the coordinate and elevation data was then uploaded into the QuickGrid_x64® programme to convert the csv file to an AutoCAD® Drawing Interchange file which then had the area plotted with the contour lines of the area of interest. Alternatively, the design of the irrigation systems could come from programmes such as Irrimaker® (Model Maker System, 2018).

5.2.6.1 Centre pivot irrigation system design

Centre pivot irrigation system is categorised as an irrigation system that moves while applying water to a field. Centre pivots are made up of steel frames and pipes, which are supported at approximately 50 m intervals by an A-frame on two wheels (Burger *et al.*, 2003j).

The equations below were used to first determine the rotation time and gross application. The speed setting of the centre pivot system was all assumed to be at 50 %. The permissible wheel slippage was assumed to be 3 % for all cases this is due to the slopes for fields with a centre pivot structure are required to be less than 5 % (Burger *et al.*, 2003j).

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The flow rate of the systems was determined using Equation 5.3 (Burger *et al.*, 2003j). The gross irrigation requirement was obtained from CropWAT 8.0 output csv file. Due to the irrigation system being able to operate during the day when solar radiation is available, the system is designed to operate for 5 hours per day. The irrigation systems will also work for all 7 days of the week. The area of each field was obtained from the AutoCAD plot of the field.

$$Q = \frac{A10GIR7}{t_d t_h} \qquad 5.31$$

where,

Q = flow rate ($m^3.h^{-1}$),

A = area (ha),

GIR= gross irrigation requirement (mm),

t_h = working hours per day (hours), and

t_d = working hours per week (days).

To determine the travel speed of the last wheel of the centre pivot at a 100 % speed setting, Equation 5.4 was used (Burger *et al.*, 2003j). So, at a 100 % speed setting the centre pivot irrigation system will operate for 2.5 hours and at a 50 % speed setting the system will operate for 5 hours. Equation 5.4 and Equation 5.5 were then used to determine the appropriate speed which then leads to select the appropriate type of drive and wheel size.

$$t = \frac{2\pi r}{60v} \qquad 5.32$$

where,

t = rotation time at 100 % speed setting (hours),

r = distance from the centre to the farthest driving wheel (m), and

v = travel speed of the farthest wheel at 100 % speed setting ($m.min^{-1}$).

$$t_v = \frac{t}{v_v} \qquad 5.33$$

where,

t_v = rotation time at a specific % speed setting (hours), and

v_v = specific speed setting (fraction).

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In the process of determining the suitable sprinkler package, Equation 5.6 was used (Burger *et al.*, 2003c). The Senninger®[1] irrigation product information was used in the calculation and determination of the sprinkler packages for all three centre pivot designs.

$$GAR = \frac{2000Qr}{R^2B} \qquad 5.34$$

where,

GAR = average gross application rate ($mm.h^{-1}$), and

B = wetted sprinkler strip width (m), and

R = total centre pivot radius (m).

Equation 5.7 was used to determine the fixed radius of each section of sprinklers in the centre pivot system.

$$q_e = \frac{2Qr_fL_e}{R^2} \qquad 5.35$$

where,

q_e = sprinkler flow rate ($l.s^{-1}$),

L_e = sprinkler spacing (m), and

r_f = radius to a fixed point (m).

The Irrigation Design Manual (Agricultural Research Council, 2003) was used to determine the electrical power requirements of the motor to drive the centre pivot structure by using the number of pivot towers of the systems.

Microsoft Office Excel 2016 was used in the design process for the centre pivot irrigation systems and the spreadsheets are presented in Appendix K. The drawings and a summary of the components required for each centre pivot irrigation system are presented in Figures 5.2 and 5.3.

Presented in Figure 5.2 is the centre pivot irrigation system design drawing for sugarcane in Cape St. Lucia in KZN, which is in the temperate interior of South Africa. The average area of

[1] Disclaimer: Use of tradenames is for information purposes and use of is not an indorsement by author/s or author/s institutions

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irrigated sugarcane for smallholder farmers in KwaZulu-Natal is 9.6 ha (James and Woodhouse, 2017). The area of the field that was selected for the design was 7.47 ha.

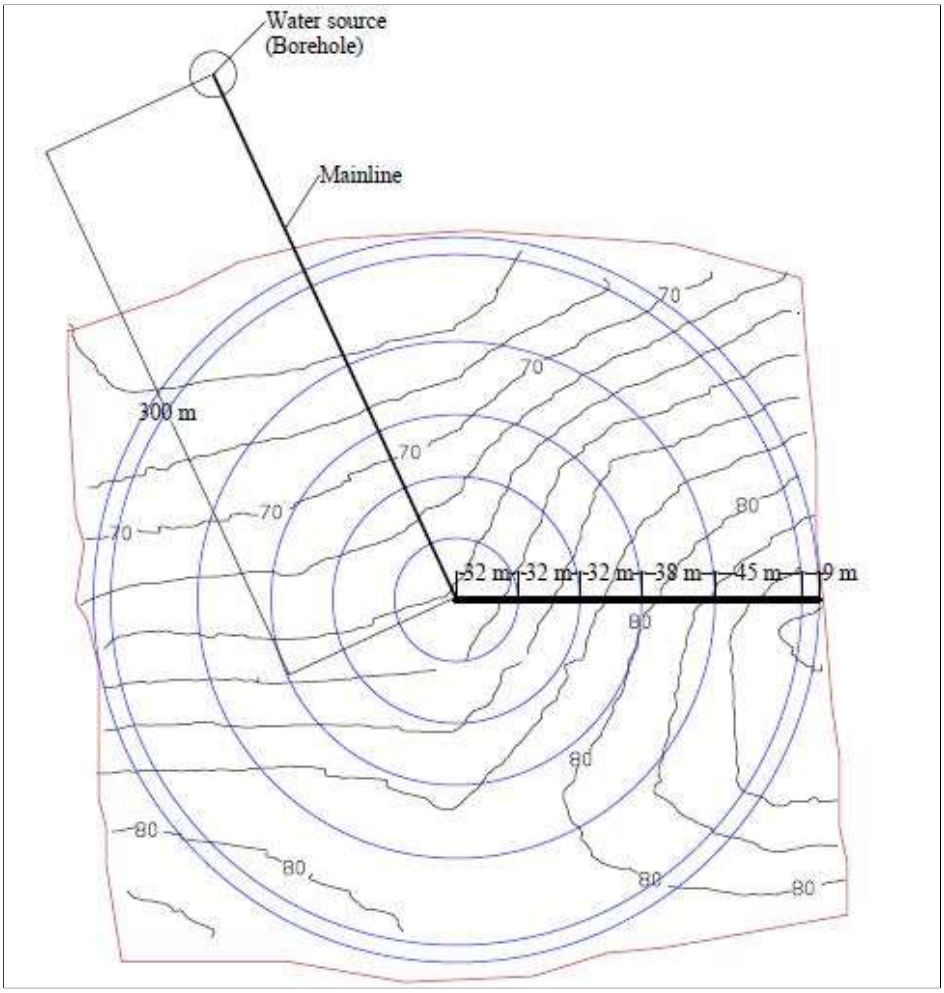

Figure 5.2 Illustration of centre pivot irrigation system design layout for sugarcane

Two types of sprinklers were selected from the Senninger® irrigation product catalogue (Senninger, 2007). Which are the I-Wob and the 6° Impact, which have a wetted strip width of 12.2 – 17.4 m and 21.4 – 30.5 m, respectively. The flow rate of the I-Wob sprinkler was determined to be 0.62 $l.h^{-1}$ and for the 6° Impact sprinkler is 2.98 $l.h^{-1}$. The spans selected for the centre pivot structure and their dimensions are presented in Table 5.22. The power requirement for the high speed motors that drive the centre pivot structure was selected to be 7.5 kW with an average amperage of 7.67 A from Burger *et al.* (2003j). The length of the mainline from the water source to the centre of the field was measured to be 300 m. The internal diameter of the mainline was 153.6 mm and the outside diameter was 160 mm and it was a Class 6 pipe. The diameter of the mainline was largely due to the system being designed to

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operate for a minimum of 5 hours. To reduce the pipe diameters the operation time can be increased by the user.

Table 5.2 Centre pivot span selection data

	No. of spans	Length of each span (m)	Internal diameter (mm)
Tower 1, 2 and 3	3	32	150
Tower 4	1	38	150
Overhang	1	20	150

Figure 5.3 shows the centre pivot design drawing for maize and wheat in Bloemfontein Free State commanding 24.7 ha. One half of the field will be used to grow and irrigate maize during the summer and the other half will be used to grow and irrigate wheat during the winter, as shown in Figure 5.3. This was done because maize is a summer crop and wheat is a winter crop and they won't be competing for land and crop rotation purposes.

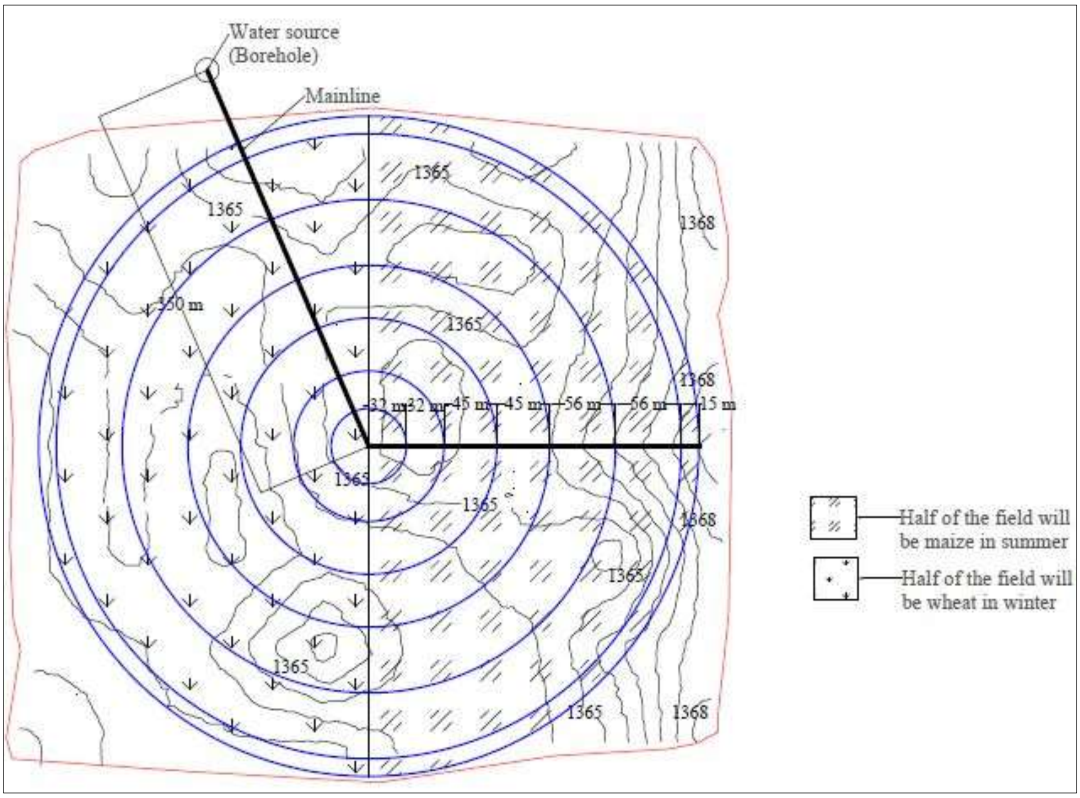

Figure 5.3 Illustration of the centre pivot irrigation system design layout for maize and wheat

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The sprinkler package selected for the centre pivot system above was Senninger® I-Wob and the 6° Impact with a wetted strip width of 12.2 – 17.4 m and 21.4 – 30.5 m sprinkler flow rate of 0.24 $l.h^{-1}$ and 1.152 $l.h^{-1}$, respectively.

The centre pivot span selection information for the irrigation system is shown in Table 5.33. The power requirement of the high speed motors required to drive the centre pivot structure was 7.5 kW with an average amperage of 8.93 A. The length of the mainline from the water source to the centre of the field was measured to be 290 m and the internal diameter was determined to be 192.2 mm and the outside diameter is 200 mm Class 6 pipe.

Table 5.3 Centre pivot span quantity and dimensions for maize and wheat in Bloemfontein

	No. of spans	**Length of each span (m)**	**Internal diameter (mm)**
Tower 1 and 2	2	32	203
Tower 3 and 4	2	45	203
Tower 5 and 6	2	56	203
Overhang	1	15	203

Figure 5.4 shows the centre pivot irrigation system design drawing for potatoes in Potchefstroom North West commanding 7.47 ha. The arrangement of the centre pivot spans is shown as well as the position of the water source and mainline.

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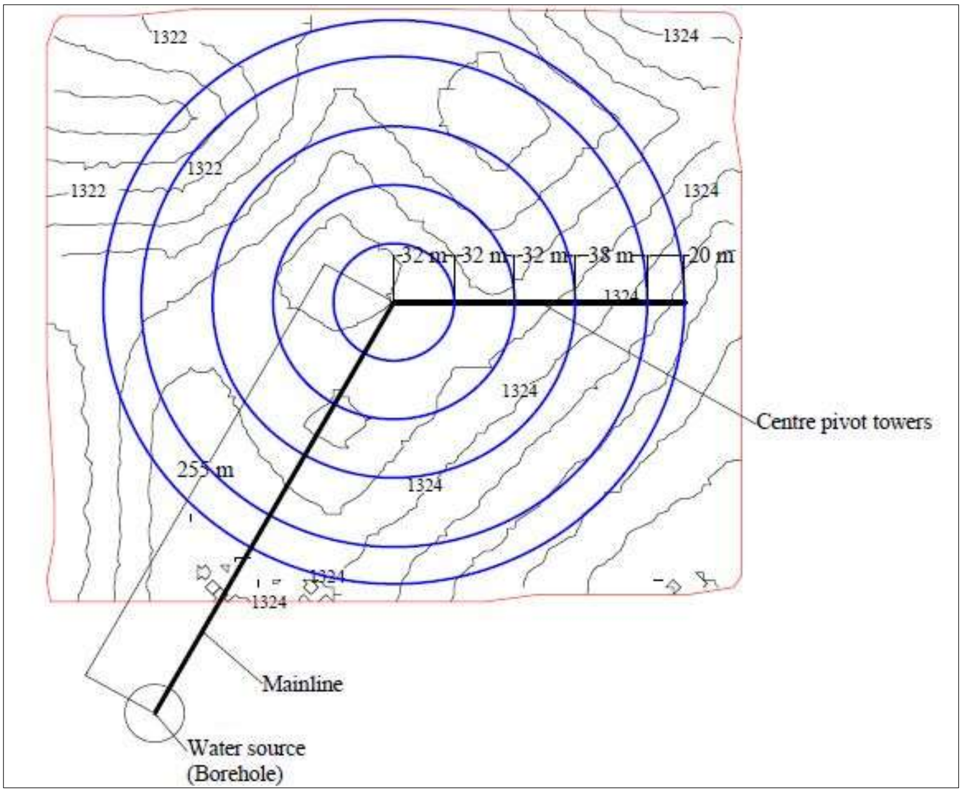

Figure 5.4 Illustration of centre pivot irrigation system design for potatoes

The sprinkler packages selected for the system are Senninger® I-Wob and 6° Impact with a wetted strip width of 12.2 – 17.4 m and 21.4 – 30.5 m and a sprinkler flow rate of 0.63 $l.h^{-1}$ and 3.024 $l.h^{-1}$, respectively. The spans selected for the centre pivot system are shown in detail in Table 5.44. The power requirements of the high speed motors that will drive the centre pivot system were 7.5 kW with an average amperage of 10.19 A. The length of the mainline was measured to be 255 m. The internal diameter of the mainline after calculations was selected to be 120 mm with an outside diameter of 125 mm Class 4 pipe.

Table 5.4 Centre pivot span quantity and dimensions for potatoes in Potchefstroom

	No. of spans	**Length of each span (m)**	**Internal diameter (mm)**
Tower 1 and 2	2	32	150
Tower 3 and 4	2	38	150
Tower 5	1	45	150
Overhang	1	15	150

`

5.2.6.2 Drip irrigation system design

Drip irrigation is a form of micro-irrigation which makes use of drippers (or emitters) to emit water at low flow rates and pressures (Burger *et al.,* 2003h). The gross irrigation requirement was calculated using CropWAT 8.0. The irrigation cycle for all systems was assumed to be 3 days with irrigation occurring for all 7 days in the week. The equations presented below were used in the design of the drip irrigation systems. Equation 5.8 was used to determine the emitter flow rate suitable for the irrigation system (Burger et al., 2003b). The NETAFIM®[2] dripper lines, drippers and other emitter product catalogue (NETAFIM, 2017) was used to select the most suitable dripper lines and drippers or emitters.

$$q_e = \frac{GIR_c}{t_s} A \qquad 5.36$$

where,

q_e = emitter flow rate ($l.h^{-1}$),

GIR_c = gross irrigation requirement per cycle (mm),

t_s = standing time (h), and

A = area irrigated by an emitter, lateral spacing (L_d) x emitter spacing (L_e) (m^2).

To size the drip irrigation groups theoretically, the equations below were used in MS Excel 2016 spreadsheets. Equation 5.9 was used to determine the flow rate for each group (Burger *et al.*, 2003h). Equation 5.10 was then used to determine the number of emitters that will be in each group (Burger *et al.*, 2003h). Then, lastly Equation 5.11 was used to determine the theoretical size of each group (Burger *et al.*, 2003h). Thus, the flow rate for each group was:

$$Q = \frac{GIR_c A_T}{t} 10 \qquad 5.37$$

where,

Q = total flow rate per group ($m^3.h^{-1}$),

A_T = total system area (ha), and

[2] Disclaimer: Use of tradenames is for information purposes and use of is not an indorsement by author/s or author/s institutions

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t = operating hours per cycle (h).

The number of emitters in each group:

$$n_e = \frac{1000Q}{q_e} \quad 5.38$$

where,

n_e = number of emitters.

And the theoretical size of each group:

$$A_g = \frac{n_e(L_d \times L_e)}{10000} \quad 5.39$$

where,

A_g = group area (ha).

After the theoretical sizing was complete, the actual sizes of each group for the irrigation designs were determined on AutoCAD from the generated areas. This is where the lateral length and the manifold length of the system was determined. The actual group sizes in some cases were not the same as the theoretical group area, therefore Equation 5.12 was used to find the practical system capacity (Burger *et al.*, 2003h).

$$Q = \frac{L.n_d}{L_e} \times \frac{q_e}{1000} \times 1.03 \quad 5.40$$

where,

L = Lateral length (m),

n_d = number of laterals per group (unitless), and

1.03 = snaking factor.

Shown in Figure 5.5 is the drip irrigation system design drawing for grapes in Cape Town Western Cape commanding an area of 6.4 ha. The system has four groups and the layout and lengths of the lateral lines, manifolds and mainline are shown in the drawing.

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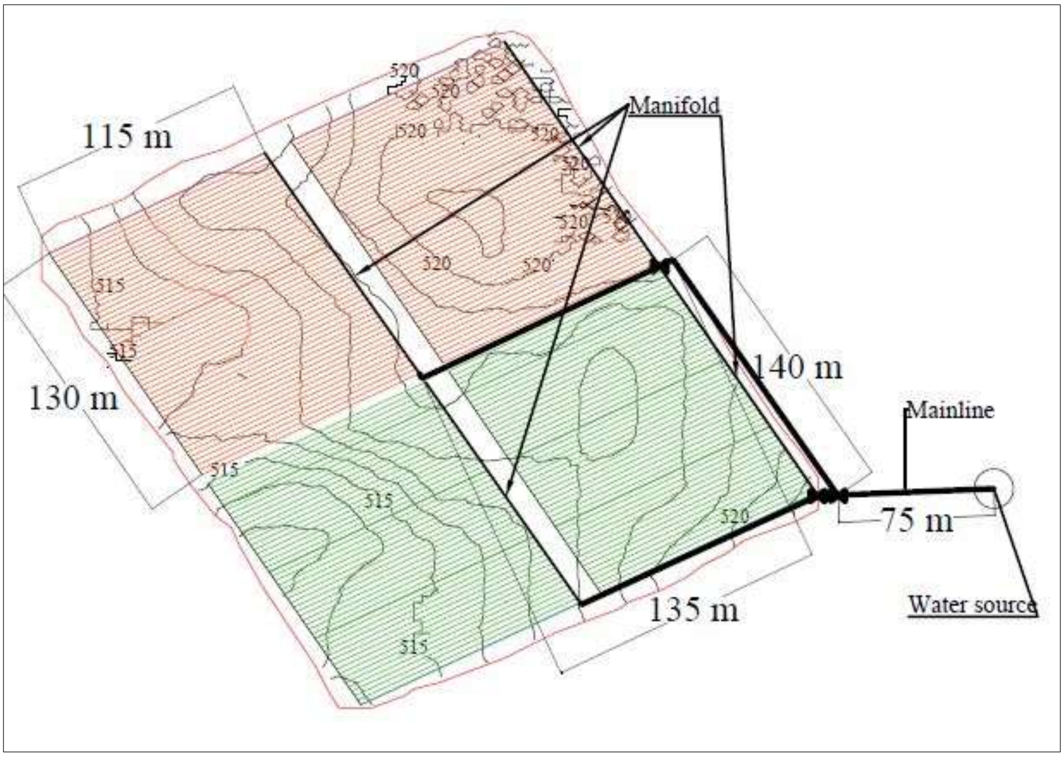

Figure 5.5 Illustration of the grape drip irrigation system design layout

The emitter flow rate selected for the irrigation system is an 8 $l.h^{-1}$ flow rate. Table 5.5 shows the pipe dimensions of the lateral lines, manifolds and mainline of the drip irrigation system design. The filter selected for the system is a 3” T (80 mm) type disc filter.

Table 5.5 Information of pipes sized in the design of the irrigation system for grapes

	Materials	Internal Diameter (mm)	Outside Diameter (mm)	Pipe Class
Lateral	Polyethylene	12		
Manifold	PVC	30.5	32	4
Mainline	PVC	86.8	90	4

Presented in Figure 5.6 is the drip irrigation design layout drawing for mangoes grown in Punda-Milia in Limpopo commanding 9 ha. The system has seven groups with two different

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sizes as shown in the drawing. The layout of the lateral lines, the manifolds and the mainline are shown in Figure 5.6.

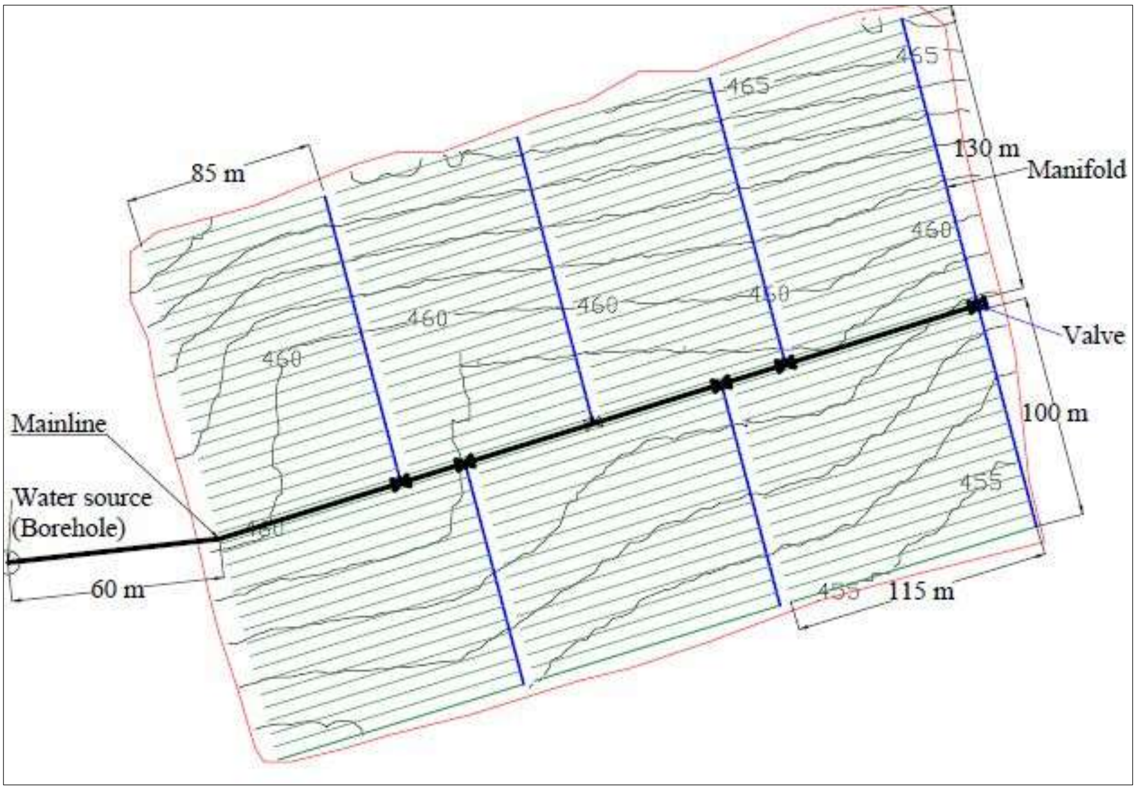

Figure 5.6 Illustration of the mango drip irrigation system design layout

For each row of trees, there are double lateral lines. The flow rate of the emitter selected is 40 $l.h^{-1}$. Table 5.6 shows the dimensions of the lateral lines, manifolds and mainline of the irrigation design system and the type of material.

Table 5.6 Information of pipes sized in the design of the irrigation system for mangos

	Materials	Internal Diameter (mm)	Outside Diameter (mm)	Pipe Class
Lateral	Polyethylene	21.2		
Manifold	PVC	86.8	90	4
Mainline	PVC	134.4	140	4

Figure 5.7 shows the drip irrigation design layout drawing of the lemon field in Upington, North West commanding 10.5 ha. The system has seven groups with two different sizes as shown in

the drawing. The layout of the lateral lines, the manifolds and the mainline are shown in the figure below.

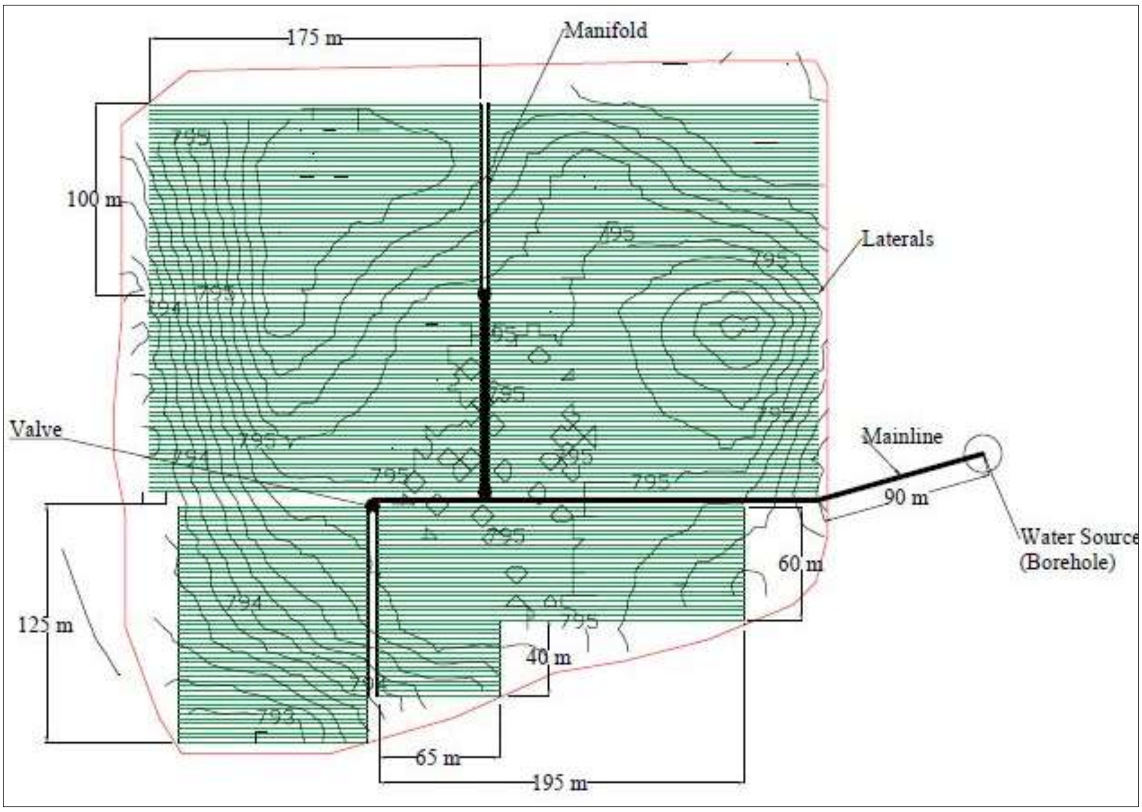

Figure 5.7 Illustration of lemon drip irrigation design layout

For each row of trees, there are double lateral lines. The flow rate of the emitter selected is 12 $l.h^{-1}$. Table 5.7 shows the dimensions of the lateral lines, manifolds and mainline of the irrigation design system and the type of material for each.

Table 5.7 Information of pipes sized in the design of the irrigation system for lemon trees

	Materials	Internal Diameter (mm)	Outside Diameter (mm)	Pipe Class
Lateral	Polyethylene	21.2		
Manifold	PVC	105.2	110	4
Mainline	PVC	153.6	160	4

Table 5.8 presents a summary of the irrigation design details used and obtained for the six crops in the different climatic zones.

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Table 5.8 Summary of the irrigation system design details

	Sugarcane	Wheat and maize	Potato	Grapes	Mango	Lemon
Area (ha)	11.2	12.4	7.5	6.4	9	10.5
GIR/month (mm)	71.6	64.9	160.7	21	172.1	154.3
T_c (days)	7	7	7	3	3	3
T_s (hours)	5	5	5	5	5	5
Q ($m^3.h^{-1}$)	53.5	134.45	40.02	19.2	64.54	38.5
q_e ($l.h^{-1}$)	4	4	3.3	8	12	40
TDH (m)	43.19	33.09	38.09	28.02	13.09	25.12

5.2.7 SPIS sizing

The SPISyst model was used to size the SPIS components for each of the designed centre pivot and drip irrigation systems. The data required to size the components of the SPIS were the total dynamic head and the flow rate of the irrigation system, which were determined in the previous section.

5.2.8 Power requirements and number of solar panels required

The next step taken was to determine the power requirements for varying flow rates and total dynamic head at a fixed pump-motor efficiency. The calculated power was then used to calculate and determine the number of solar panels required in each location for the summer and winter seasons. Figure 5.8, which comes from Equation 5.13 was used to calculate the power requirements for varying flow rate and total dynamic head (Burger et al., 2003k) in a spreadsheet and is presented in Appendix B.

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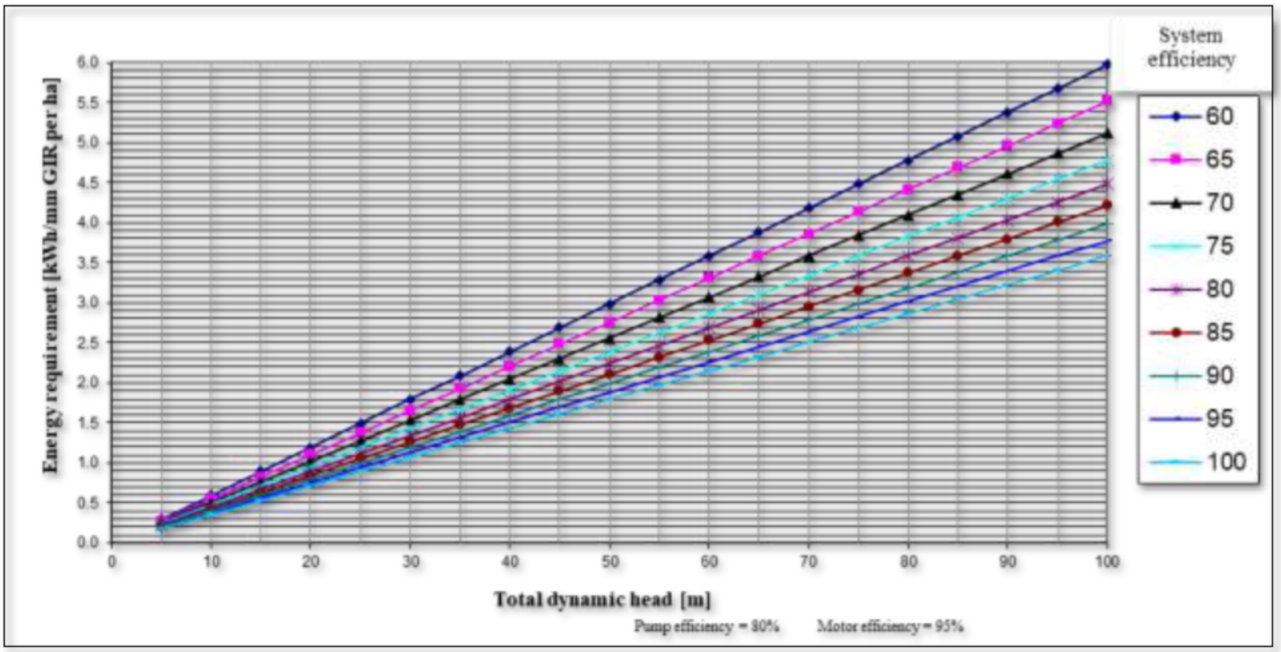

Figure 5.8 Motor-pump energy requirement versus total dynamic head graph (after Burger *et al.* 2002d).

$$E_H = \frac{\rho g Q H_p}{3{,}6 \times 10^4 \eta_{mp}} \qquad 5.41$$

where,

E_H = power requirement of pump (kW),

ρ = density of water ($kg.m^{-3}$),

g = gravitational acceleration ($m.s^{-2}$),

H_p = total dynamic head (m),and

η_{mp} = pump efficiency at duty point (%).

Equation 5.14 is then used to determine the power required from the solar panels which will provide the motor-pump system with the power to pump water, see Chapter 4 for details.

$$P_{el} = \frac{1000}{[1 - \alpha_c(T_c - T_{a)})]\eta_{mp}} \times \frac{E_H}{H_T} \qquad 5.42$$

where,

P_{el} = electrical power required from solar panels (kW)

α_c = PV cell temperature coefficient ($°C^{-1}$),

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T_c = temperature of the cell in the module (°C),

T_a = air temperature (°C),

η_{mp} = motor-pump efficiency(unitless), and

H_T = intensity of MAD tilted solar irradiation of a surface (kWh,m^{-2}.day^{-1})

5.3 Results and Discussion

This section presents the results obtained from the tests conducted from the SPISyst model for the six climatic zones for the irrigation systems that are designed above.

5.3.1 SPISyst output for the six climatic zones

The irrigation systems designed above are all too large to have a storage water tank option for sizing because the total dynamic head (TDH) of the systems are greater than 9 m. So, the two types of SPIS that were sized by the SPISyst model are direct coupled and the battery coupled system. Table 5.9 shows the electrical energy required by the irrigation system from the solar panels in the base unit kW.mm^{-1}.ha^{-1}.m^{-1} head, which is made up of P_{el}.GIR^{-1}.ha^{-1}.m^{-1}TDH, for the six direct and battery coupled systems. The results obtained from the sizing of the SPIS for each irrigation system are shown in Table 5.10 to Table 5.15. The results that are presented in the tables are the SPIS component details that are suitable for each irrigation system.

The critical months for the irrigation systems were determined to be April for grapes, September for maize and wheat, mangoes and potatoes, and December for sugarcane and lemons as shown in Table 5.9. For the direct coupled system, the grapes obtained the highest electrical power required of 0.01809 kW.mm^{-1}.ha^{-1}.m^{-1} head from the solar panels. This is because in April the solar irradiation obtained in the temperate interior is low compared to the other climatic zone critical month solar irradiation. Based on that, solar irradiation is measured in kW.m^{-2}, therefore more solar panels will be required, which will occupy a larger area compared to the other climatic zones, resulting in a high power requirement for the solar panels. The arid interior received the lowest electrical power required of 0.01048 kW.mm^{-1}.ha^{-1}.m^{-1} head from the solar panels. The arid interior in South Africa, which is located on the west coast of the country receives the highest levels of solar irradiation compared to other climatic zones (Singh, 2016). This means less area is required to capture solar irradiation from the solar panels, resulting in a low power rating for the solar panels.

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The battery coupled system, compared to the direct coupled system, requires less electrical power for all six climatic zone examples shown in Table 5.9. The climatic zone that has the lowest electrical power requirements for the battery coupled system is the arid interior with 0.00677 $kW.mm^{-1}.ha^{-1}.m^{-1}$head. The reason for this is that the batteries will store excess electrical power produced by the solar panels, and the batteries are sized to store power for two days of autonomy, which means when the solar panels are not producing the required electricity the battery pack will be supplying the electricity to operate the irrigation system.

Table 5.10 to Table 5.12 show the SPIS components that were sized for the three centre pivot irrigation systems. The SPIS components sized are for the pump power requirements and the motors that drive the centre pivot tower around the field. Firstly, the direct coupled system and the battery coupled system SPIS were sized for a 5-hour operation a day. The centre pivot irrigation system for potatoes in Table 5.12 obtained the largest SPIS with a 21 kW motor, which runs a 20 – 55 m and 112 $m^3.h^{-1}$ pump and 61 by 325 W solar panels for the direct coupled SPIS. The battery coupled system obtained 72 from 1954 Ah 2 V battery cells and 4 by MPPT 200 V 150 A charge controllers. So, the direct coupled system will not be able to operate during completely cloudy days, while the battery coupled system will, at most, be able to operate for two days of little to no sunlight available, provided the battery pack is fully charged. The battery coupled system will come with higher investment costs for the battery pack and the charge controllers and the system will be more complex compared to the direct coupled system.

Presented in Table 5.13 to Table 5.15 are the SPIS components that are sized for drip irrigation systems for a direct coupled, battery coupled 5-hour irrigation operation time and a battery coupled 10-hour irrigation operation time. Table 5.14 shows that the drip irrigation system designed for lemons obtained the largest SPIS compared to the other drip irrigation systems. For the direct coupled and battery coupled 5-hour operating time system, the pump size selected was a 3 phase 15 kW motor, which runs a 10 – 35 m and 126 $m^3.h^{-1}$ submersible pump for both configurations. The battery coupled system with a 10-hour irrigation operation time has the same number of solar panels as well due to the energy requirement not changing requires a 7 kW 3 phase motor to run a 5 – 30 m and 76 $m^3.h^{-1}$ pump. The pump size selected is smaller due to the increase in operation time, which resulted in a reduced flow rate.

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Table 5.9 The electrical power required from the solar panels for the different irrigation systems.

	Sub-tropical coastal (Sugarcane)	Cold interior (Maize and Wheat)	Temperate interior (Potato)	Arid interior (Lemon)	Temperate coastal (Grapes)	Hot interior (Mango)
Critical month	December	September	September	December	April	September
Direct coupled P_{el} GIR^{-1} ha^{-1}.TDH^{-1}(kW mm^{-1}.ha^{-1} m^{-1} head)	0.01493	0.01366	0.01282	0.01048	0.01809	0.01235
Battery coupled P_{el} GIR^{-1} ha^{-1}.TDH^{-1}(kW mm^{-1}.ha^{-1} m^{-1} head)	0.01023	0.00901	0.00852	0.00677	0.01118	0.00823

Table 5.10 SPIS components for centre pivot irrigation system for sugarcane in KZN

Direct Coupled System		
Component	Quantity	Size
Pump	1	10 – 50 m 65 m^3 h^{-1}
Motor	1	15 kW
Solar Panels	52	325 W (99.78 m^2)
Battery Coupled System- 5-hour operation per day		
Pump	1	10 ─ 50 m 65 m^3 h^{-1}
Motor	1	15 kW
Solar Panels	36	320 W (69.08 m^2)
Battery Pack	36	1660 Ah
Charge Controller	4	MPPT 200 V/ 100 A

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Table 5.11 SPIS components for centre pivot irrigation system for maize and wheat in the Free State

Direct Coupled System		
Component	Quantity	Size
Pump	1	10 – 35 m 126 $m^3 h^{-1}$
Motor	1	15 kW
Solar Panels	39	320 W (74.83 m^2)
Battery Coupled System- 5-hour operation per day		
Pump	1	10 – 35 m 126 $m^3 h^{-1}$
Motor	1	15 kW
Solar Panels	26	320 W (49.89 m^2)
Battery Pack	36	1380 Ah
Charge Controller	4	MPPT 200 V/ 100 A

Table 5.12 SPIS components for centre pivot irrigation system for potatoes in North West

Direct Coupled System		
Component	Quantity	Size
Pump	1	20 – 55 m 112 $m^3 h^{-1}$
Motor	1	21 kW
Solar Panels	61	325 W (117.05 m^2)
Battery Coupled System- 5-hour operation per day		
Pump	1	20 – 55 m 112 $m^3 h^{-1}$
Motor	1	21 kW
Solar Panels	41	325 W (78.67 m^2)
Battery Pack	72	1954 Ah
Charge Controller	4	MPPT 200 V/ 100A

`

Table 5.13 SPIS components for a drip irrigation system for grapes in the Western Cape

Direct Coupled System		
Component	Quantity	Size
Pump	1	10 ─ 45 m 26 $m^3 h^{-1}$
Motor	1	4 kW
Solar Panels	20	325 W – (38.38 m^2)
Battery Coupled System- 5-hour operation per day		
Pump	1	10 ─ 45 m 26 $m^3 h^{-1}$
Motor	1	4 kW
Solar Panels	16	260 W (26.19 m^2)
Battery Pack	24	420 Ah
Charge Controller	2	MPPT 150V / 35 A
Battery Coupled System- 10-hour operation per day		
Pump	1	10 ─ 40 m 13 m^3 h
Motor	1	1.8 kW
Solar Panels	16	260 W (26.19 m^2)
Battery Pack	24	420 Ah

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Table 5.14 SPIS major components for the drip irrigation system for mangos in Mpumalanga.

Direct Coupled System		
Component	Quantity	Size
Pump	1	2 ─ 16 m 120 m^3 h^{-1}
Motor	1	7 kW
Solar Panels	60	320 W (115.1 m^2)
Battery Coupled System- 5-hour operation per day		
Pump	1	2 ─ 16 m 120 m^3 h^{-1}
Motor	1	7 kW
Solar Panels	40	320 W (76.8 m^2)
Battery Pack	36	1660 Ah
Charge Controller	4	MPPT 150V/ 35 A
Battery Coupled System- 10-hour operation per day		
Pump	1	6 ─ 16 m 59 $m^3.h^{-1}$
Motor	1	4 kW
Solar Panels	40	320 W (76.75 m^2)
Battery Pack	36	1660 Ah
Charge Controller	4	MPPT 150V / 35 V

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Table 5.15 SPIS components for the drip irrigation system for lemons in the Northern Cape.

Direct Coupled System		
Component	Quantity	Size
Pump	1	10 ─ 35 m 126 $m^3\ h^{-1}$
Motor	1	15 kW
Solar Panels	43	325 W (82.51 m^2)
Battery Coupled System- 5-hour operation per day		
Pump	1	10 ─ 35 m 126 $m^3\ h^{-1}$
Motor	1	15 kW
Solar Panels	28	325 W (53.73 m^2)
Battery Pack	36	1380 Ah
Charge Controller	4	MPPT 200 V/ 100 A
Battery Coupled System- 10-hour operation per day		
Pump	1	5 ─ 30 m 76 $m^3.h^{-1}$
Motor	1	7 kW
Solar Panels	28	325 W (53.73 m^2)
Battery Pack	36	1380 Ah
Charge Controller	4	MPPT 200 V/ 100 A

5.3.2 Power requirements versus the number of solar panels

Figure 5.9 to Figure 5.17 below illustrates the relationship between the pump power requirements and the electrical power required from the solar panels for direct-coupled SPIS for 9 regions in the provinces in South African for January, which represents summer and June, which represents winter. The relationship between pump power requirements and the electrical power required from the solar panels was a linear relationship and the equations of each trend line are presented in the figures. The generic equation is of the form is presented as Equation 5.15 as follows:

$$P_{el} = ME_H \qquad 5.15$$

where,

P_{el} = electrical power required from solar panels (W),

`

E_H = pump power requirement (W) (Equation 5.13), and

M = slope of the relationship which is the number of solar panels per pump power required (unitless).

Equation 5.16 was used to estimate the number of solar panels with a wattage that ranges between 200 - 325 W.

$$N_x = \frac{P_{el}}{x} \quad 5.16$$

where,

N_x = number of x Watts solar panels for the direct SPIS (unitless), and

x = the wattage of the solar panels (200 – 325 W solar panels) (W).

The graphs and the equations presented above can be used to estimate the number of solar panels required for direct-coupled SPIS if the pump power requirements are known by the user. A comparison between the number of solar panels determined by the SPISyst model and the graphs is presented in Table 5.16.

The figures for each province can be used to determine the number of 30 W solar panels that will be required for specific pump power requirements, which is the flow rate, the total dynamic head and the operation time, for the location selected in that province. The operation time is fixed at 5 hours for all data points. Figure 5.12 and Figure 5.13 show that for the winter season, the Western Cape and the Eastern Cape have the highest and the second highest gradients at 0.5366 and 0.4695, respectively. Practically this means these two provinces offer less solar irradiation compared to other provinces, therefore they would require more solar panels for the same pumping requirements. Figure 5.12 and Figure 5.14 illustrate for the summer season, the Western Cape and the Northern Cape have the lowest and second lowest gradients at 0.2581 and 0.2741, respectively. This shows that these two areas will require the least solar panels at a specific pump power requirement for a direct-coupled system. The summer and winter data points for Figure 5.10 and Figure 5.11 are very close to each other compared to the other provinces, but the winter period still required more solar panels for winter than for summer for a specific pump power requirement. In Table 5.16 the solar panels sized with the graphs are either more than or less than the solar panels sized with the model. The maize and wheat example used Figure 5.17 to obtain the slope for the generic equation to determine the number of solar panels sized with the graph was the same as the number of solar panels sized with the

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SPISyst model. The grape example obtained the highest percentage error of 10 % for the number of solar panels sized with Figure 5.14. The reason for the high error for the grapes is that the critical month of the irrigation system is April, which falls under the autumn season in South Africa. So, an average between the summer and winter slope was used to determine the number of solar panels required for the direct-coupled SPIS.

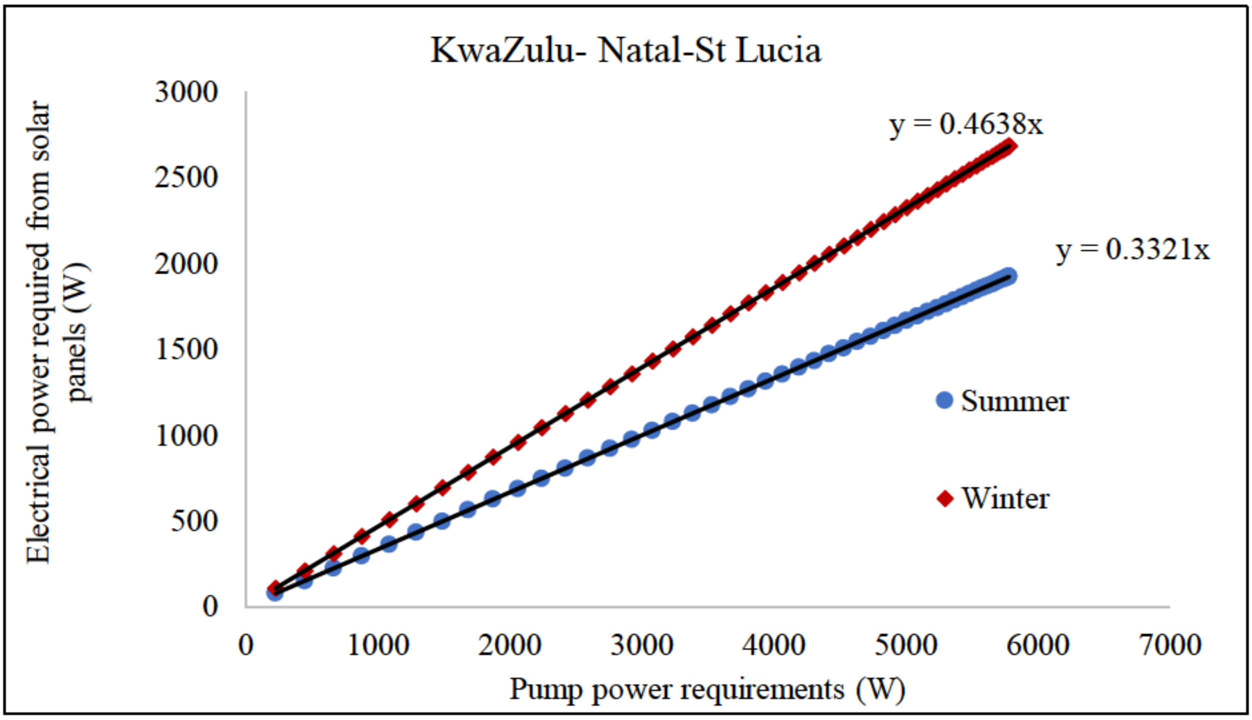

Figure 5.9 Electrical power required from solar panels for pump power requirements for the KwaZulu-Natal province

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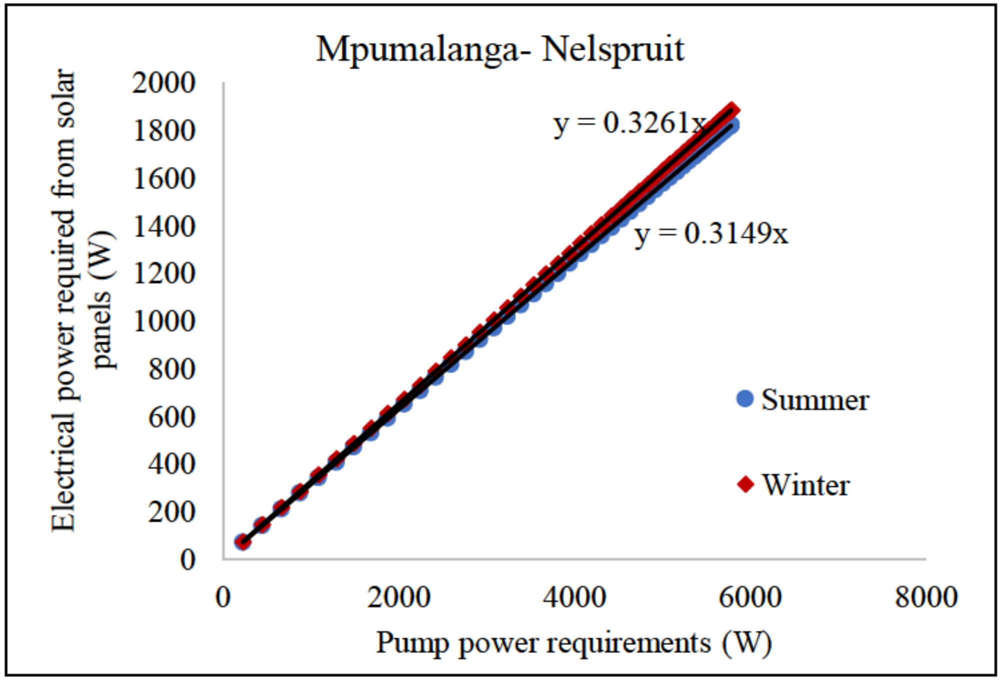

Figure 5.10 Electrical power required from solar panels for pump power requirements for the Mpumalanga province

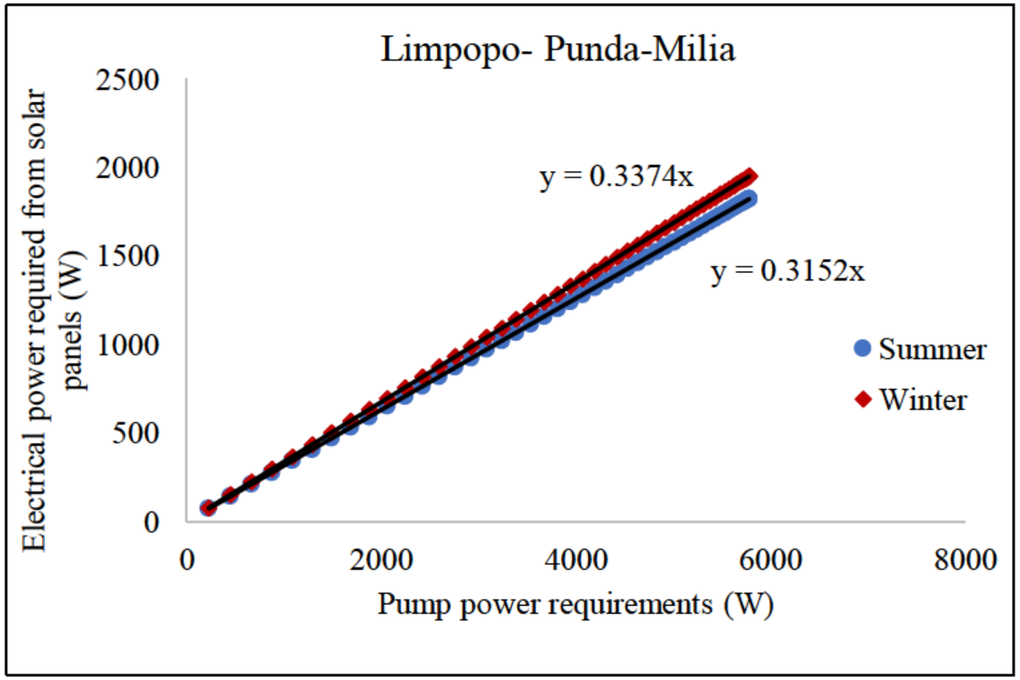

Figure 5.11 Electrical power required from solar panels for pump power requirements for the Limpopo province

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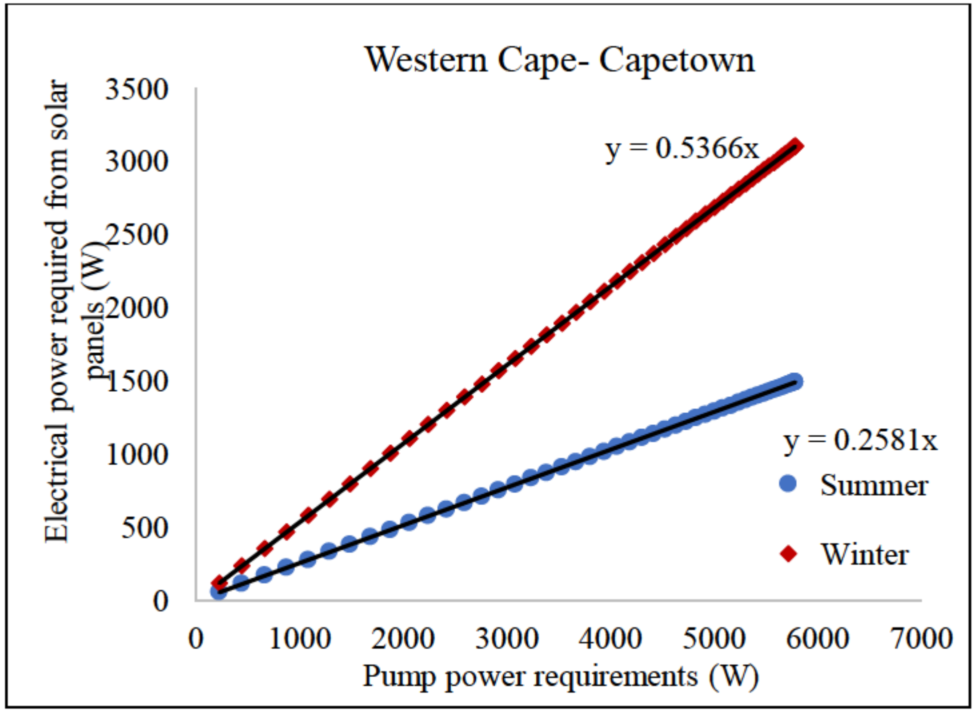

Figure 5.12 Electrical power required from solar panels for pump power requirements for the Western Cape province

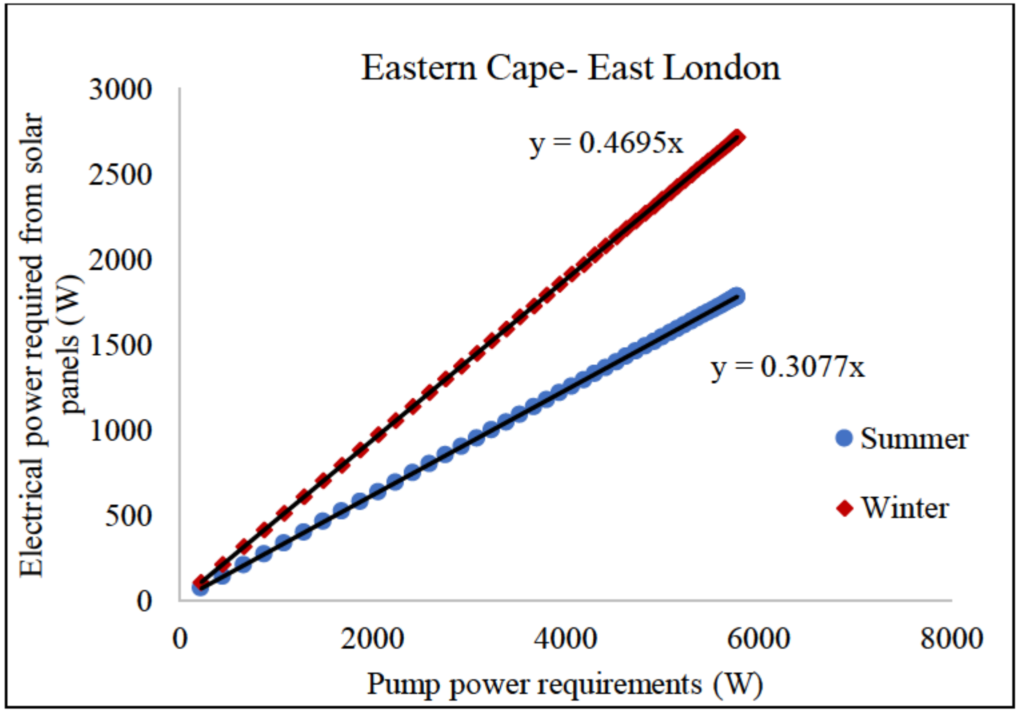

Figure 5.13 Electrical power required from solar panels for pump power requirements for the Eastern Cape province

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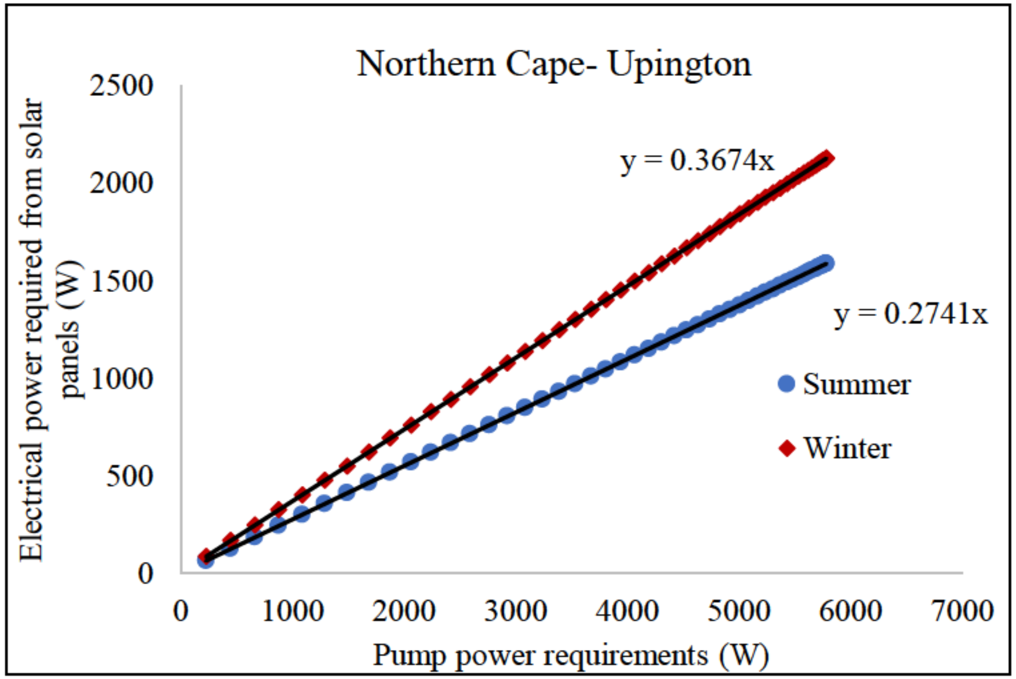

Figure 5.14 Electrical power required from solar panels for pump power requirements for the Northern Cape province

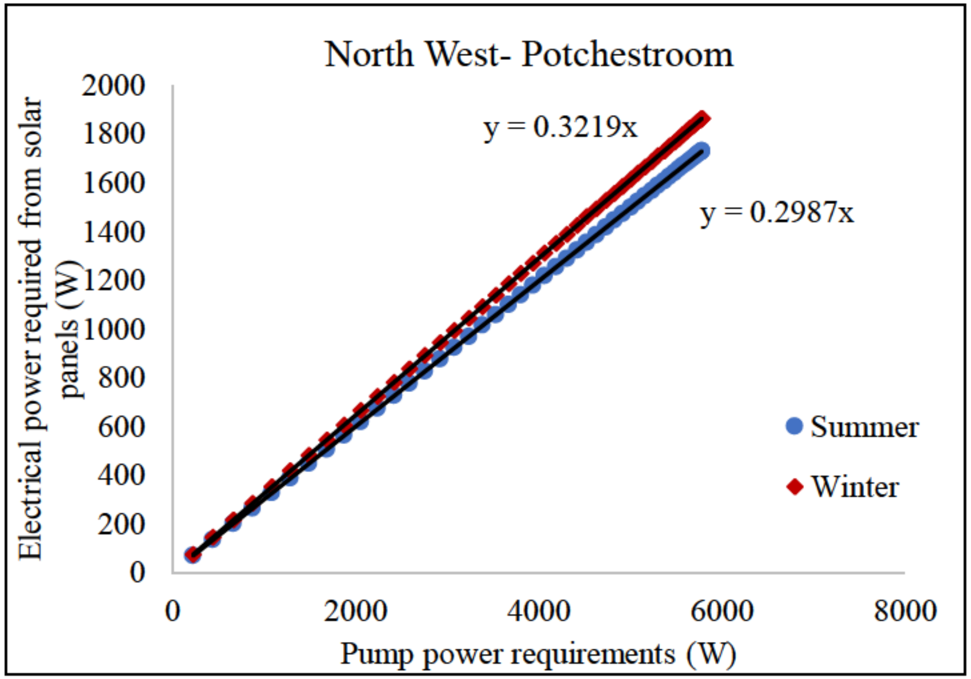

Figure 5.15 Electrical power required from solar panels for pump power requirements for the North West province

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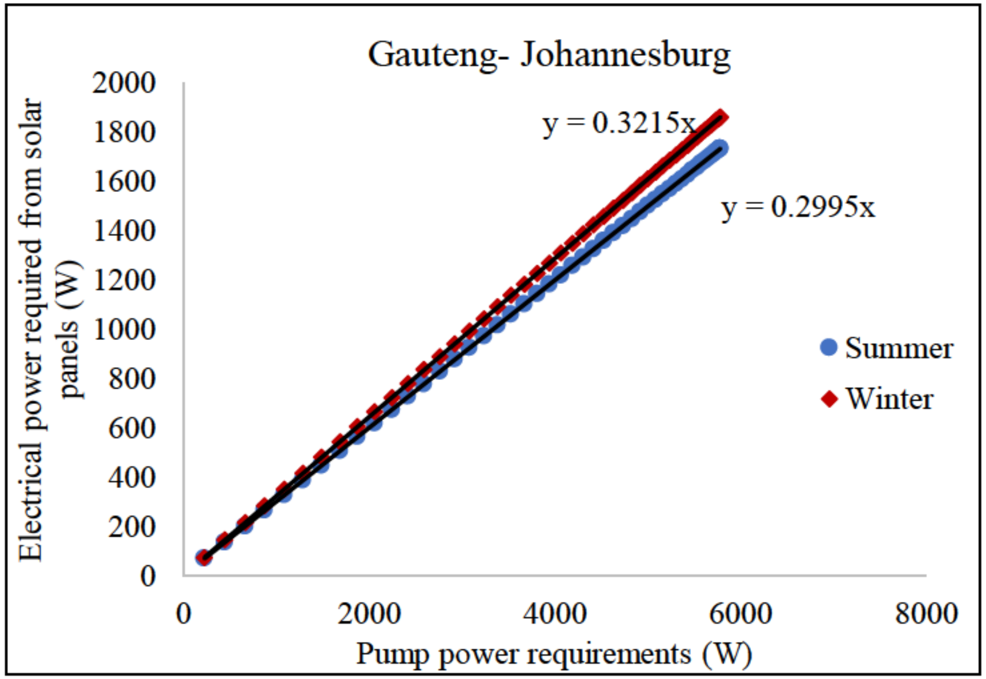

Figure 5.16 Electrical power required from solar panels for pump power requirements for the Gauteng province

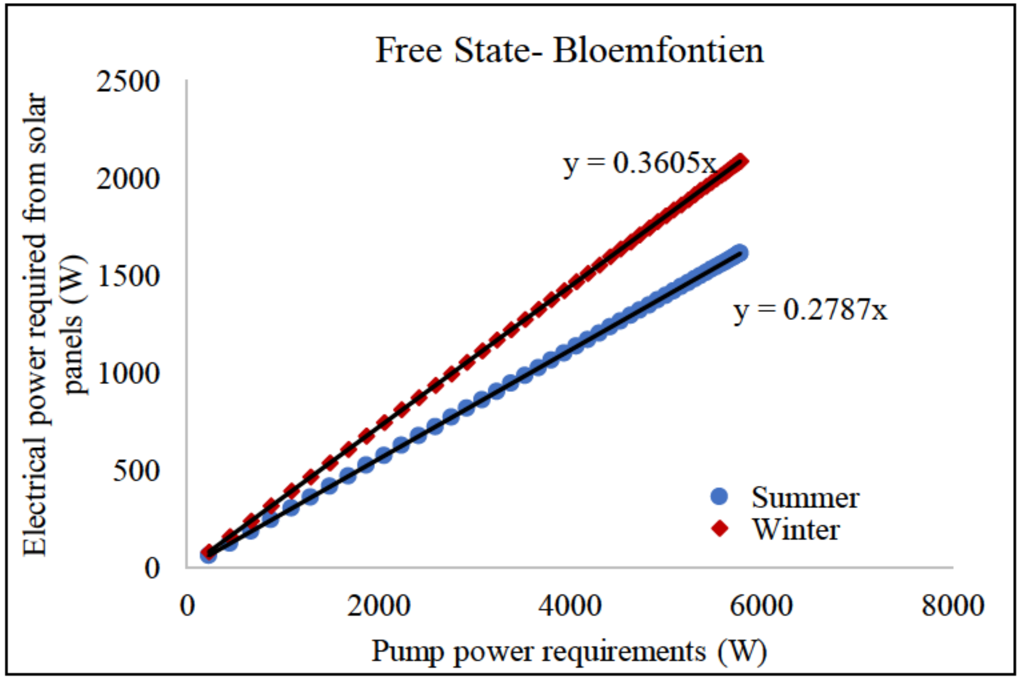

Figure 5.17 Electrical power required from solar panels for pump power requirements for the Free State province

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An example that demonstrates how to size the number of solar panels required for a direct-coupled irrigation system is presented below.

Table 5.16 Comparison of the number of solar panels required for an irrigation system determined with the model and the graphs

	Sugarcane	Maize and wheat	Potatoes	Grapes	Mangoes	Lemons
Solar panels size (W)	325	325	325	325	320	325
No. of solar panels determined from the graphs	50	39	64	18	62	45
No. of solar panels determined from the SPISyst model	52	39	61	20	60	43
Variance (%)	+ 3.85	0	- 4.92	+ 10	- 3.33	- 4.65

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5.4 Conclusion

In this chapter, the SPISyst model was tested by subjecting the model through irrigation design scenarios based on the six climatic zones in South Africa. The crops, soil type and irrigation techniques selected for the design scenarios were selected from the literature. The irrigation designs were then completed manually.

The temperate coastal gave the highest electrical power requirement of 0.01809 $kW.mm^{-1}.ha^{-1}.m^{-1}$ head from the solar panels compared to the other climatic zones for direct-coupled configuration. The direct-coupled configuration obtained higher electrical power requirements from the solar panels compared to the battery-coupled system. This was due to the design of the battery being designed to store excess energy for 2 days of autonomy. The direct-coupled and battery-coupled component outputs were presented for the centre pivot irrigation design for potatoes in the temperate interior that required the largest SPIS components.

A generic equation to estimate the electrical power of solar panels required and the number of solar panels was developed for each of the nine provinces in South Africa. The Western Cape was determined to have the steepest slope for the winter compared to the other provinces because it obtained a gradient of 0.5366. To estimate the number of solar panels required for a direct-coupled SPIS using the graphs was determined and the highest percentage error was 10 %. The graphs can be used as a preliminary design tool. The SPISyst model was able to size SPIS components for both direct-coupled and battery-coupled systems for all six scenarios. A rule of thumb was also established to estimate the size of solar panels for a given pump power requirement for South Africa.

It is recommended that smaller areas are selected for the evaluation of the model to obtain components for the direct-coupled system with a storage water tank. The reliability of the battery-coupled system can also be further investigated so that a choice in the percentage reliability can be made by the user, which will vary the battery pack size. Other irrigation techniques can also be investigated to quantify and size the required SPIS components for these systems.

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6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

South Africa is a semi-arid country where parts of the country's cultivated agriculture are under irrigation to provide crop water requirements. Most irrigation systems use pumps with electric motors to distribute water to crops. The source of electricity is mainly coal, which is a fossil fuel. South Africa has experienced load shedding since 2008, which has negatively affected farmers in the country. There had also been electricity tariff increases which resulted in the cost of production for farms increasing. Renewable energy sources are alternatives that can be considered for the sustainable growth of irrigated agriculture. The use of solar power in irrigation is an alternative source more favoured compared to other renewable resources due to its correlation between crop water requirements and power production from solar irradiation. South Africa receives high levels of solar radiation and this energy can be captured to pump water for irrigation systems. With solar the energy source is clean, and the farmer is no longer dependent on the electricity supplier. The literature showed different types of solar powered irrigation systems (SPIS) configurations and the main types are the direct-coupled system, the battery-coupled system and the storage water tank configuration. Drip irrigation and centre pivot irrigation are documented as being the best irrigation systems suited to integrate with SPIS due to their high water use efficiency (WUE) and relatively low head operation. Submersible motor-pumps are mainly used with SPIS in literature. Some models size solar powered systems and are available for sale and download online. The study was undertaken to obtain information on SPIS implementation in South Africa. A model was developed to size SPIS in South Africa. The model was tested for 6 climatic zones in South Africa.

6.2 Conclusion

To determine the extent of SPIS in South Africa, online questionnaires were developed using SurveyMonkey®. The questionnaires targeted SPIS engineers, designers, installers and SPIS users. The participants were contacted by requesting questionnaires to be sent to institutions that had access to the required participants and emails with the link to the online survey. A total of 13 SPIS users and 18 SPIS engineers, installers and designers completed the online questionnaires. The data obtained from the questionnaires showed that the Western Cape and the Eastern Cape provinces had the most SPIS implemented. The majority of the SPIS systems

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were implemented between the years 2010 – 2016, which correlate with the issues that came with load shedding. The solar panels used were predominantly poly-crystalline panels due to their high efficiency compared to thin-filmed solar panels. Drip and centre pivot irrigation systems were the most that were integrated with solar power. The extent of SPIS use in South Africa was determined at 364,415 ha. An idea of the extent of SPIS in South Africa was established with the SPIS installers, engineers and designers but details on these systems were determined only by the number of SPIS users that participated in the questionnaire in South Africa.

An SPIS model, named SPISyst, was developed using MS Excel. Drip and centre pivot irrigation systems were the irrigation techniques considered for the model. CLIMWAT and CROPWAT were used to obtain temperature data and determine the crop water and irrigation requirements of crops of interest. The NASA Prediction of World Energy Resources (POWER) website was used to obtain the monthly average daily (MAD) horizontal solar irradiation data. Three configurations were considered for the SPISyst model. The Visual Basic Application feature in MS Excel was used to create the user forms of the SPISyst model. PVGIS was used to simulate if the design of the SPISyst model would be able to provide the power requirements. The battery-coupled centre pivot irrigation system configuration was tested with the PVGIS simulation. The PVGIS simulation showed that the solar array sized for the irrigation system would be able to meet the power requirements. PVGIS estimated that the state of charge of the battery pack sized by the SPISyst model will be 100 % for 63 % of the days during the critical month of the irrigation system. The PVGIS simulation also showed that the state of charge of the battery pack will be between 95 – 100 % for 35 % of the days of the year. A model to size SPIS was designed and developed. The SPISyst model results were also simulated and obtained positive results.

The SPISyst model was then tested for the six climatic zones in South Africa, where the major crops in each climatic zone were selected and had to be irrigated with either solar powered drip irrigation or a centre pivot irrigation system. The power required to pump irrigation water for each climatic zone was determined for both direct-coupled and battery-coupled systems. The direct-coupled system had higher power requirements than the battery-coupled system. This is due to the configuration not having backup power storage. The SPIS major components were sized for both direct and battery-coupled systems. A generic equation to determine the electrical solar power required for a given amount of motor-pump requirement was developed

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for each of the South African provinces for the summer and the winter season. The SPISyst model was tested and it was able to size SPIS components for 6 scenarios in different climatic zones in South Africa. A rule of thumb was also established to estimate the number of solar panels required for an SPIS for a given pump power requirement.

6.3 Recommendations

A better survey can be conducted to find and determine the total area in South Africa under solar powered irrigation. With the development of the SPISyst, it is recommended to incorporate hybrid SPIS where solar is paired with diesel or with other renewable energy sources such as wind energy. The model can also be improved by adding the sizing of grid tied SPIS. The SPISyst model can also be improved by adding more types of solar water pumps such as surface water pumps. Further research can be done by using the model to size either a small-scale drip or centre pivot SPIS and collect data on the performance of the system. The actual economics of SPIS in South Africa for different crops and regions can be investigated.

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7. APPENDICES

7.1 Appendix A

UNIVERSITY OF KWAZULU-NATAL

INYUVESI YAKWAZULU-NATALI

2 August 2017

Ms Piwe Vuyo Piliso 212505759
School of Engineering
Howard College Campus

Dear Ms Piliso

Protocol reference number: HSS/1039/017M
Project title: The development of a Model for a Low-cost Solar Powered Irrigation System in South Africa

Full Approval – Expedited Application

In response to your application received 12 June 2017, the Humanities & Social Sciences Research Ethics Committee has considered the abovementioned application and the protocol has been granted **FULL APPROVAL.**

Any alteration/s to the approved research protocol i.e. Questionnaire/Interview Schedule, Informed Consent Form, Title of the Project, Location of the Study, Research Approach and Methods must be reviewed and approved through the amendment /modification prior to its implementation. In case you have further queries, please quote the above reference number.

PLEASE NOTE: Research data should be securely stored in the discipline/department for a period of 5 years.

The ethical clearance certificate is only valid for a period of 3 years from the date of issue. Thereafter Recertification must be applied for on an annual basis.

I take this opportunity of wishing you everything of the best with your study.

Yours faithfully

....

Dr Shenuka Singh (Chair)
Humanities & Social Sciences Research Ethics Committee

/pm

cc Supervisor: Dr Aidan Senzane & Dr Khumbulani Dhavu
cc. Academic Leader Research: Professor Christina Trois
cc. School Administrator: Ms Nombuso Dlamini

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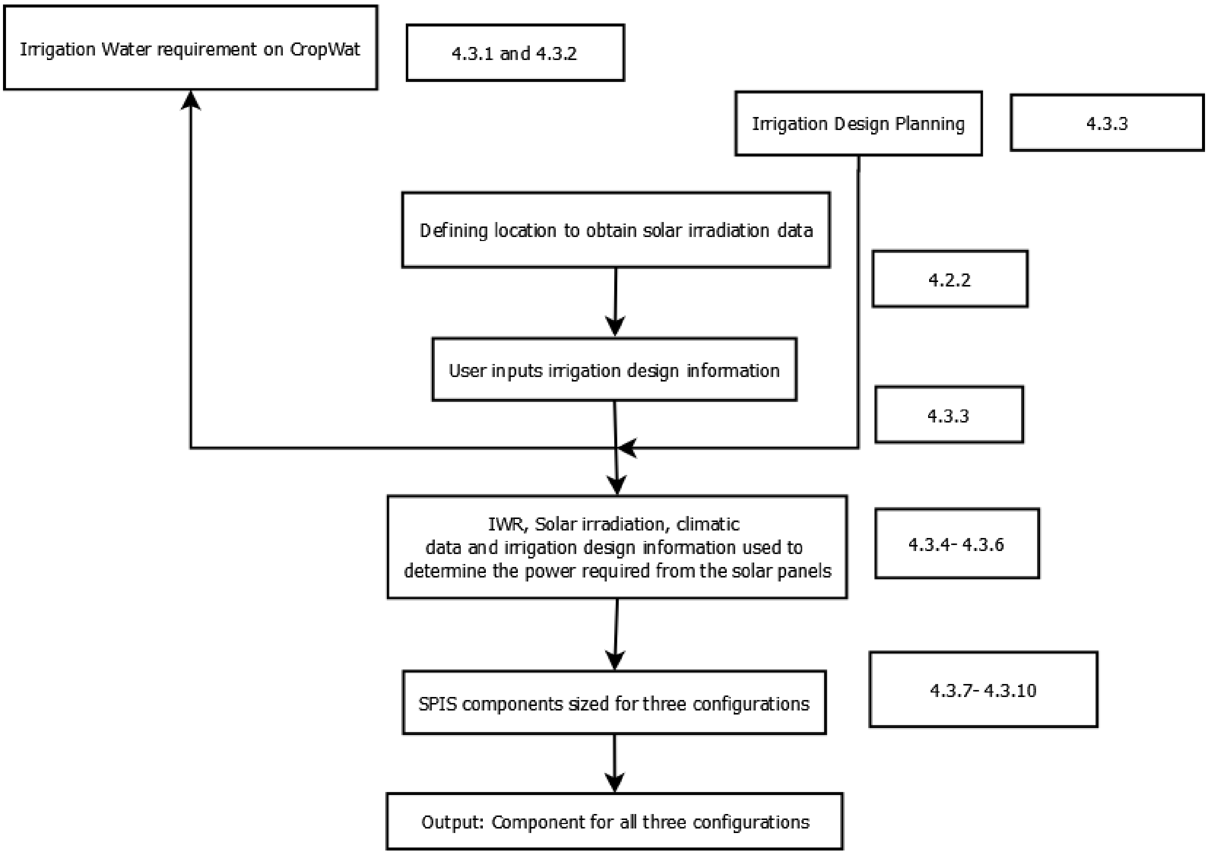
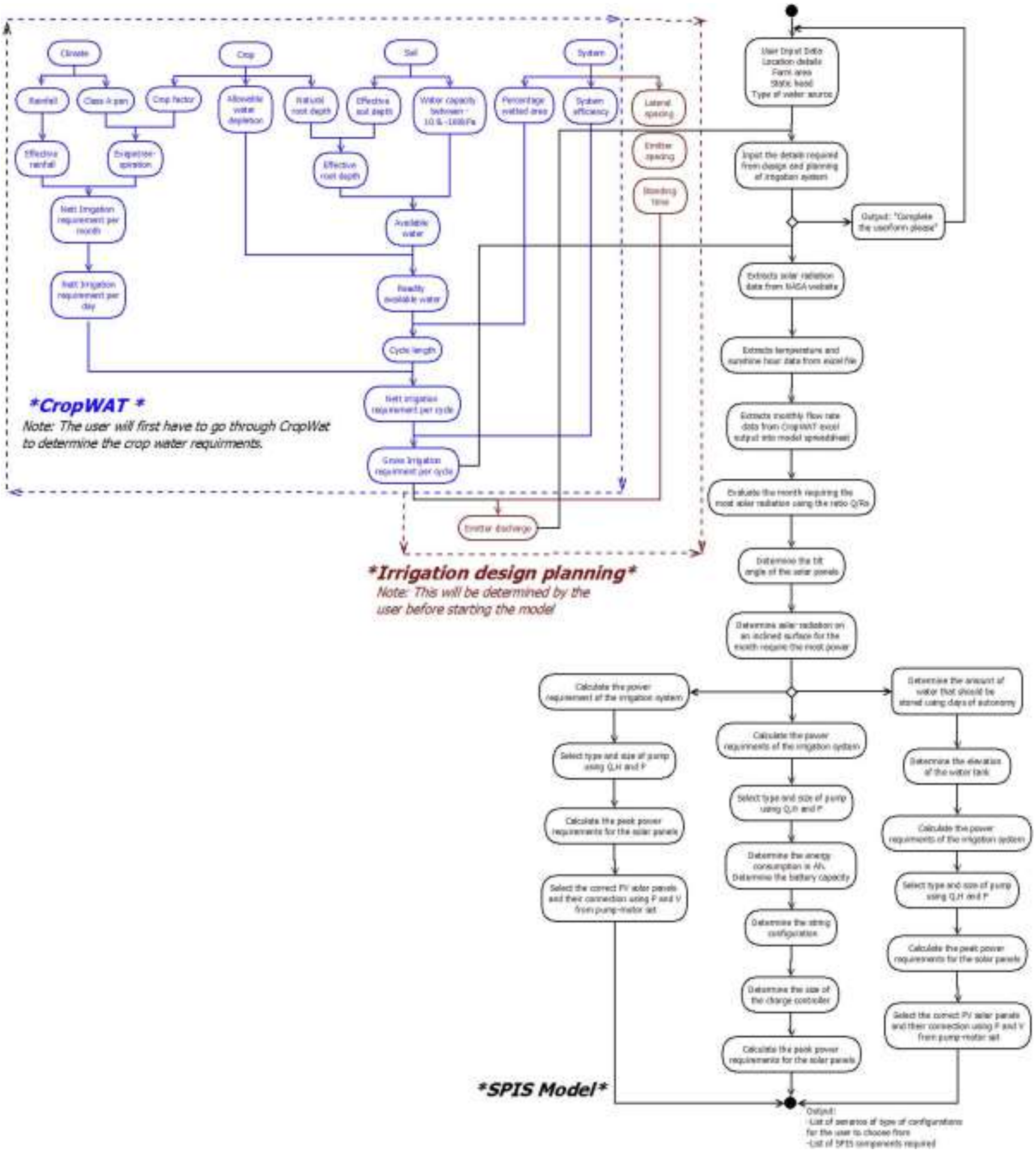
7.2 Appendix B Flow chart of SPISyst model development sub-sections



7.3 Appendix C Flow Chart of SPISyst model



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7.4 Appendix D

Table 7.1 The solar panel brands and sizes used in the SPISyst model (Current Automation, 2018a; Sustainable.co.za, 2018b)

	Panel model	Nominal power (W)	Open circuit voltage (Voc)	Maximum voltage (Vmp)	Maximum current (A)	Short Circuit current
Renewsys Solar	SP-RENE-100W	100	21.92	17.92	5.59	5.95
Renewsys Solar	SP-RENE-125W	125	22.08	18.04	6.94	7.38
Renewsys Solar	SP-RENE-140W	140	22.21	17.55	7.98	8.49
Renewsys Solar	SP-RENE-150W	150	22.79	18.44	8.15	8.67
Renewsys Solar	SP-RENE-180W	180	22.6	18.08	10.25	11.22
Renewsys Solar	SP-RENE-250W	250	37.89	30.63	8.16	8.8
Renewsys Solar	SP-RENE-255W	255	37.98	30.62	8.33	8.99
Yingli solar	YL255	255	37.6	30	8.49	8.9
Renewsys Solar	SP-RENE-260W	260	37.7	30.72	8.47	8.82
Canadian Solar	CS6P-260P	260	37.5	30.4	8.56	9.12
Renewsys Solar	CS6K 260P-FG	260	38.4	30.4	8.56	9.12
Renewsys Solar	SP-RENE-265W	265	38.46	30.77	8.63	8.99
Canadian Solar	CS6P-265P	265	37.7	30.6	8.66	9.32

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Canadian Solar	CS6K 265P-FG	265	37.7	30.6	8.66	9.23
Renewsys Solar	SP-RENE-270W	270	38.7	30.95	8.73	9.12
Canadian Solar	CS6K 270P-FG	270	37.9	30.8	8.75	9.32
Renewsys Solar	SP-RENE-300W	300	45.65	36.52	8.22	8.56
Renewsys Solar	SP-RENE-305W	305	45.94	36.75	8.3	8.65
Yingli Solar	YL310C-36b	310	45.8	36	8.76	9.21
Canadian Solar	CS6X 315P-FG	315	45.1	36.6	8.61	9.45
Canadian Solar	CS6X 320P-FG	320	45.3	36.8	8.69	9.26
Canadian Solar	CS6X 325P-FG	325	45.5	37	8.78	9.34
Canadian Solar	CS6P 315P	315	45.1	36.4	8.52	9.18
Canadian Solar	CS6X 320P	320	45.3	36.6	8.61	9.26
Canadian Solar	CS6X 325P	325	45.5	36.8	8.69	9.32
Canadian Solar	CS6U 330P	330	45.6	37.2	8.88	9.34

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7.5 Appendix E

Table 7.2 List of Lorentz® submersible centrifugal solar water pumps (Bundu Power, 2018)

Model	Operating Voltage (V)	Voltage (V)	Power (W)
PS200-HR-14	24	48	200
PS200-HR-07	24	48	200
PS200-HR-04	24	48	200
PS600-C-SJ8-5		48	600
PS600-C-SJ5-8		48	600
PS600-HR-14		48	600
PS600-HR-04		48	600
PS600-HR-10		48	600
PS600-HR-07		48	600
PS600-HR-03		48	600
PS600-HR-04H		48	600
PS600-HR-03H		48	600
PS1800-C-SJ42-1		96	1800
PS1800-C-SJ30-1		96	1800
PS1800-C-SJ17-2		96	1800
PS1800-C-SJ12-4		96	1800
PS1800-C-SJ8-7		96	1800
PS1800-HR-14		96	1800
PS1800-C-SJ5-12		96	1800
PS1800-HR-04		96	1800
PS1800-C-SJ3-18		96	1800
PS1800-HR-10		96	1800
PS1800-HR-23		96	1800
PS1800-C-SJ1-25		96	1800
PS1800-HR-03		96	1800
PS1800-HR-07		96	1800
PS1800-HR-14H		96	1800
PS1800-HR-04H		96	1800
PS1800-HR-07H		96	1800
PS1800-HR-03H		96	1800
PS1800-HR-05HL		96	1800
PS4000-C-SJ60-1		238	4000
PS4000-C-SJ60-2-2		238	4000
PS4000-C-SJ42-2		238	4000
PS4000-C-SJ30-2		238	4000
PS4000-C-SJ17-4		238	4000

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PS4000-C-SJ8-15		238	4000
PS4000-C-SJ5-25		238	4000
PS4000-HR-14HL		238	4000
PS4000-C-SJ3-32		238	4000
PS4000-HR-05HHL		238	4000
PS7K2-C-SJ95-1		575	7000
PS7K2-C-SJ42-3		575	7000
PS7K2-C-SJ30-6		575	7000
PS7K2-C-SJ17-9		575	7000
PS9K2-C-SJ30-7		575	9000
PS9K2-C-SJ17-11		575	9000
PS9K2-C-SJ8-44		575	9000
PS15K2-C-SJ150-1		575	15000
PS15K2-C-SJ95-2		575	15000
PS15K2-C-SJ75-3		575	15000
PS15K2-C-SJ42-6		575	15000
PS15K2-C-SJ30-12		575	15000
PS15K2-C-SJ17-18		575	15000
PS21K2-C-SJ120-2-1		575	21000
PS21K2-C-SJ75-4		575	21000
PS21K2-C-SJ42-10		575	21000
PS21K2-C-SJ30-16		575	21000
PS25K2-C-SJ150-2-2		575	25000
PS25K2-C-SJ95-4		575	25000
PS25K2-C-SJ42-12		575	25000
PS25K2-C-SJ30-22		575	25000
PS40K2-C-SJ120-3		575	40000
PS40K2-C-SJ95-7		575	40000
PS40K2-C-SJ42-19		575	40000

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7.6 Appendix F

Table 7.3 Lead acid deep cycle batteries listed in the SPISyst model (Current Automation, 2018b)

Battery (Lead Acid Deep Cycle)	Capacity of cell (AH)	Voltage (V)
Raylite Batteries R- Solar	50	12
Forbatt	65	12
Trojan	85	12
Raylite Batteries R- Solar	96	12
Enertec (Discover)	100	12
Forbatt	100	12
Vision- Fully sealed	100	12
Enervision E- Guard	102	12
Trojan	225	6
Trojan	240	6
Trojan	420	6
Raylite M- Solar	530	6
Raylite M- Solar	600	6
Raylite M- Solar	750	6
Raylite M- Solar	900	6
Raylite M- Solar	1050	4
Raylite M- Solar	1380	4
Raylite M- Solar	1660	4
Trojan SPRE	1255	2
Trojan	1954	2
Trojan	2405	2

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7.7 Appendix G

Table 7.4 Charge controllers listed in the SPISyst model (Sustainable.co.za, 2018a).

Type	Brand	Model Name	Max. Current (A)	Max. Voltage (V)
PWM	Steca	PRS 3030	30	17.2
PWM	Phocos	CX40 40 12V/48V	40	50
MPPT	Victron Blue Solar	MPPT 100V/30A	30	100
MPPT	Victron Blue Solar	MPPT 100V/50A	50	100
MPPT	Victron Blue Solar	MPPT 150V/35A	35	150
MPPT	Morningstar Tristar	TS 45A 12V/24V/48V	45	150
MPPT	Morningstar Tristar	TS 60A 12V/24V/48V	60	150
MPPT	Victron Blue Solar	MPPT 150V/ 70A	70	150
MPPT	Victron Blue Solar	MPPT 150V/85A	85	150
MPPT	Microcare	MPPT 200V/100A	100	200
MPPT	Victron Blue Solar	MPPT 150V/100A	100	150

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7.8 Appendix H

Table 7.5 CropWAT output for sugarcane

SCHEME SUPPLY												
ETo station: DURBAN-(LOUIS-BOTHA)												
Rain station: DURBAN-(LOUIS-BOTHA)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Precipitation deficit												
1. Sugarcane (Ratoon)	20.6	5.7	0	0	0.7	42.9	48.1	13.2	21	22.7	27.2	53.3
Net scheme irr.req.												
in mm/day	0.7	0.2	0	0	0	1.4	1.6	0.4	0.7	0.7	0.9	1.7
in mm/month	20.6	5.7	0	0	0.7	42.9	48.1	13.2	21	22.7	27.2	53.3
in l/s/h	0.08	0.02	0	0	0	0.17	0.18	0.05	0.08	0.08	0.1	0.2
Irrigated area (% of total area)	100	100	0	0	100	100	100	100	100	100	100	100
Irr.req. for actual area (l/s/h)	0.08	0.02	0	0	0	0.17	0.18	0.05	0.08	0.08	0.1	0.2
Cropwat 8.0 Bèta 26/03/19 7:28:05 PM												

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7.9 Appendix J

Table 7.6 Drip irrigation design example used for Chapter 4

Drip Irrigation Example		
area	4,5	Ha
Emitter pressure	12	M
Emitter flow rate	4,32	Lph
Crops per row	25	
Eemitter per crop	3	
q dripline	0,324	m3/h
Dripline length	148	M
Dripline diameter	0,016	M
1. no of laterals	26	
1. manifold length	78	M
1. q manifold	8,424	m3/h
1. manifold diameter	0,05	M
2. no of laterals	24	
2. manifold length	72	M
2. q manifold	7,78	m3/h
2. manifold diameter	0,05	M
3. no of laterals	26	
3. manifold length	78	M
3. q manifold	8,424	m3/h
3. manifold diameter	0,063	M
4. no of laterals	24	
4. manifold length	72	M
4. q manifold	7,78	m3/h
4. manifold diameter	0,05	m
Last 2 manifolds 3 and 4		
1. mainline q1	16,20	m3/h
1. mainline L 1 to 1-3 manifold	150	m
1. mainline diameter 1	0,075	m
1. mainline q2	7,78	m3/h
1. mainline L2 3-4 manifold	78	m
1. mainline diameter 2	0,063	m
First 2 manifolds 1 and 2		
2. mainline q1	16,20	m3/h
2. mainline L1	78	m
2. mainline diameter 1	0,075	m
Supply line		
Supply line Q	16,20	m3/h
Supply line L	25	m
Supply line D	0,075	m
Suction lift	2	m
Elevation diff from water source to highest point in the field	8,2	m

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7.10 Appendix K

Table 7.7 Centre pivot irrigation design for the sugarcane scenario

Centre Pivot Irrigation – Sugarcane		
Infiltration rate (mm/h)	10	Assumption
AT (ha)	12.9	(Half of field wheat and other half maize)
Sprinkler 1 flow rate (l/s/h)	0.24	
Sprinkler 2 flow rate (l/s/h)	1.152	
$m^3/hr/ha$	4.1472	
System capacity (m^3/hr)	53.49888	
permissible slippage (%)	3	
manufacture's brochure speed (m^3/s)	2.12	Worm drive with 25 rpm and 11,2"*38"
driving speed (m^3/s)	2.1	
centre pivot length (m)	188	
rotation time (hrs)	4.7	half of the field will be used
a(more defined)(ha)	5.551823	
gross application (mm)	4.529049	Lower than soil infiltration rate
rotation time at 50% speed setting (hrs)	9.4	
gross application @ 50 % speed (mm)	9.058097	Lower than soil infiltration rate
Sprinkler spacing (m)	2.3	
Sprinkler 1 wetted strip width (m)	10	
Sprinkler 2 wetted strip width (m)	20	
Sprinkler 3 wetted strip width (m)	20	
GAR (mm/hour)	28.45685	
Maximum radius for next sprinkler 2 (m)	188	
Maximum radius for next sprinkler 2 (m)	94	
Check Flow rates!		
Sprinkler 1 flow rate	0.654508	
Sprinkler 2 flow rate	2.61803	
Sprinkler 3 flow rate	3.927045	
operating pressure (m)	20	
10% of operating pressure	2	
Tower 1 length (m) ID(150)	32	
Tower 2 Length (m) ID (150)	32	
Tower 3 Length (m) ID (150)	32	
Tower 4 Length (m) ID (150)	38	
Tower 5 Length (m) ID (150)	45	
Overhang length (m) ID (150)	9	
	188	
Mainline length (m)	300	
Mainline diameter (mm) minimum	137.5207	
Mainline internal diameter (mm)	153.6	
Mainline outside diameter (mm)	160	
Electrical req. for centre pivot (Standard motor)		
Average current (A)	8.93	
Power (kW)	7.5	

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Table 7.8 Centre pivot irrigation design for the maize and wheat scenario

Centre Pivot Irrigation - Maize and Wheat		
Infiltration rate (mm/h)	10	
AT (ha)	24.7	(Half of field wheat and other half maize)
l/s/h	0.63	
l/s/h	3.024	
$m^3/hr/ha$	10.8864	
m^3/hr	134.447	
permissible wheel slippage (%)	3	
manufacture's brochure speed (m3/s)	2.89	
driving speed (m^3/s)	2.81	
centre pivot length (m)	280.4	
rotation time (hrs)	5.3	half of the field will be used
a(more defined)(ha)	12.35025	
gross application (mm)	5.769673	Lower than soil infiltration rate
rotation time at 50% speed setting (hrs)	10.6	
gross application @ 50 % speed(mm)	11.53935	
Sprinkler spacing	2.1	
Sprinkler 1 wetted strip width (m)	7	
Sprinkler 2 wetted strip width (m)	17	
Sprinkler 3 wetted strip width (m)	30	
GAR	31.96553	
Maximum radius for next sprinkler 2 (m)	158.8933	
Maximum radius for next sprinkler 2 (m)	65.42667	
Check Flow rates!		
Sprinkler 1 flow rate	0.469893	
Sprinkler 2 flow rate	2.282339	
Sprinkler 3 flow rate	4.027657	
Operating pressure (m)	20	
10 % operating pressure	2	
Tower 1 length (m)	32	
Tower 2 Length (m)	32	
Tower 3 Length (m)	45	
Tower 4 Length (m)	45	
Tower 5 Length (m)	56	
Tower 6 Length (m)	56	
Overhang length (m)	15	
	281	
Mainline length (m)	290	
Mainline minimum internal diameter	192.2143	
Mainline internal diameter (mm)	192.2	
Mainline outside diameter (mm)	200	
Electrical req. for centre pivot (Standard motor)		
Average current (A)	10.19	
Power (kW)	7.5	

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Table 7.9 Centre pivot irrigation design for the potatoes scenario

Centre Pivot Irrigation - Potatoes		
Infiltration rate (mm/h)	10	
Total area (ha)	7.47	(Half of field wheat and other half maize)
l/s/h	0.62	
l/s/h	2.976	
m^3/hr/ha	10.7136	
m^3/hr	40.0153	
permissible wheel slippage (%)	3	
manufacture's brochure speed (m3/s)	3.08	47 rpm Worm drive with 11.2"*24" wheels
driving speed (m^3/s)	3	
centre pivot length (m)	154.3	
rotation time (hrs)	2.7	half of the field will be used
a(more defined)(ha)	3.739829	
gross application (mm)	2.888937	Lower than soil infiltration rate
rotation time at 50% speed setting (hrs)	5.4	
gross application @ 50 speed(mm)	5.777874	
Sprinkler spacing	2.1	
Sprinkler 1 wetted strip width (m)	9	
Sprinkler 2 wetted strip width (m)	15	
Sprinkler 3 wetted strip width (m)	15	
GAR	34.57792	
Maximum radius for next sprinkler 2 (m)	154.3	
Maximum radius for next sprinkler 2 (m)	92.58	
Check Flow rates!		
Sprinkler 1 flow rate	0.653523	
Sprinkler 2 flow rate	2.178409	
Sprinkler 3 flow rate	3.267613	
Operating pressure (m)	20	
10 % Operating pressure (m)	2	
Tower 1 length 150 mm ID (m)	32	
Tower 2 Length 150 mm ID(m)	32	
Tower 3 Length 150 mm ID(m)	32	
Tower 4 Length 150 mm ID(m)	38	
Overhang length 150 mm ID(m)	20	
	154	
Mainline Length	255	
Mainline minimum internal diameter (mm)	119.3362	
Mainline internal diameter (mm)	120	
Mainline outside diameter (mm)	125	
Electrical req. for centre pivot (Standard motor)		
Average current (A)	7.67	
Power (kW)	7.5	

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Table 7.10 Drip irrigation design for the grapes scenario

Drip Irrigation – Grapes		
GIR- month (mm)	21	
GIR- week (mm)	5.25	
Crop spacing-w (m)	2	
Crop spacing-d (m)	2.6	
Emitter spacing (m)	0.6	
AT (ha)	6.4	
Standing time (hr)	17.5	
emitter flow rate (m^3/h)	4	
Flow rate (m^3/h)	19.2	
emitter flow rate (m^3/h)	8	
number of emitters	2400	
Group area (ha)	1.6	
Number of groups	4	
Number of blocks	4	
width of field (m)	240	
length of field (m)	282	
Lateral line length (m)	115	
Drip line diameter (mm)	12	
Operating pressure of emitter (m)	30	
Number Lateral rows	28	
System capacity (m3/h)	22.11067	
Manifold length	130	From drawing
manifold internal diameter (mm)	28.37001	
* manifold internal diameter (mm)	30.5	class 4
* manifold outside diameter (mm)	32	
mainline length (m)	350	From drawing
mainline internal diameter (mm)	121.3885	
*mainline internal diameter (mm)	134.4	class 4
*mainline outside diameter (mm)	140	
Filter selection head (m)	0.6	3"T Disc filter

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Table 7.11Drip irrigation design for the mangoes scenario

Drip Irrigation System for the Mangoes scenario		
	172.1	
GIR- week (mm)	21.5125	
AT (ha)	9	
Crop spacing-w (m)	3	
Crop spacing-d (m)	6	
Emitter spacing (m)	1.5	
Standing time (hr)	5	
Cycle length (hr)	30	7 days
emitter flow rate (l/h)	38.7225	This is for 2 emitters according to the design
emitter flow rate of 1 emitter (l/h)	19.36125	
Flow rate (m^3/h)	64.5375	Theoretical
emitter flow rate (l/h)	40	Selected from manufactures catalogue
number of emitters	807	
Group area (ha)	0.8	
Number of groups	**12**	
Number of blocks	0.75	
width of field (m) Group 1 and 2	280	
length of field (m) Group 1 and 2	70	
Half of the length (m) Group 1 and 2	50	
Lateral line length (m) (Group 1, 2 and 3)	85	
Lateral line length (m) (Group 4, 5, 6 and 7)	115	
Drip line diameter (mm)	21.2	
Operating pressure of emitter (m)	10	Thick walled polyethelyne dripper lines
Number Lateral rows (Group 1, 2 and 3)	**12**	
Number of total laterals per block (Group 1, 2, and 3)	**24**	Two laterals per row of trees
Number Lateral rows (Group 4, 5, 6 and 7)	**9**	
Number of total laterals per block (Group 4, 5, 6 and 7)	**18**	
Number Lateral rows (Group4)	**36**	
Number of total laterals per block (Group4)	**32**	
System capacity (m^3/h)	**56.032**	Practical System Capacity
System capacity (m^3/h)	**56.856**	Practical System Capacity
Manifold length (Group 1 and 2)	**80**	
Manifold length (Group 3)	**60**	
Manifold length (Group 4)	**96**	
10% of operating pressure of emitters-hf	**1**	
manifold internal diameter (mm)	**100.5997**	
* manifold internal diameter (mm)	134.4	class 4 uPVC pipe
* manifold outside diameter (mm)	140	
mainline length (m)	330	
mainline internal diameter (mm)	**165.0479**	
*mainline internal diameter (mm)	240.2	class 6 uPVC pipe
*mainline outside diameter (mm)	250	
Filter selection head (m) clean	3	C2FA4P Disk Filter
Filter selection head (m) dirty	5	

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Table 7.12 Drip irrigation design for the lemons scenario

Drip Irrigation- Citrus		
	154.3	
GIR- week (mm)	19.2875	
AT (ha)	10.5	
Crop spacing-w (m)	3	
Crop spacing-d (m)	2.5	
Emitter spacing (m)	1.5	
Standing time (hr)	10	
Cycle length (hr)	30	3 days
emitter flow rate (l/h)	5.304063	This is for 2 emitters according to the design
emitter flow rate of 1 emitter (l/h)	2.652031	
Flow rate (m^3/h)	67.50625	Correct
emitter flow rate (l/h)	12	
number of emitters	2813	
Group area (ha)	1.1	
Number of groups	**10**	
theoretical area of each group	**1.05**	
Number of blocks	6	
length of blocks (m) (Group1-4)	100	
Lateral line length (m) (Group1-4)	175	
length of blocks (m) (Group5)	125	
Lateral line length (m) (Group5)	100	
length of blocks (m) (Group6)	60	
Lateral line length (m) (Group6)	195	
length of blocks (m) (Group6)	40	
Lateral line length (m) (Group6)	65	
Drip line diameter (mm)	21.2	
Operating pressure of emitter (m)	10	Thick walled polyethelyne dripper lines
Number Lateral rows (G1-4)	**40**	
Number of total laterals per group (G1-4)	**80**	Two laterals per row of trees
Number Lateral rows (G5)	**50**	
Number of total laterals per group (G5)	**100**	Two laterals per row of trees
Number Lateral rows G6-1	**24**	
Number of total laterals per group G6-1	**48**	
Number Lateral rows G6-2	**16**	
Number of total laterals per group G6-2	**32**	
System capacity (m3/h) (Group1-4)	**115.36**	The system maximum capacity
System capacity (m3/h) (Group5)	**82.4**	
System capacity (m3/h) (Group6)	**94.2656**	
Manifold length	**110**	
10% of operating pressure of emitters-hf	**1**	
manifold internal diameter (mm)	**136.0717**	
* manifold internal diameter (mm)	134.4	class 4 uPVC pipe
* manifold outside diameter (mm)	140	
mainline length (m)	315	
mainline internal diameter (mm)	**219.7304**	
*mainline internal diameter (mm)	240.2	class 4 uPVC pipe
*mainline outside diameter (mm)	250	
Filter selection head (m) clean	3	C2FA4P
Filter selection head (m) dirty	5	

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