DESIGN OF A MODEL FOR LOW COST SOLAR POWERED IRRIGATION SYSTEMS IN SOUTH AFRICA: LITERATURE REVIEW AND PROJECT PROPOSAL

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PREFACE

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ABSTRACT

South Africa has been identified as having a high potential for solar powered irrigation. 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. In the last few years, South Africa has gone through load shedding which has affected many farmers in the country, particularly commercial farmers. Some smallholder and subsistence farmers are in remote areas where there is no electricity. These farmers usually depend on diesel powered irrigation systems or irrigate their crops manually. The increasing price of fossil fuels is problematic for farmers in South Africa. Even though the investment cost of solar energy is high, the electricity produced by the system is free. With this being the case, if the system is designed accurately, the system will be able to pay off the investment in a few years' time. There is a lack of literature on SPIS in South Africa. Literature available only explores the use of SPIS with drip irrigation mainly, while there is little to no literature on SPIS being integrated with other irrigation systems worldwide. In the literature review the need for SPIS's is highlighted through identifying the advantages of using renewable energy specifically solar energy in the world and in South Africa. SPIS main components such as the solar panels, inverter, and energy storage methods are discussed in detail. The different photovoltaic water pumps that are available in the market were identified, the use of the pumps is specified and the limitations of the pumps are presented. Water use and energy in South Africa is discussed where the cost of the different types of energy are highlighted. Five irrigation techniques, namely: (a) drip irrigation, (b) micro sprinkler irrigation, (c) furrow irrigation, (d) sprinkler irrigation, and (e) center pivot irrigation are presented and they are also conceptualised with SPIS's. The methods and procedures used to determine crop water requirements and irrigation water requirements are presented. The irrigation management methods are discussed and were also conceptualised in terms of SPIS. The gap in research is identified as the lack of literature which evaluates both the technical and economic feasibility of SPIS's implemented under multiple irrigation techniques.

TABLE OF CONTENTS

Page

ABSTRACT..III

LIST OF FIGURES VII

LIST OF TABLES..VIII

1. INTRODUCTION 1

2. LITERATURE REVIEW 3

2.1 Solar Energy...3

2.1.1 Solar radiation in South Africa 3

2.1.2 Photovoltaic technology..4

2.2 PV System Primary Components...5

2.2.1 PV solar panels 6

2.2.1.1 PV technology efficiency..7

2.2.1.2 PV technology solar collectors 7

2.2.2 Inverter...7

2.3 Grid- Connected and Off Grid PV System (Energy Storage)..................................8

2.3.1 Battery storage and water tank...9

2.4 Economics of PV Systems 9

2.5 PV Irrigation System Configuration 10

2.5.1 Battery-coupled system...10

2.5.2 Direct driven system 11

2.6 PV Pump Types 12

2.6.1 Submerged three-phase motor 13

2.6.2 Surface mounted motor with submerged pump 14

2.6.3 Floating pump 15

2.6.4 Suction lift system 15

2.7 Water Use and Energy in Agriculture in South Africa 16

2.8 Irrigation Technique 17

2.8.1 Drip irrigation 18

2.8.2 Sprinkler irrigation 18

2.8.2.1 Micro sprinkler irrigation 20

2.8.2.2 Center pivot irrigation 20

2.8.3 Furrow irrigation 21

2.9 Crop Water Requirements 22

2.10 Irrigation Water Requirements 23

2.11 Irrigation Management 25

2.12 Photovoltaic Electrical Output Modelling 26

3. DISCUSSION AND CONCLUSION 29

4. RESEARCH PROPOSAL 31

4.1 Research Problem 31

4.2 Aims and Objectives 32

4.3 Research Questions 32

4.4 Methodology 33

4.4.1 Specific methodology 1 33

4.4.2 Specific methodology 2: 34

4.4.3 Specific methodology 3 34

4.5 Data Analysis 35

4.6 Health, Safety, Environmental and Ethical Considerations 35

4.7 Time and work schedule 37

4.8 Budget 38

5. APPENDIX 46

LIST OF FIGURES

Page

Figure 2.1 Interconnection of a solar cell, module, and array (Solar, 2004) 6

Figure 2.2 Battery coupled photovoltaic water pump system (Chandel et al., 2015)..............11

Figure 2.3 Direct driven PV water pump system (Shehadeh, 2015) 12

Figure 2.4 Graph of different types of pumps with total head and daily water requirement limitations (RETScreen, 2004) 13

LIST OF TABLES

Page

Table 2.1 Estimated costs for different types of PV systems (Ahlfeldt and Economics, 2013) 6

Table 2.2 The suitability of irrigation techniques with relation to solar pumps (Action, 2012) 17

Table 2.3 Different sprinkler pressures, flow rates and typical applications (Burger et al., 2003d) 19

Table 4.1 Gantt chart 37

Table 4.2 Project budget 38

1. INTRODUCTION

The production of power from fossil fuels is a major contributor to 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 clean energy is solar energy. There is a large amount of solar energy that enters the earth's atmosphere (Sontake and Kalamkar, 2016). In the last few years, solar energy has grown rapidly amongst other energy sources. However, this has happened at a low scale. 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 50 to 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 through the use of 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 are mostly appropriate to use in regions where there is a lack of electricity. Since the invention of solar powered water pumps, they 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).

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 needless (Shrestha, 1996; Andrada and Castro, 2008).

Cuadros *et al.* (2004) developed a method to size a SPIS which is based on climatic conditions of the region, the geographical location, soil quality and crop water requirements which were applied to 10 hectares of an olive grove farm in Spain. The economic feasibility of this study was not evaluated. In South Africa, there is a lack of literature into the design and implementation of SPIS for all irrigation techniques as well as lack of research into the feasibility of SPIS for any irrigation technique. There is a need to develop a system that will size solar powered irrigation systems for South African conditions and determine whether the systems are economically feasible or not.

The aim of this research is therefore to determine the extent to which SPIS are implemented in South Africa. It is also to develop a model that will size a 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.

2. LITERATURE REVIEW

2.1 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 energy sectors, even though this was at a low scale. 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. The units for solar irradiance can be 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 solar radiation penetrates the earth's atmosphere, it gets split into two types of solar radiation. The first is direct solar radiation which comes directly from the sun's surface to the earth's surface. The other is 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 captured on a horizontal surface is referred to as global solar radiation (Kahle *et al.*, 2003).

2.1.1 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 realised 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 insolation rates in the world with some provinces having solar insolation 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 energy 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.

2.1.2 Photovoltaic technology

Photovoltaic (PV) cells are semiconductor devices which generate electrical power by enabling photons to remove electrons from a molecular lattice, leaving a freed electron and a 'hole' pair which 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 utilized more often than mono and poly-crystalline systems (Niekerk, 2013).

The price trends of PV technology in South Africa mirror international trends even though there is a slight lag. The price trend is generally decreasing (Niekerk, 2013).

The electrical power output of a PV system is usually expressed in terms of the peak power such as the 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 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. 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).

2.2 PV System Primary Components

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, 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 system 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**
Utility scale fixed tilt	R22.47/W
Utility scale fixed tracking system	R24.51/W
Commercial/industrial scale	R20.00/W
Residential grid-supported	R27.50/W
Residential off-grid	R47.00/W

2.2.1 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 in 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. The 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: amorphous, polycrystalline and mono- crystalline.

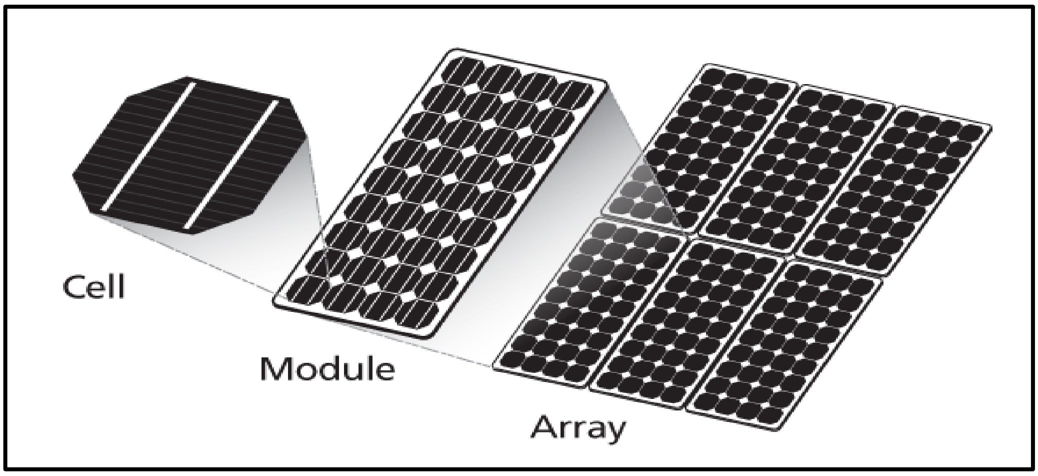

Figure 2.1 Interconnection of a solar cell, module, and array (Solar, 2004)

2.2.1.1 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).

2.2.1.2 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 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 which only make use of the direct solar radiation. Therefore, for areas which experience many cloudy days during the year, the system will not be suitable.

2.2.2 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).

2.3 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 energy can be stored in batteries or excess water stored in elevated water tanks.

2.3.1 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:

(1) When solar energy is available, and the system needs water, water is directly pumped to the system using solar power.
(2) When solar energy is available, and water is required by the system but the system does not use all the electricity produced, excess electricity is fed into the grid.
(3) 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.
(4) When solar energy is available, and the system does not require any water, electricity is fed into the grid.
(5) When solar energy is not available, and the system requires water, the 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 (1), (3), and (5) 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).

2.3.2 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 of 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, the 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 the ease of recyclability of the lead (Monsour and Burton, 2002; Buschermohle and Burns, 2014).

2.4 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 been developed yet (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 are 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).

2.5 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 of storing energy generated by the photovoltaic water pumping system which are namely, the battery coupled and the directly driven solar water pumping systems.

2.5.1 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 therefore resulting in the low efficiency. Designing the batteries to be fully charged and discharged during the operation of the system will make the battery have a 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 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). Figure 2.2 shows the set-up of a battery coupled PV irrigation system.

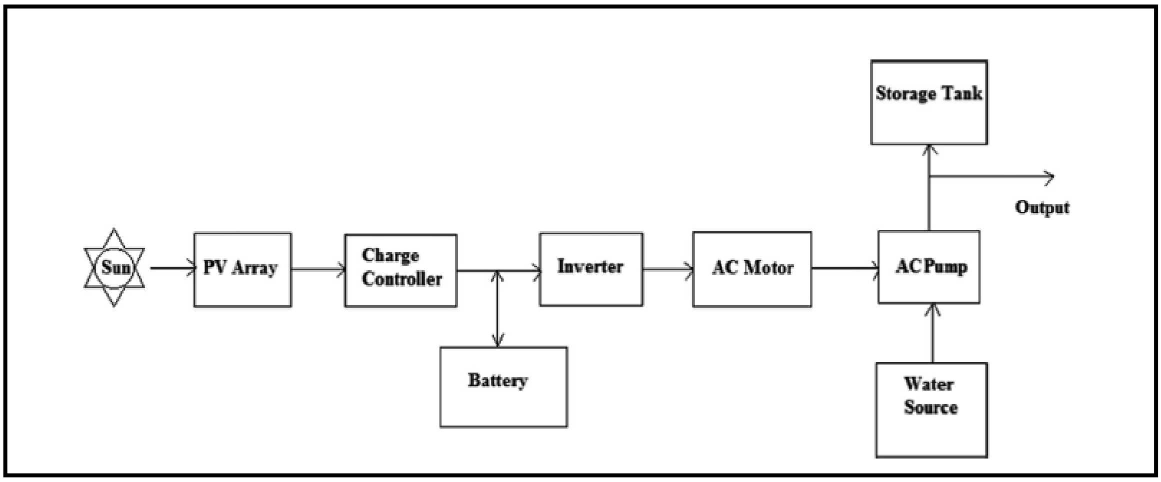

Figure 2.2 Battery coupled photovoltaic water pump system (Chandel *et al.*, 2015)

2.5.2 Direct driven system

The electricity produced by the PV solar panels in a direct driven SPIS is supplied to the pump. In this system, the 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 a 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, the water is pumped when solar radiation is available in 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 during the evening and the 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.

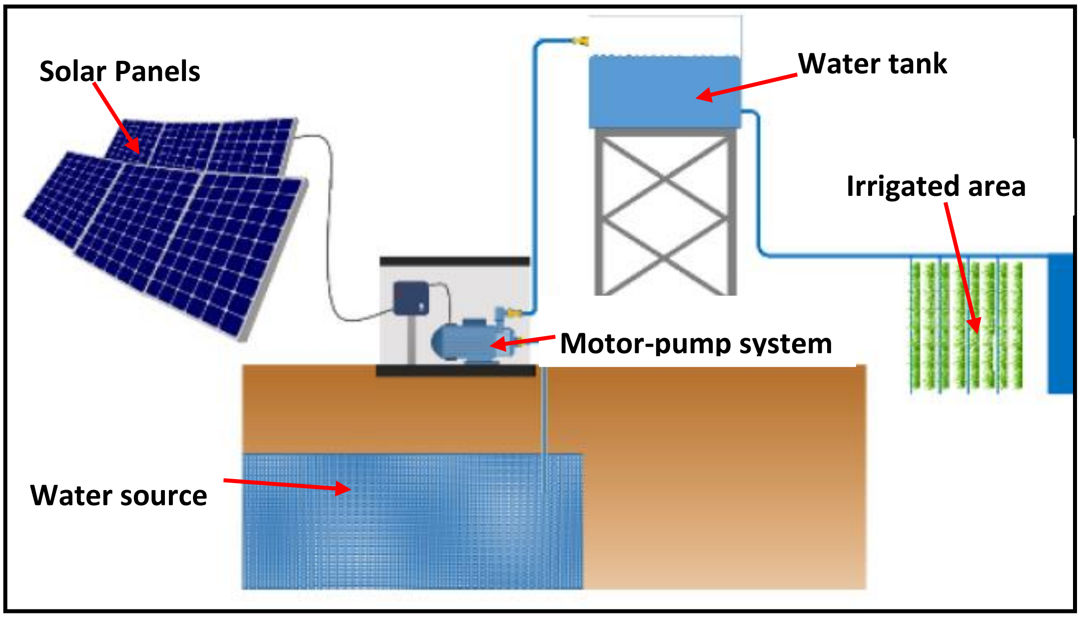

Figure 2.3 Direct driven PV water pump system (Shehadeh, 2015)

2.6 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 pumps 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, the lack of fuel requirement, they are environmentally friendly and the simplicity in the installation process of the system (Deveci *et al.*, 2015). The drawbacks of PVWP is 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).

There is a range of different water pumps available and PVWP are 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 sections 2.4.1 -2.4.5.

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

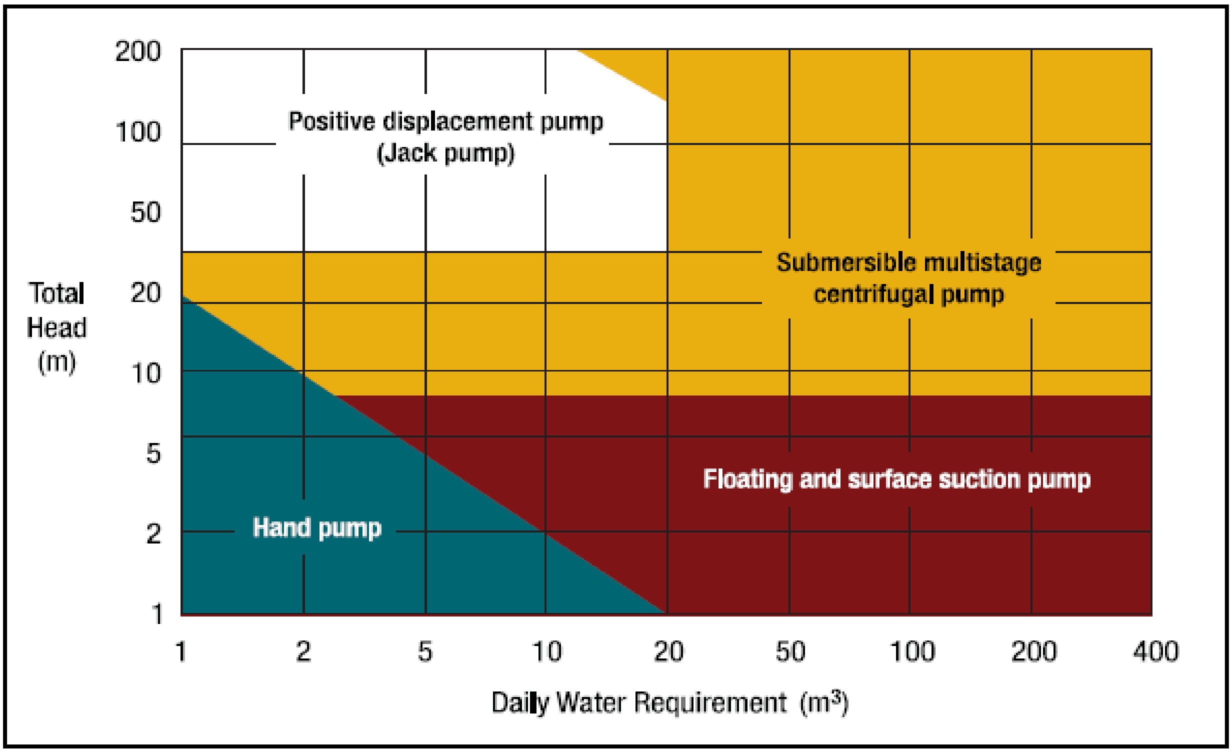

Figure 2.4 Graph of different types of pumps with total head and daily water requirement limitations (RETScreen, 2004)

2.6.1 Submerged three-phase motor

A submerged three-phase motor is commonly used for borehole applications. A three-phase motor is directly coupled to a multi-stage centrifugal pump which is submerged in water within a borehole. The motor used in this configuration is an induction motor (Monsour and Burton, 2002). The induction motor consists of components such as stator windings and a rotor. The stator windings are made up of wire windings which have a low resistance and are permanently attached to the frame of the motor (Bednarczyk, 2012). A rotating magnetic field is produced by a three-phase AC current in the stator windings. The magnetic field then induces a current and a magnetic field in the rotor. The pump is driven by the rotor which is turned by interacting with the stator fields. The rotor has no external electrical connections. The supply current is restricted to the stator windings which can be protected from water thus making it possible for the motor to work with the rotor in water. This results in the submerged AC pump being reliable (Monsour and Burton, 2002).

The advantage of this type of pump is that the installation is simple. It is often done with a flexible lay-flat pipework which is attached to the motor pump set which is lowered into a borehole and submerged from potential damage and vandalism (Monsour and Burton, 2002; Action, 2012). Gaining access to the pump/motor unit is restricted, but the high reliability of the mechanism does not make that a huge issue.

2.6.2 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. The way in which the motor/ pump is designed is perfectly protected from water. If the DC motor is brushed then the system equipment will need to be pulled out at least every two years to replace the brushes. This is a disadvantage due to the limited access to the motor-pump system. If a brushless DC motor is utilized, it requires less maintenance as it has no brushes to be replaced every two years (Monsour and Burton, 2002; Action, 2012).

2.6.3 Surface mounted motor with submerged pump

Two types of pumps can be used for this system which includes centrifugal pumps or the more commonly used positive displacement pumps. The rod connections in both cases 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. Commonly, the motors are connected to the drive shaft with the use of a V-belt (this allows the speed ratio to be changed). The borehole has to be straight due to the riser being rigid (Monsour and Burton, 2002).

The motor is on the surface, therefore, permanent magnet brushed DC motors are used. This allows for easy changing of the brushes of the motor and other maintenance. The disadvantage of the system is the low efficiency caused by the power losses experienced in the shaft bearings. The system is being replaced with the submerged motor and pump set.

2.6.4 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. The most commonly used pump for this unit is a submerged centrifugal pump, but diaphragm and progressive cavity pumps can also be used for the unit. A DC brushless motor is usually used for this type of system.

The advantages of this type of pump system are as follows:

- Pump inlet remains submerged irrespective of the water level provided the water source has not dried up.
- PV system can be made portable by incorporating a wheelbarrow type trolley to allow transportation.

The disadvantage of the PV pump system is that it is often applied to low lift or low head requirement irrigation application systems.

2.6.5 Suction lift system

It is possible to place and mount the motor-pump system 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) characteristics of the pump utilised. Precaution must be taken if the pump being used is not self-priming, where the pump is primed when it not running. Diaphragm and centrifugal pumps are used for suction lift systems.

The primary chamber keeps the pump body filled with water acting as a reservoir making the pump system primed. When the pump system starts operating, the stored water within the primary chamber is pulled through the pump, thus allowing sufficient suction to draw water through the suction pipe. Some installations incorporate a non-return valve at the submerged end of the suction pipe (Monsour and Burton, 2002).

The disadvantages of the suction lift system are:

- It is only suitable for low head applications and obtains a maximum head of 8 m.
- The system requires an operator to be always in attendance for maintenance and security for the exposed parts.

2.7 Water Use and Energy in Agriculture in South Africa

The water requirements for irrigation are roughly 60 % of the total water requirements in South Africa, while industry 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).

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 (Plessis, 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 (Plessis, 2017).

The main drivers towards 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 adequacy of power and their ability to deliver the power to the user.

2.8 Irrigation Technique

Literature reveals that solar powered irrigation is preferable for certain irrigation techniques. Table 2.2 shows the irrigation methods that are suitable for solar powered irrigation.

Table 2.2 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 a number of 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.

2.8.1 Drip irrigation

Drip irrigation is at times 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.*, 2003b). The operating pressure of drip irrigation systems ranges between 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.

A drip irrigation system comprises of 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 the water can be distributed horizontally by means of capillary action and vertically by means of gravity. Soils that possess the 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 a 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.*, 2003f).

2.8.2 Sprinkler irrigation

Sprinkler irrigation is a method where water is sprayed onto the crops and soil in the 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 are 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).

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.*, 2003d). 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.*, 2003d).

Table 2.3 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 2.3 Different sprinkler pressures, flow rates and typical applications (Burger *et al.*, 2003d)

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

2.8.2.1 Micro sprinkler irrigation

Micro sprinkler irrigation systems operate like sprinkler irrigation systems. Compared to sprinkler irrigation systems the operating pressure and the 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 water application efficiency of the micro sprinkler irrigation system, even though clogging of the system rarely occurs.

When a micro-sprinkler irrigation system is well managed, it can produce increased yields and increase water use efficiency. Water is given 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 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).

2.8.2.2 Center pivot irrigation

A form of sprinkler irrigation, center pivot irrigation is a system that applies a small amount of at frequent intervals (Ruffino, 2009; Ahmed, 2013). The components that make up a center 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, a water meter and safety valves. The laterals are fixed at the center 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 center pivot irrigation is minimal with only drip irrigation having a lower water loss than the center pivot irrigation system. Compared to other irrigation systems, such as other sprinkler irrigation systems and furrow irrigation, the center pivot produces a 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.*, 2003d).

Center pivots that operate at low pressures with drop nozzles usually have a water application efficiency of 85 % (Brown, 2008). According to Berne (2015), center 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. Center pivots also need additional power to move the center pivot tower around the field.

Amend (2005) suggests solar powered center 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 center pivot system 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 center of the pivot which will also reduce operating cost for maintenance (Sedki, 2014).

2.8.3 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 requirements 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 the investment costs are limited (Burger *et al.*, 2003e).

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 productions. 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 more than PV panels required for a drip irrigation system.

2.9 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 which influence the crop water requirements and these include radiation, temperature, humidity and the 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.*, 2003f).

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

where,

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

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

f = crop factor (unitless).

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

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 in order 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.

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

where,

k_r = ground cover reduction factor.

2.10 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 the 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 shows how to determine the effective rainfall (Burger *et al.*, 2003f).

$$\mathrm{P_e = \frac{P-20}{2}} \tag{2.4}$$

where,

P = long term monthly average rainfall ($mm.month^{-1}$)

P_e = effective rainfall ($mm.day^{-1}$).

The net irrigation requirement per day (NIR_d) is calculated using Equation 2.5. 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 avoid 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.*, 2003f).

$$NIR_d = \frac{ET_c - P_e}{n} \tag{2.5}$$

where,

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

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

The ground water readily available to the crops is determined with Equation 2.6 (Burger *et al.*, 2003f).

$$RAW = SWHC \times ERD \times \alpha \tag{2.6}$$

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 into the total amount of readily available water per cycle. This is presented in Equation 2.7 (Burger *et al.*, 2003f).

$$t_c = \frac{RAW \times W}{NIR_d \times 100} \tag{2.7}$$

where,

t_c =cycle length (calendar days), and

W = percentage wetted area (%).

The gross irrigation requirement takes into the irrigation systems efficiency in delivering the water required to the plant and this is shown in Equation 2.8 (Burger *et al.*, 2003f).

$$\mathrm{GIR_c} = \mathrm{NIR_d} \times \mathrm{t_c} \times \frac{100}{\eta_s} \tag{2.8}$$

where,

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

η_s = system efficiency (%).

The system flow rate is determined by Equation 2.9 (Burger *et al.*, 2003f).

$$\mathrm{Q} = \frac{\mathrm{GIR_c} \times \mathrm{A_T}}{\mathrm{t}} \times 10 \tag{2.9}$$

where,

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

t = operating hours per cycle (h), and

A_T = total system area (ha).

2.11 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 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 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 irrigation demand for a region even though these conditions will not last for a long time, thus resulting in the pump having 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).

2.12 Photovoltaic Electrical Output Modelling

The sizing and optimisation of the pumping system, the PV accessories and the PV solar panels are the most delicate 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 is required for the system to operate effectively (Bouzidi *et al.*, 2009). These models have been determined through the simulation of the operation of each sub-section of the PV system.

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

1. To determine the irrigation requirements of the irrigation system as per the characteristics of the crop, soil and climate.
2. Performing a hydraulic analysis of the pumping system as per the depth of the water source and the head needed to stabilise pressure in the irrigation system.
3. To determine the peak PV power required to irrigate the area of land.

The determine the nominal electrical power of the PV solar panels , in referential condition (Standard Test Condition (STC)), according to Kenna and Gillett (1985) is as shown in equation 2.10.

$$P_{EL} = \frac{1000}{[1-\alpha_c(T_{c(i)}-T_o)\eta_{mp}f_m} \times \frac{E_H}{E_T} \quad (2.10)$$

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,

f_m = load matching factor to PV solar panels characteristics (unitless),

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, 1985; Glasnovic and Margeta, 2007; Zegeye *et al.*, 2014). This equation shows that the hydraulic head requirement is varying with head and irrigation demand.

$$E_H = \frac{\rho g Q_d H_{TE}}{3600 \times 1000} \quad (2.11)$$

where

ρ = density of water (kg.m^{-3}),

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

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 with equation 2.12 as follows:

$$T_C = T_a + \left(\frac{NOCT - 20}{0.8n}\right) E_T \quad (2.12)$$

where

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

n = monthly average daily hours of bright sunshine, and

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

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

3. 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 have declined in the recent years, specifically the prices of solar panels. Two thousand hectares of land in South Africa is 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 price. Due to the limited amount of DC powered motors, an inverter is required for 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 with 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 a specific potential energy which in turn can supply the dynamic head required by the system.

There are different solar 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 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 lot 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 center pivot irrigation systems and furrow irrigation systems. All 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 the irrigation scheduling which helps in avoiding over irrigating and optimizes 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 available 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 unnecessarily high investment cost or farmers not considering the technology, as it is perceived to be too expensive. Therefore, it is imperative to design a model that will size a low-cost SPIS for South African climatic conditions, soil types and crop types for different irrigation techniques.

4. RESEARCH PROPOSAL

4.1 Research Problem

South Africa has 12.76 million hectares of cultivated land, of which nearly 10.45 million hectares (82 %) is used for commercial farming purposes (DoE, 2012). Land that is that is permanently cultivated is only 0.79 million hectares (6.19 %) and more than 10.83 million hectares is rain-fed cultivated land (AgriSETA, 2010). In the agricultural sector, most energy is consumed in traction (66 %), followed by irrigation (8 %).

When the focus is placed on electricity, irrigation consumes the largest amount of electricity at 28 % (DoE, 2012). As irrigation consumes the most electricity in the agricultural sector, efforts to reduce the use of grid electricity should be considered, such as the use of renewable energy. Using renewable energy technologies for water services such as irrigation in developing countries is able to address both the need for energy and the need for water services in 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 SPIS model, the most important parameters to identify accurately are the hydraulic head of the system and the solar irradiation of the location during the irrigation months. These will lead to the sizing of a SPIS that is optimally sized, therefore 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 areas 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 use of SPIS in commercial farms would lead to farmers being less affected by the electricity price increases and load shedding.

In spite of the diminishing solar energy technology prices, 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 that has been 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.

There are some off the shelf PV water pumps kits that are available for purchase in South Africa. There are companies such as LORENTZ which have implemented SPIS's in some parts of the country such as the Eastern Cape and Northern Cape, which range from small scale to large scale systems. These systems are mainly used for stock watering and drinking water supply. These systems produce a flow rate between 7.3 $m^3.d^{-1}$ – 570 $m^3.d^{-1}$ (Lorentz, 2016).

The literature available for SPIS is mainly for small-scale farmers in other countries 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 system mostly integrated with solar power. Irrigation systems such as sprinkler, micro sprinkler, center pivot and furrow irrigation systems have barely been integrated with SPIS.

When the technical feasibility is determined then the economic feasibility of the system will be determined to make sure the system is low cost.

4.2 Aims and Objectives

The aim of this project is 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 determine most suitable or optimal low-cost SPIS.
c) evaluate the model for different climatic conditions, crop types and crop selections, soils, irrigation techniques and field size.

4.3 Research Questions

This research seeks to answer the following questions:

- What are the factors determining or driving the implementation of SPIS's in South Africa?
- To determine the appropriate size of a SPIS, what critical parameters should be considered in the development of a model?
- For which conditions are SPIS's technically feasible to be implemented in South Africa?

4.4 Methodology

The study will begin with a detailed literature review. This will be followed by a questionnaire to determine the extent of extent of SPIS in South Africa. Then a model will be developed using appropriate software.

4.4.1 Specific methodology 1

To determine the extent to which SPIS are implemented and what types are being utilised in South Africa, a questionnaire will be developed for farmers and the Department of Agriculture extension officers for a region. The internet will also be used to try find companies that are involved with SPIS and find farms that have SPIS. Ethical clearance is needed for the questionnaire to be administered to any respondent. The questions asked will include the following aspects:

- How many farms are in the region?
- What are the irrigation techniques practised in the area?
- How many irrigation systems are solar powered?
- What types of SPIS are utilised?
    - Direct coupled solar which stores pumped water in a tank?
    - Solar systems with battery pack with no storage tank?
    - SPIS connected to the grid?
- What motivated the use of SPIS?
- Has there been an improvement in water management and crop yield since the SPIS system has been introduced?
- Effects of implementing the SPIS in the area (positive and negative)?
- Anyone with discontinued use of SPIS, and if so, why?

The information obtained the questionnaire will be of a qualitative and quantitative nature.

4.4.2 Specific methodology 2

The purpose of the model is a first-step sizing optimisation, mainly putting focus on the sizing of the mostly costly component of the SPIS, which is the solar panels. The nature of the problem is multistage. The process of sizing a SPIS is of a sequential nature, therefore dynamic programming will be used for this model.

The model will be developed on Microsoft (MS) Excel. Visual Basic for Application which is found on MS Excel to create a Userfrom which will make it easier for users to enter data required by the model. The model will be integrated with CLIMWAT and CROPWAT, which will be used to determine the crop water requirements for the observed period. The information required by these two programmes include, the location, soil information, the type of irrigation system that will be used and the type of crop being irrigated. The NASA Surface Meteorlogy and Solar Energy: Data Subset, which be used to obtain the average monthly insolation incident on a horizontal surface and the average monthly temperature, will also be integrated with model. To obtain these information from the website both latitudes and longitudes of two diagonal corner of the region are required. The data obtained from these sources will be used for the model.

The model will be a black box model. The user will not have access to the calculations of the model. When the user has completed entering the input variables required by the model in the MS Excel Userform, the model output will be the preliminary sizing of the SPIS. The flow chart of the model is presented in the appendix.

4.4.3 Specific methodology 3

The technical feasibility of SPIS's will be determined and limitations of the above mentioned variables for SPIS's will be determined. This will be done by evaluating the model by using different farms from smallholder farms to commercial farms and sizing a SPIS. Then the investment costs of the different SPIS's will also be investigated and determined.

4.5 Data Analysis

ArcGIS will be used to plot the farms that participate in the questionnaire based on their location on South Africa map shapefile. The information such as the farm area, type of farm, irrigation technique, SPIS configuration, etc will be placed in the attribute tables in the programme. The information obtained from the questionnaire will help to determine the key drivers to SPIS adoption or implementation is RSA. Such information will be utilised in the development of the model.

The model will be analysed through running the model which should determine the most suitable SPIS for predetermined field conditions (input variables). The cost of the SPIS and economical feasibility of the system will be compared to the current irrigation system and the power source of the farm.

4.6 Health, Safety, Environmental and Ethical Considerations

This research project is mainly a desktop study. If the model is applied, there will be some environmental effects. Solar energy is an environmentally friendly energy source, and the use of solar energy in place of grid electricity and diesel power will reduce the carbon footprint of a farm.

4.7 Time and work schedule

Table 4.1 below shows the Gantt chart for this project, where various stages of this project have been highlighted from December 2016 to April 2018. The time periods may alter slightly depending on the outcome of each task.

Table 4.1 Gantt chart

List of Activities	2016		2017														2018			
	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Literature Review and Project Proposal	■	■	■	■																
Corrections					■															
Development of Questionnaire and Ethical Clearance Application						■	■	■	■	■										
Field Research											■	■								
Model Development									■	■	■	■	■							
Data Analysis													■	■	■	■				
First draft submission																	■	■		
Final thesis submission																			■	■

4.8 Budget

The table below shows the budget set for this project.

Table 4.2 Project budget

Item	**Cost (R)**
Transport	

• 2 trips to farms for 1108 km @ R1.03/km
  ○ 1 trip to Springfontien (Free State) for 703 km
  ○ 1 trip to Jozini (KZN) for 405 km
	2283

• 2 trip to ARC/DAFF for 544 km @ R1.03/km	2240
Equipment and Software	
• SurveyMonkey- Online survey development cloud 2 month subscription @ R349.00/month	698
• Software for developing model (Excel VBA)	0
• Electronic meter for measuring efficiency of SPIS	0
Field assistance	
• 1 Research Assistants for 5 days @ R260/day for field evaluation of SPIS efficiency	1300
Miscellaneous costs	
• Meals	
Total budget	6521

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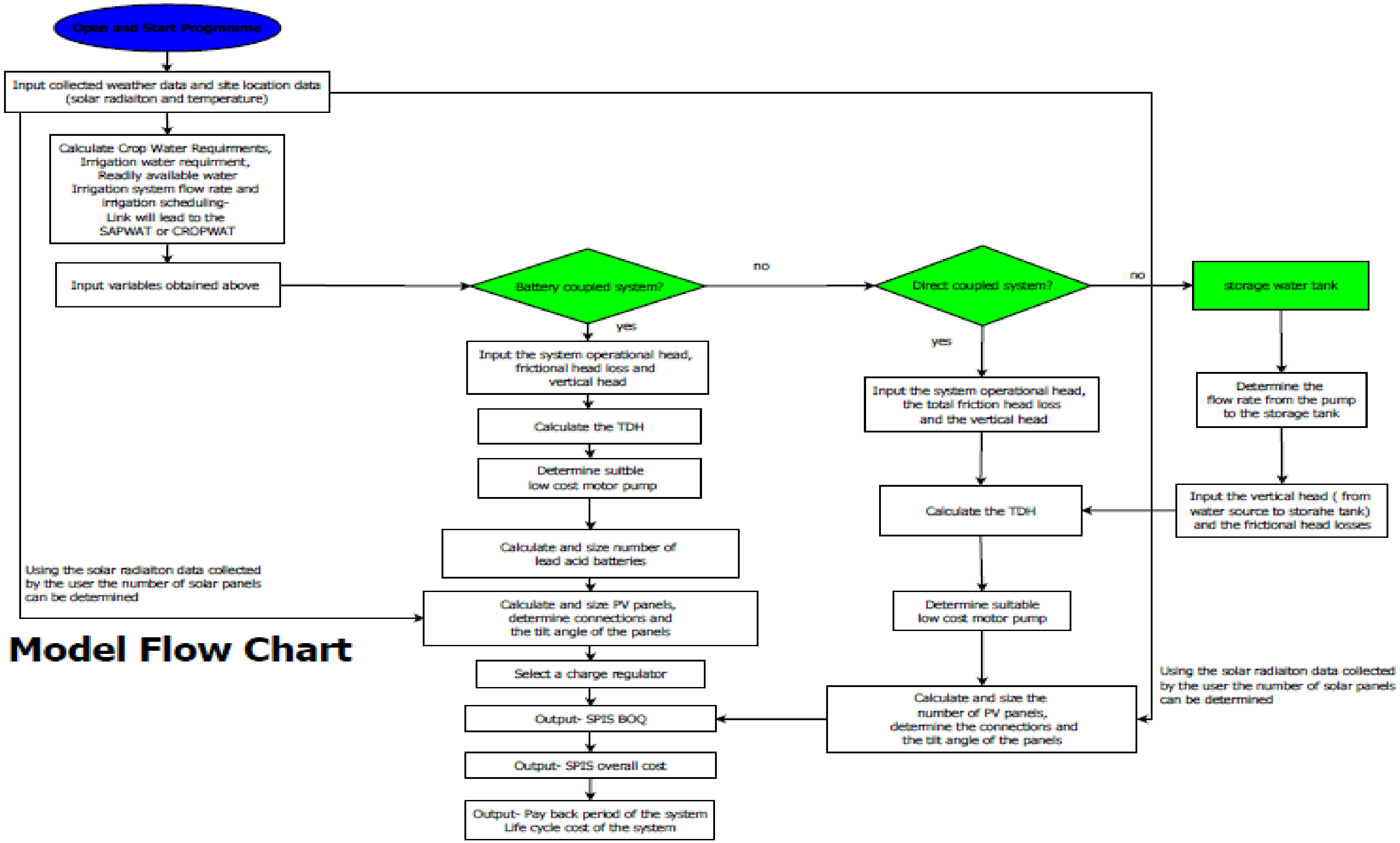
6. APPENDIX



SPIS Model Flow Chart