AN APPROACH FOR DESIGN AND MANAGEMENT OF A SOLAR-POWERED CENTER PIVOT IRRIGATION SYSTEM

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ABSTRACT

Emerging financial and environmental challenges associated with conventional power sources have increased global interest in consuming unpolluted, renewable energy sources for irrigation sector. Solar energy may be an attractive choice in this regard due to its strong influence on crop water use and related energy requirement. However, a comprehensive approach for a reliable and economically viable photovoltaic (PV) system design to produce energy from solar source is required to accurately explore its potential.

This thesis describes the development and application of a reliability assessment model, identifies a suitable solar irrigation management scheme, and provides guidelines for evaluating economic viability of a solar-powered center pivot irrigation system. The reliability model, written in MATLAB, was developed based on the loss of power supply probability (LPSP) technique in which various sub-models for estimating energy production, energy requirement and energy storage were combined. The model was validated with actual data acquired from the study site located at Outlook, Saskatchewan, Canada and an excellent agreement was found. For example, normalized root mean square error (NRMSE) for the battery current was found to be 0.027. Irrigation management strategies (irrigation depth, frequency and timing) were investigated by comparing the PV system sizing requirement for a conventional (25-35 mm per application) and for a frequent light irrigation management strategy (5-8 mm per application). The results suggest that the PV sizing can be reduced significantly by adopting frequent light irrigations which utilize the power as it is produced during daylight hours, rather than relying on stored energy. The potential of a solar-powered center pivot irrigation system was revealed for three different crops (canola, soybean and table potato) at the site by conducting a detailed economic analysis for the designed PV system. High value crops with moderate water requirements such as table potatoes appeared to be the most feasible choice for the study site. However, the potential may greatly vary for different crops in altered locations due to management, agronomic, climate, social, and economic variations.

It can be concluded that a holistic approach described here can be used as a tool for designing an appropriate PV powered center pivot irrigation system under variable operating and meteorological conditions. Furthermore, its potential can be accurately explored by conducting a detailed economic analysis for a given location, considering different available crop choices.

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NOMENCLATURE

A	irrigated area (ha)
AC	alternating current (A)
ASM	available soil moisture (mm)
Ah	ampere hours
CB	battery capacity (Ah)
CSDIC	canada saskatchewan diversification irrigation center
DC	direct current (A)
$DPPLT$	distance of pivot point from the last tower (m)
E	energy (Wh)
EP	effective precipitation (mm)
ET	evapotranspiration (mm)
FC	field capacity (mm)
G	irradiation (W m^{-2})
g	acceleration due to gravity (9.8 m s^{-2})
I	Current (A)
IR	irrigation depth (mm)
K_c	crop factor or crop coefficient
k	boltzman constant
LPS	loss of power supply
$LPSP$	loss of power supply probability
$LTTS_{100}$	last tower travel speed at 100 % timer setting (m s^{-1})
MPP	maximum power point

m	idealizing factor
P	power (W)
PV	photovoltaic
PTS	percent timer setting (%)
$PFRT$	pivot full rotation time (h)
SOC	state of charge
T	temperature (°C)
TDH	total dynamic head (m)
t	time
Δt	time interval
V	voltage (V)
WHC	water holding capacity of soil (mm)
η	efficiency

Note: the superscripts and subscripts are used in the text with these symbols to specify their representation for a certain element

1. INTRODUCTION

1.1 BACKGROUND

Water plays an important role in photosynthesis, cooling through transpiration, and is a driving force for the movement of nutrients in the plants. Therefore, adequate soil moisture availability in the crop root-zone is critical for optimum crop production. The available soil moisture for a crop is supplied by precipitation and consumed through evapotranspiration (crop water use). The evapotranspiration rate depends upon weather parameters, crop type and crop maturity stage. In many regions of the world, precipitation is insufficient to meet the crop water requirements. Therefore, water is applied by artificial means, such as irrigation. Currently, 15% to 20% of the worldwide cultivated area is under irrigation, which contributes approximately 40% of the total agricultural production (FAO, 2013). This illustrates that the crop yield can be increased significantly by practicing irrigation along with several additional benefits such as crop diversification and improvement in its quality. There are different methods available for irrigation; ranging from traditional (gravity) with low application efficiencies (40% to 60%) to modernized high efficiency (70% to 95%) such as center pivot, sprinkler, and trickle irrigation systems. The adoption of high efficiency irrigation systems is increasing in order to tackle rapidly growing global water scarcity issues. In Canada, the center pivot sprinkler system is one of the most commonly adopted irrigation methods. Currently, three phase electricity or combustion engines are the most common power sources in irrigated agriculture.

The motivation to utilize renewable and clean energy resources in irrigated agriculture has raised the importance of solar energy. This is potentially more viable as compared to the other renewable resources because the crop water requirement is strongly dependent on incoming solar irradiation. Thus, the energy requirement as well as the energy production relies on the same source. A typical standalone photovoltaic (PV) irrigation system may consist of a PV array, controller and/or inverter, battery bank (for providing power in the absence of sun-light), a solar pump, a motor and other mounting and wiring accessories. The potential for PV system applications in the irrigation sector is increasing due to lower PV system component prices (mainly resulting from improvement in panel efficiencies and development of an extensive solar energy market).

Solar-powered water pumps have been tested and applied for surface irrigation, which relies on pumping and storing the water in a storage tank, and applying it later by gravity when needed (Chandratilleke and Ho, 1986; Meah et al., 2008; Kelly et al., 2010; Mokeddem et al., 2011; Belgacem, 2012). The technology has also been coupled and successfully demonstrated with low pressure drip irrigation systems (Pande et al., 2002; Senol, 2012). Unfortunately, few efforts have been made in studying the applications of PV technology with a center pivot irrigation system, in which power is required to pump the water at the desired flow and pressure as well as to run the pivot machine drive motors, leading to a comparatively high power system. The energy requirement for a given day depends upon the pivot specifications (flow, total dynamic head, pump and motor efficiencies, drive motor power) and the adopted irrigation management strategy. Therefore, selection of an appropriate design parameters and adoption of a suitable irrigation management strategy can influence the system reliability. However, detailed investigations are required for identifying appropriate design parameters and a management strategy.

1.2 PROBLEM STATEMENT

A comprehensive approach for determining and improving the technical and economic feasibility of a solar-powered center pivot irrigation system in a given environment is required. It must consider and combine various interacting design (crop water requirement, soil moisture monitoring, irrigation system flow rate and operating pressure, power production by the PV array, and performance evaluation of solar batteries) and management (irrigation scheduling) factors.

1.3 PURPOSE

The main purpose of this study is to develop a holistic approach for exploring the feasibility of a solar-powered center pivot irrigation system, and to investigate the effect of design and management practices. Accordingly, the core objectives of this research are:

- to develop a model for determining the reliability of the selected PV system under variable operating (crop, soil type, irrigation management strategy, and pivot system specifications) and meteorological conditions;
- to identify a suitable irrigation management practice for improving feasibility of a solar-powered center pivot irrigation system;
- to demonstrate guidelines for the economic feasibility evaluation of the designed system.

1.4 THESIS STRUCTURE

This thesis follows a manuscript style, each of the predefined objectives are exclusively addressed in a separate manuscript. A general literature review pertaining to the overall study goal is presented separately in chapter 2 whereas more technical and supportive review with respect to the specific objectives is presented in each relevant manuscript (Chapter 3, 4 and 5 for objectives 1, 2 and 3 respectively). The preamble describing the relevancy of the manuscript's objective with the main purpose of study is provided at the start of each manuscript. The materials and methods adopted to achieve the desired objectives along with the results are discussed in depth in the relevant manuscripts. The general discussions are then carried out to enlighten the factors which may influence the potential of a solar-powered center pivot irrigation system in any given environment. Finally, the study accomplishments, findings, and their application potential are discussed to conclude the work followed by the recommendations determined from this study. The citations which appear in the text are referenced in the last section of the respective chapter.

1.5 REFERENCES

Belgacem, B. G. 2012. Performance of submersible water pumping systems in Tunisia. *Energy for sustainable development* 16: 415-420.

Chandratilleke, T.T., and J. C. Ho. 1986. A study of a photovoltaic array for water pumping. *Solar and Wind Technology* 3: 59-71.

FAO. 2013. The practice of irrigation. Guidelines for designing and evaluation surface irrigation systems. Available at http://www.fao.org/docrep/t0231e/t0231e03.htm. Accessed 02 August 2013.

Kelley, L.C., E. Gilbertson., A. Sheikh., S.D. Eppinger., and S. Dubowsky. 2010. On the feasibility of solar-powered irrigation. *Renewable and Sustainable Energy Reviews* 14: 2669–2682.

Meah, K., S. Fletcher., and S. Ula. 2008. Solar photovoltaic water pumping for remote locations. *Renewable and Sustainable Energy Reviews* 12: 472-487.

Mokeddem, A., A. Midoun., D. Kadri., S. Hiadsi., and I.A., Raja. 2011. Performance of a directly coupled PV water pumping system. *Energy Conversion and Management* 52: 3089-3095.

Pande, P. C., A. K. Singh., S. Ansari., S. K. Vyas., and B. K. Dave. 2002. Design development and testing of a solar PV pump based drip system for orchards. *Renewable Energy* 28: 385-396.

Senol, R. 2012. An analysis of solar energy and irrigation systems in Turkey. *Energy Policy* 47: 478-486.

2. REVIEW OF LITERATURE

2.1 IRRIGATION IN CANADA

Canada has an abundance of water resources: about 9% of the world’s fresh water supply flows in Canadian rivers (Coote and Gregorich, 2000), which suggests a high potential for irrigation. It has been practiced in Canada since its settlement; however, it has now evolved from the flood irrigation schemes to predominantly modernized high efficiency sprinkler systems (Derdall, 2008). About 75% of agricultural water withdrawn in the country takes place on the prairies and approximately 85% of that is used for irrigation (Harker, 2004). Currently, the province of Saskatchewan has the highest potential for irrigation development as compared to the other provinces (Madramootoo et al., 2008).

Saskatchewan has a history of irrigation dating back to early 1900s. The expansion of irrigation in the province was slow up to the 1960s with only 32,000 ha added in irrigated agriculture during these sixty years. A substantial growth of irrigated agriculture occurred in 1960s particularly after the construction of Gardiner Dam in 1967 (Gross, 2008). An increase of about 108,000 ha in irrigated area was observed from 1960 to 2000. Despite this growth, the province still has 400% to 500% irrigation expansion potential (Madramootoo et al., 2008). Center pivot irrigation systems are the most commonly adopted methods for irrigation. In 2003, about 53% of the total irrigated area was under sprinkler or pivot irrigation in the province (Madramootoo, 2006).

2.2 CENTER PIVOT IRRIGATION SYSTEM

Center-pivot irrigation is a form of sprinkler irrigation, in which a small amount of water is applied at frequent intervals (Ruffino, 2009). A typical center pivot irrigation system consists of a pump, motor, mainline, laterals (spans) mounted on wheeled towers and equipped with a driving system, emitting devices (sprinklers and end-guns) and accessories such as control switches, pressure gauges, a water meter and safety valves. In this system the lateral is fixed at one end (the center of the field) and rotated around the field at some specified rotational speed (Jarrett and Graves, 2010). Water is generally supplied to the lateral through a buried pipe (mainline). Pivots are available as low, medium and high pressure units based on sprinkler or spray nozzle operating pressure (Evans and Sneed, 1996). There are many advantages of the center-pivot irrigation system such as less land-levelling, low labor cost, and high water application efficiency. The system has some limitations such as high initial cost, unsuitability for odd shape fields, maintenance cost, and non-uniformity due to wind speed. Many technological improvements have been made since the invention of the pivot system to minimize the limitations in its adoption as well as to conserve the water, energy and time. Many early center pivots (spray nozzle and gun) operated at high pressure (550-690 kPa) with lower application efficiency have been replaced with more efficient, low pressure (70-105 kPa) systems in the last six decades (New and Fipps, 2002). The other technological advancements accomplished so far include: ensuring uniform discharge with varying pressure, turning end-guns on and off based upon field positions, adjusting the speed of travel multiple times during an irrigation event, using computer control and automation over the system (Kranz et al., 2010).

2.3 PHOTOVOLTAIC (PV) POWER SYSTEM COMPONENTS

A typical photovoltaic (PV) system for generating, storing and supplying power to the irrigation system consists of a PV array, a controller, inverter, battery storage, and control switches. The main advantages of this system include their environmental friendliness, low maintenance, long life, no fuel requirement (so no operational cost), and easy installation (Cuadros et al., 2004). However, the technology has also some limitations such as low efficiency, high initial cost, and sophisticated electronics required when controllers and batteries are used.

2.3.1 PV array

A photovoltaic array is comprised of one or more PV modules made of PV cells wired together in series and/or in parallel to produce a specific voltage and current respectively under a given level of irradiance (Helikson et al., 1991). Each cell of the module has two or more layers of semiconductor material which produces direct current upon exposure to sunlight. These layers are either made of the crystalline or thin film (Morales, 2010). Crystalline is generally made of silicon whereas thin film is made of metal and several metals are used for the purpose.

Crystalline modules are more efficient (12% to 15%) as compared to the thin film (3% to 9%) in terms of power production (Vick and Clark, 2009). Furthermore, there are three types of crystalline modules: amorphous, polycrystalline and mono-crystalline. Mono crystalline panels are the most efficient and amorphous silicon type are the least efficient (Meah et al., 2008).

The performance of a solar cell is usually evaluated by representing it as an electrical equivalent one diode model (fig. 2.1) in which the diode current is the current generated by an inactive solar cell (at dark times) and series resistance represents the resistance inside as well as in between the cells (Lorenzo, 1994). The voltage and current produced by a PV array depends upon the connection pattern of the cells and modules respectively. Power produced by the PV array is a product of voltage and current (Helikson, 1991).

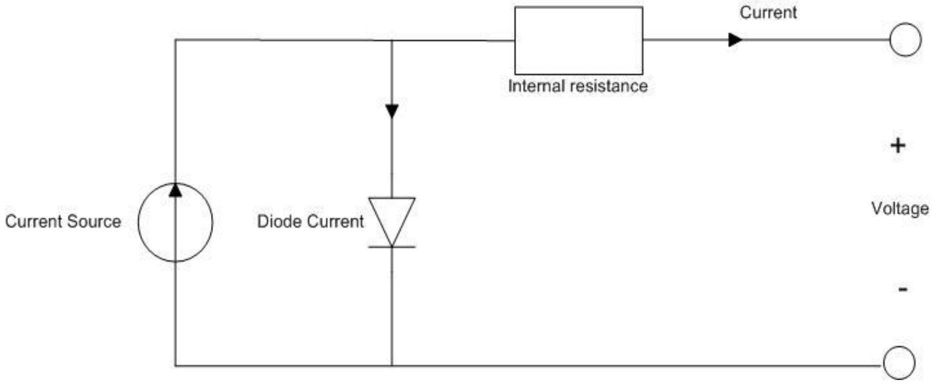


Figure 2.1. Electrical diagram for a PV module cell (adapted from Hansen et al., 2000)

The short circuit current is a linear function of ambient irradiation whereas the voltage varies slightly with it (Hansen et al., 2000) as shown in figure 2.2. Therefore, solar panels with irradiation tracking mechanisms may be adopted to improve the PV system performance. A practical alternative for improving performance is to tilt the PV panel at some fixed angle, which is plus or minus 15 degrees from the latitude of the location for winter and summer months respectively (Morales, 2010). Performance of tracking and non-tracking (fixed angle) solar panels have been evaluated (Abdallah, 2004; Huang and Sun, 2007) and it has been realized that the additional cost associated with a tracking system can be avoided by fixing the panels at some tilt angle, with only a minor loss in efficiency.

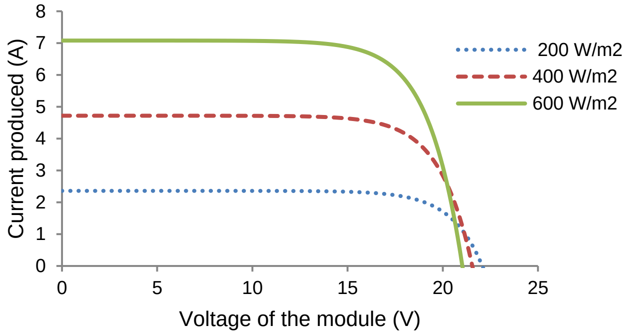


Figure 2.2. I-V characteristics variation with irradiation

An increase in cell temperature causes a linear decrease in open circuit voltage of a PV module resulting in reduction of module efficiency (Hansen et al., 2000). Higher power output is achieved at colder module temperatures (fig. 2.3). The cell temperature of a PV module is largely influenced by the ambient temperature and irradiance (Garcia and Balenzategui, 2004). It also depends upon the PV panel material because different materials have variable dependence on temperature (Lasnier and Tony, 1990).

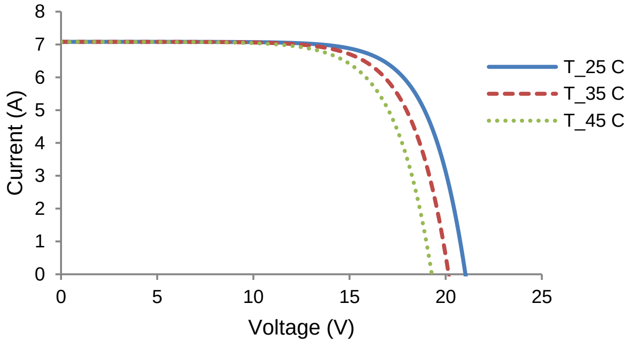


Figure 2.3. Influence of cell temperature on PV module

The affordability of PV modules has been significantly improved over the last few decades. For example, the solar panels price characterized in terms of peak power produced, were reduced from \$33.44 W^{-1} in 1979 to less than \$10.00 W^{-1} in 2007 (Reichelstein and Yorsten, 2013). The trend of price declination continued making them available at about \$ 3.5-\$ 4.5 W^{-1} in 2013 (fig. 2.4). This drastic drop in panel prices has increased the application potential of the technology in the irrigation sector and has become an important consideration in terms of on-site energy generation.

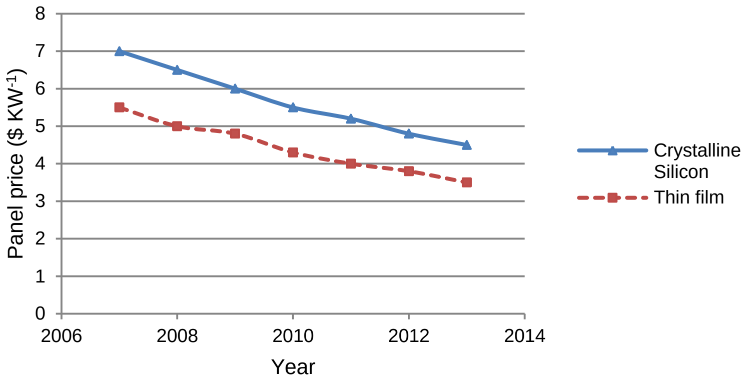


Figure 2.4. PV panel price trend (Adapted from Rose, 2012)

2.3.2 Controller and/or Inverter

A controller is very useful component of a PV water pumping system. It can perform multiple tasks such as limiting the power supply to the battery charger, adjusting voltage and current to improve pumping performance, allowing switches to disconnect automatically to perform different jobs such as disconnecting PV modules with pump, protecting the motor from running dry when water level in the well or tank is below the pumping intake and can shut off the pump when the tank is full (Vick and Clark, 2009). It is considered the most vulnerable component of the PV system since it contains sophisticated electronics and it has to operate in varying environmental conditions (Meah et al., 2008). Three types of controllers may be used in PV pumping for controlling the power input: maximum power point (MPP), constant voltage tracking and voltage/frequency modulation (Odeh et al., 2010). In maximum power point mode, the voltage and current produced by the PV panel is adjusted in order to produce the maximum power at given conditions (Hohm and Ropp, 2003). In constant voltage mode, PV array is operated at a fixed voltage without considering MPP. In voltage/frequency modulation mode, the voltage of the PV array is adjusted by the controller based on output frequency value in order to maintain a constant voltage/frequency (Odeh et al., 2010). Direct current (DC) is produced by the PV array whereas many motors coupled with pump require alternating current (AC); therefore, inverters are used to convert the current from DC to AC. Power losses caused by the inverter may vary from 10% to 20% (Baltus et al., 1997).

2.3.3 Battery Storage

The purpose of the battery is to store the power when the PV array produces more power than required by the pumping unit. Two types of batteries, lead-acid and nickel-iron, may be used with PV applications. Nickel-iron batteries are not preferred due to their high self-discharge rate (Achaibou et al., 2008). The charging and discharging of a lead-acid battery is regulated by the charge controller (Morale, 2010). Several procedures have been identified over the years for evaluating the performance of a battery (Facinelli, 1983; Hyman et al., 1986; Manwell and Mcgowan, 1993; Copetti et al., 1993; Jackey, 2007; Fakham et al., 2011; Achaibou et al., 2012). The Centro de Investigaciones Energeticas, Medioambientales y Technologicas (CIEMAT) model (Copetti et al., 1993) is the most extensively adopted method for monitoring the battery performance because of its simplicity and low parameter requirement (Seigneurbieuk et al., 2006). This model is based on the electrical diagram shown in figure 2.5, describing the battery in terms of its voltage and internal resistance, considering ambient temperature effects.

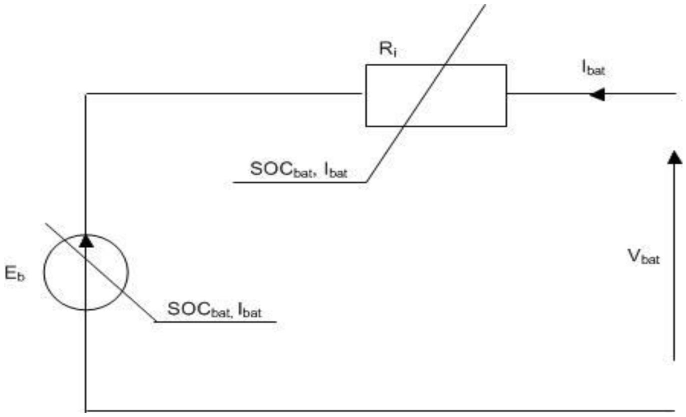


Figure 2.5. Equivalent electrical diagram for a battery element (Adapted from Gergaud et al., 2003)

V_{bat} and I_{bat} are the battery voltage and current, R_i is the internal resistance, E_b is the electromotive force as a function of the battery state of charge (SOC_{bat}). The ratio of present and nominal battery capacity is termed as SOC_{bat}, where zero represents the completely discharged battery (Hansen et al., 2000). It is recommended to maintain the SOC_{bat} between 20% to 80% to avoid a high rise or drop in battery voltage which may affect the battery life (Ghozzi and Mahkamov, 2011). Gergaud et al. (2003) suggested that the lower limit of SOC_{bat} should be 30% to increase the performance and ensure the safe operation of the battery.

2.4 SOLAR ENERGY ESTIMATION

The energy produced by a PV panel can be estimated from the generated power by integrating over the given time. Power produced by the PV panels depends upon the incoming solar irradiance and ambient temperature. A long term and accurate data set of net solar irradiance is not available in most parts of the world due to technical, financial, and institutional limitations. Therefore, many studies have been carried out to develop reliable methods and/or models for its estimation (Zaharim et al., 2009). These methods are based on other meteorological variables such as sunshine hours (Almorox and Hontoria, 2004; Chen et al., 2006), air temperature (Diodato and Bellocchi, 2007; Paulescu et al., 2006), and precipitation and air humidity (Wu et al., 2007). Solar irradiance may also be measured by instruments, and the pyranometer is the most commonly used instrument for the purpose. A pyranometer is a light sensor made up of silicon that measures the solar irradiance in the range of 0-1280 Wm^{-2} (Johnson, 2011). The accuracy of the measurement depends upon the accuracy of the instrument, its calibration and spectral sensitivity (Bekker, 2007).

2.5 SOLAR POWERED PUMPING

Solar water pumps are increasingly being used for agriculture in remote regions with limited access to electricity but ample sunshine. Their production has greatly increased during the last thirty years and they have been installed at numerous locations around the globe (Butler, 2012). Performance of PV powered diaphragm, helical and centrifugal pumps have been evaluated (Hamidat et al., 2003; Vick and Clark, 2011). In most of applications, pumped water is stored in storage tanks located at some altitude and then supplied to the field by gravity. Procedures have also been described for modeling and sizing of such systems based on economic feasibility (Samimi et al., 1996; Shrertha and Goel, 1998; Glasnovic and Margeta, 2007; Vick and Clark, 2009; Marales, 2010). The technology has also been successfully demonstrated for drip irrigation technology; sizing procedures have been described, and field testing has been conducted (Cuadros et al., 2004 and Pande et al., 2003). However, detailed investigation of solar powered pivot irrigation systems has been extremely limited in the literature. Derdall (2008) conducted a study on such systems but solar power was only used drive the pivot.

2.6 EVAPOTRANSPIRATION

Evapotranspiration (ET) is a collective term which includes the loss of water from the vegetation as well as from the surrounding surface (Dodds et al., 2005). At the time of sowing, 100% ET comes from soil evaporation whereas more than 90% comes from transpiration at full crop cover stage (Mukhala, 2001). Weather parameters, crop characteristics, environmental conditions, and management aspects are the major factors affecting ET (Kisekka et al., 2010). Accurate knowledge of ET is of high importance for proper design of irrigation systems, effective irrigation scheduling, and appropriate water management in agriculture. The direct measurement of ET is not only difficult, but also time consuming and costly (Doorenbos and Pruit, 1977). Therefore, it is estimated for a reference crop in a given environment and modified for the actual crop using the respective crop coefficient (K_c). Reference evapotranspiration (ET_{ref}) is defined as the ET from a uniform surface of dense, actively growing vegetation having a specified height and surface resistance, and not short of soil water (Allen et al., 2005). There are about 50 methods available for estimation of ET_{ref}; however, the results of these methods are inconsistent because of different assumptions and input data requirements (Grismer et al., 2002). These methods can broadly be classified into three categories based on their input data requirements: temperature based, radiation based and combination methods. Hargreaves & Blaney Criddle, Priestley-Taylor, and Penman-Monteith methods are well known examples for these respective categories (Wang et al., 2006). The FAO experts agreed unanimously in 1990 that the Penman-Monteith method is an excellent method to estimate evapotranspiration for a reference crop (Kassam and Smith, 2001). The equation used in this method was initially developed by Penman (1948) by combining energy balance and mass transfer methods. Later, this was modified by Monteith (1965), incorporating the combined effects of aerodynamic and surface resistances (Oswald, 2006). The Food and Agriculture Organization (FAO) of the United Nations provided a standardized approach to determine the parameters involved in the Penman-Monteith equation in its paper FAO-56 by Allen et al. (1998).

2.7 IRRIGATION MANAGEMENT

Irrigation management is critical for effective and efficient utilization of water and energy resources as well as to improve producer income. Various management practices that enhance water use efficiency include: irrigation scheduling, water flow measurement, drainage flow management, conservation tillage, land leveling, nutrient management, and minimizing losses by evaporation, runoff and deep percolation (Aillery, 2006). Irrigation scheduling is the most important management practice as it prevents over-application of water while minimizing yield loss due to water shortage and thus optimizing water and energy usage (Evans et al., 1996). The purpose of irrigation scheduling is to apply water required by the plants at appropriate times during different stages of crop development (Broner, 2005). The irrigation interval is determined by considering the amount of water held in the root-zone and its consumption rate by the crop, which depends upon soil texture, soil structure, crop water requirement, maximum allowable depletion, depth of effective root zone, and crop development stage (MacMullen, 2000). Various strategies can be adopted to maintain the soil moisture between the desired limits i.e. field capacity and permanent wilting point. Soil moisture monitoring is critical for successfully executing any irrigation management strategy. There are a number of methods available to determine soil moisture including the hand feel method, neutron probe, electrical resistance, soil tension, plant indicators and computerized model methods (Martin, 2009).

2.8 PV SYSTEM ECONOMICS

Cost of the photovoltaic (PV) system depends upon the power production (panel sizing), and storage (batteries) components. Although the operational cost of such systems is negligible, high initial investment is one of the main barriers for its wide scale adoption (Firatoglu and Yesilata, 2004). Improvement in efficiencies of solar panels, batteries, solar pumps, motors, and controllers has improved economic viability of the PV systems (Whitfield et al., 1995). A dramatic drop in panel prices has been observed over the last three decades (Reichelstein and Yorsten, 2013). However, a vigilant economic analysis is still required for exploring the application potential of the technology. Procedures have been described in literature for evaluating the economic viability of PV systems and along with its comparison with other conventional power sources such as electricity and combustion engines (Odeh et al., 2006; Meah et al., 2008; Kelly et al., 2010; Branker et al., 2011).

2.9 REFERENCES

Abdallah, S., 2004. The effect of using sun tracking systems on the voltage–current characteristics and power generation of flat plate photovoltaics. *Energy Conversion and Management* 45: 1671-1979.

Achaibou, N., M. Haddadi., and A. Malek. 2008. Lead acid batteries simulation including experimental validation. *Journal of Power Sources* 185: 1484-1491.

Achaibou, N., M. Haddadi., and A. Malek. 2012. Modeling of lead acid batteries in PV systems. *Energy Procedia* 18: 538-544.

Aillery, M. 2006. Production management. http://www.ers.usda.gov/publications/ah712/ah7124-6.pdf. Accessed 05 January 2012.

Almorox, J., and C. Hontoria. 2004. Global solar radiation estimation using sunshine duration in Spain. *Energy Conversion & Management* 45: 1529-1535.

Allen, R.G., I.A. Walter., R. Elliott., T. Howell., D. Itenfisu., and M. Jensen. 2005. ASCE Standardized Reference Evapotranspiration Equation. *ASCE-EWRI Task Committee Report*: American Society for Civil Engineers.

Allen, R.G., L.S. Pereira., D. Raes., and M. Smith. 1998. Crop evapotranspiration - Guidelines for computing crop water requirements. FAO Irrigation and Drainage Papers 56. http://www.fao.org/docrep/X0490E/X0490E00.htm. Accessed 02 June 2012.

Baltus, C.W.A., J.A. Eikelboom., R.J.C. V. Zolingen. 1997. Analytical monitoring of losses in PV systems. *In Proc. 14th European Photovoltaic Solar Energy Conference*. Barcelona: Netherlands Energy Research Foundation.

Bekker, B. 2007. Irradiation and pv array energy output, cost, and optimal positioning estimation for south Africa. *Journal of Energy in Southern Africa* 18(2): 16-25.

Broner, I. 2005. Irrigation scheduling. *Fact Sheet No. 4.708*. http://www.ext.colostate.edu/pubs/crops/04708.html Accessed 05 January 2012.

Branker, K., M.J.M. Pathak., and J.M. Pearce. 2011. A review of solar photovoltaic levelized cost of electricity. *Renewable and Sustainable Energy Reviews* 15: 4477-4482.

Butler, R. 2012. Water pumping. *Solar and Wind Power*. http://www.four-winds-energy.com/solar-water-pumps.html Accessed 24 April 2012.

Chen, R., S. Lu., E. Kang., J. Yang., and X. Ji. 2006. Estimating daily global radiation using two types of revised models in China. *Energy Conversion and Management* 47: 865-878.

Copetti, J.B., E. Lorenzo., and F. Chenlo. 1993. A general battery model for PV system simulation. *Progress in photovoltaic: Research and Applications* 1: 283-292.

Coote, D.R., and L.J. Gregorich. 2000. The health of our water: towards sustainable agriculture in Canada. *Publication 2020/E*: Agriculture and Agri-Food Canada.

Cuadros, F., F. L.Rodriguez., A. Marcos., and J. Coello. 2004. A procedure to size solar-powered irrigation (photoirrigation) scheme. *Solar Energy* 76: 465-473.

Derdall, E. 2008. Best management practices of a solar powered mini-pivot for irrigation of high value crops. M.Sc. thesis. Saskatoon, Saskatchewan: University of Saskatchewan, Department of Agricultural and Bio-resource Engineering.

Diodato, N. & Bellocchi, G. 2007. Modeling solar radiation over complex terrains using monthly climatological data. *Agricultural and Forest Meteorology* 144: 111-126.

Dodds, P.E., W.S. Meyer., and A. Barton. 2005. A Review of Methods to Estimate Irrigated Reference Crop Evapotranspiration across Australia. CRC for Irrigation Futures Technical Report No. 04/05. Australia: CSIRO Land and Water.

Doorenbos, J., and W. O. Pruitt. 1977. Guidelines for prediction of crop water requirements. *FAO Irrig. and Drain. Paper No. 24* (revised). Rome, Italy: United Nations FAO.

Evans, R., and R.E. Sneed. 1996. Selection and management of efficient center-pivot and linear move irrigation systems. EBAE-91-151. Carolina: North Carolina Cooperative Extension Service.

Evans, R., R.E., Saneed., and D.K. Cassel. 1996. Irrigation scheduling to improve water- and energy-use efficiencies. Publication Number: AG 452-4: North Carolina Cooperative Extension Service.

Facinelli, W.A. 1983. Modeling and simulations of lead acid batteries for photovoltaic systems. *In Proc.18th IECEC.*

Fakham H., D. Lu., and B. Francois. 2011. Power control design of a battery charger in a hybrid active PV generator for load following applications. *IEEE Transaction on Industrial Electronics* 58: 85-94.

Firatoglu, Z., and Yesilata, B., 2004. New approaches on the optimization of directly coupled PV pumping systems. Solar Energy 77, 81–93.

Garcia, M.C.A., and J.L. Balenzategui. 2004. Estimation of photovoltaic module yearly temperature and performance based on nominal operation cell temperature calculations. *Renewable Energy* 29: 1997-2010.

Gergaud, O., G. Robin., B. Multon., and H.B. Ahmad. 2003. Energy modeling of lead acid battery within hybrid wind/ photovoltaic systems. *ISBN:90-75815-07-7:* SATIE-Brittany Branch, ENS de Cachan- Ker Lann Campus, France.

Ghozzi, S., and K. Makhamov. 2011. Case study: modeling and sizing of standalone PV system for powering mobile phone stations in Libya. *World Renewable Energy Conference.* Sweden.

Glasovic, Z., J. Margeta. 2007. A model for optimal sizing of photovoltaic irrigation water pumping systems. *Solar Energ*y 81: 904-916.

Grismer, M. E., M. Orang, R. Snyder, and R. Matyac. 2002. Pan evaporation to reference evapotranspiration conversion methods. *Irrig. and Drain. Eng*. 128(3): 180-184.

Gross, G. 2008. It’s time to irrigate. http://www.agriculture.gov.sk.ca/agriview-december-2008-8. Accessed 01 January 2012.

Hamidat, A., B. Benyoucef., T. Hartani. 2003. Small-scale irrigation with photovoltaic water pumping system in Sahara regions. *Renewable Energy* 28: 1081–1096.

Hansen, A.D., P, Sorensen., L.H. Hansen., and H. Binder. 2000. Models for a standalone PV system. *Riso-R-1219 (EN)/ SEC-R-12*. Roskilde.

Harker, B., J. Lebedin, M.J. Goss., C. Madramootoo., D. Neilsen., B. Paterson., and T. V. Gulik. 2004. Threats to water availability in Canada. *ISSN 1499-5905; no. 3*. Burlington, Ontario: Environment Canada.

Helikson, H.J., D.Z. Haman., and C.D. Baird. 1991. Pumping water for irrigation using solar energy. *Fact sheet EES-63. Florida*: University of Florida.

Hohm, D. P., and M. E. Ropp. 2003. Comparative study of maximum power point tracking algorithm. Progress in Photovoltaic: *Research and Applications* 11: 47-62.

Huang, B.J. and F.S. Sun. 2007. Feasibility study of one axis three positions tracking solar PV with low concentration ratio reflector. *Energy Conversion and Management* 48: 1273-1280.

Jacky, R.A. 2007. A simple, effective lead-acid battery modeling process for electrical system component selection. *The Mathworks, Inc.* 2007-01-0778.

Jarrett, A.R., and R.E. Graves. 2010. Irrigation of liquid manures with center-pivot irrigation systems. *F-256*: College of Agriculture Sciences, PENNSTATE. http://panutrientmgmt.cas.psu.edu/pdf/F256.pdf. Accessed 05 April 2012.

Johnson,C. 2011. Basics of solar. *Allegheny College Clean Energy Education Initiative*. https://sites.google.com/a/allegheny.edu/cleanenergy/carrhallsolar/basics. Accessed 18 January 2012.

Kassam, A., and M. Smith. 2001. FAO Methodologies on Crop Water Use and Crop Water Productivity. *Paper No. CWP-M07*. Rome: Expert Meeting on Crop Water Productivity. December 3-5.

Kelly, L.C., E. Gilbertson., A. Sheikh., S.D. Eppinger., S. Dubowsky. 2010. On the feasibility of solar-powered irrigation. *Renewable and Sustainable Energy Reviews* 14: 2669-2682.

Kisekka, I., K.W. Migliaccio., M.D. Dukes., B. Schaffer., J.H. Crane., and K. Morgan. 2010. Evapotranspiration-Based irrigation for agriculture: sources of evapotranspiration data for irrigation scheduling in Florida. *AE-455*: University of Florida.

Kranz, W.L., R.G. Evans., F.R. Lamm., S.A.O. Sahughnessy., and T.G. Peters. 2010. A review of center pivot irrigation control and automation technologies. Paper Number: IRR10-9632. *In Proc. American Society of Agricultural and Biological Engineers, Conference*.

Lansier F. and G.A. Tony. 1990. Photovoltaic engineering handbook. Bristol : Adam Hilger. ISBN: 0852743114.

Lorenzo, E. 1994. Solar electricity engineering of photovoltaic systems. Artas Graficas Gala, Spain.

MacMullen,B. 2000. Irrigation Scheduling. http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0004/127282/Irrigation-scheduling.pdf. Accessed 05 January 2012.

Madramootoo. C. 2006. Food grows where water flows. A presentation prepared for Sustainable Irrigation for the Prairies Workshop. March 22 & 23, 2006. Available from Brace Centre for Water Resources Management, Macdonald campus of McGill University, 21111 Lakeshore Road, Ste. Anne de Bellevue, QC, H9X 3V9.

Madramootoo, C., R. Baker., A Shady. 2008. Global challenges in water management: The Canadian Context. NATO Workshop, ICWC, Tashkent. March 18-20.

Manwell, J.F., and J.G. McGowan. 1993. Lead acid battery storage model for hybrid energy system. *Solar Energy* 50(5): 399-405.

Martin, E.C., 2009. Methods of measuring for irrigation scheduling—when. *Arizona Water Series No.30*: College of Agriculture and Life sciences, The University of Arizona.

Meah, K., S. Fletcher., and S. Ula. 2008. Solar photovoltaic water pumping for remote locations. *Renewable and Sustainable Energy Reviews* 12: 472-487.

Monteith, J.L. 1965. Evaporation and environment. *The State and Movement of Water in Living Organisms* 19: 205-234, Symposium of the Society for Experimental Biology, NY.

Morales, T.D. 2010. Design of small photovoltaic (pv) solar-powered water pump systems. Technical Report No.28. Natural Resources Conservation Service, United States Department of Agriculture.

Mukhala, E. 2001. In-service training manual of the SADC regional remote sensing unit. Training paper series no.8. Gaborone, Botswana: Food and Agriculture Organization.

New, L., and G. Fipps. 2002. Center pivot irrigation. Texas Agriculture Extension Service. *B-6096*: The Texas A&M University Systems. http://www.extension.org/mediawiki/files/0/02/Center_pivot_irrigation.pdf. Accessed 10 April 2012.

Odeh, I,. Y.G. Yohanis., and B. Norton. 2006. Economic viability of photovoltaic water pumping systems. *Solar Energy* 80: 850-860.

Odeh, I., Y.G. Yohanis., and B. Norton. 2010. Simulation procedure for the co-optimization of photovoltaic water pumping systems. *Journal of Power and Energy* 224: 629.

Oswald, J.K. 2006. Automated water management for center pivot irrigation systems. Unpublished M.Sc. thesis. Dakhota: Agricultural and Biological Engineering, South Dakota State University.

Pande, P. C., A. K. Singh., S. Ansari., S. K. Vyas., and B. K. Dave. 2002. Design development and testing of a solar PV pump based drip system for orchards. *Renewable Energy* 28: 385-396.

Paulescu, M., Fara, L. & Tulcan-Paulescu, E. 2006. Models for obtaining daily global solar irradiation from air temperature data. *Atmospheric Research* 79: 27-240.

Penman, H.L. 1948. Natural Evaporation from Open Water, Bare Soil and Grass. *In Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*. Vol. 193, No. 1032 (Apr. 22, 1948): 120-145

Reichelstein, S., and M. Yorsten. 2013. The prospects for cost competitive solar PV power. *Energy Policy* 55: 117-127.

Simimi, J., E.A. Selaemani., M.S. Zabihi. 1996. Optimal sizing of photovoltaic systems in varied climates. *Solar Energy* 6(2): 97-110.

Rose. 2012. What Affects the Price of Solar Panels?. Remember economics? Supply and demand?. The Solar Company: http://www.thesolarco.com/what-affects-the-price-of-solar-panels/. Accessed 06 August 2013.

Ruffino,L. 2009. Irrigation Systems: Water conservation technical brief. http://www.saiplatform.org/uploads/Library/Technical%20Brief%201%20%20Irrigation%20Systems.pdf. Accessed 02 January 2012.

Seigneurbieux, J., G. Robin., H.B. Ahmad., and B. Multon. 2006. Optimization with energy management of PV battery stand-alone systems over the entire life cycle. *In Proc. 21th European Photovoltaic Conference.* Dresdon.

Shrertha, GB. and L. Goel . 1998. A study on optimal sizing of stand-alone photovoltaic stations. *Energ Conv* 13: 373.

Vick, B.D. and R.N. Clark. 2009. Determining the Optimum Solar Water Pumping System for Domestic Use, Livestock Watering or Irrigation. *In proceedings of ASES National Solar Conference*. New York. May 11-16.

Vick, B.D. and R.N. Clark. 2011. Experimental investigation of solar powered diaphragm and helical pumps. *Solar*

Energy 85: 945-954.

Wang, X., A.M. Melesse., and W. Yang. 2006. Influences of potential evapotranspiration estimation methods on swat's hydrologic simulation in a northwestern minnesota watershed. American Society of Agricultural and Biological Engineers ISSN 0001−2351. Vol. 49(6): 1755−1771.

Whitfield, G., R. Bentley, and J. Burton. 1995. Increasing the cost effectiveness of small solar photovoltaic water pumping system. Renewable Energy 6, 483–486.

Wu, G., Liu, Y. & Wang, T. 2007. Methods and strategy for modeling daily global solar radiation with measured meteorological data – A case study in Nanchang station, China. *Energy Conversion & Management* 48: 2447-2452.

Zaharim, A., A.M. Razali., T.P. Gim., K. Sopian. 2009. Time series analysis of solar radiation data in the tropics. *European Journal of Scientific Research*. Vol. 25 (4): 672-678.

3. DESIGNING A SOLAR-POWERED CENTER PIVOT IRRIGATION SYSTEM USING A RELIABILITY MODEL

3.1 PREAMBLE

This chapter presents an approach to design a PV powered center pivot irrigation system under variable operating and meteorological conditions. The aim was achieved by developing a model capable of accurately predicting the energy production, storage and load requirement based on the climate data, site attributes and system specifications in order to estimate the reliability of the system. The design components that may be altered to achieve the desired reliability of the system were explored. The model application was demonstrated by evaluating a 1.4 ha solar-powered center pivot irrigation system installed at Outlook, Saskatchewan, Canada. Therefore, this chapter addresses the technical feasibility evaluation feature of a solar-powered center pivot irrigation system design.

3.2 ABSTRACT

Photovoltaic (PV) technology, used for generating power from solar energy, has great potential for adoption in irrigated agriculture since both the energy production and requirement (load demand) depend on solar irradiation. However, design parameters must consider simultaneously the irrigation system specifications, climatic region, crop type, soil profile, and the irrigation management strategy in order to maximize reliability. The objective of this study is to develop a model for assessing the reliability of a PV powered center pivot irrigation system by combining power production, storage and requirement (load demands) sub-models considering variable operating and meteorological conditions. Given the required input variables, the developed model determines the reliability of the PV system by analyzing the time of irrigation for which both power produced by the generator and stored in the batteries are sufficient to fulfill the load demands. The model was validated by comparing the model results to field measurement of a small (1.4 ha) solar powered center pivot irrigation system, installed at Outlook, Saskatchewan, Canada. The simulated battery current was in excellent agreement

(NRMSE, 0.027) with the actual field data. The model may be used in any given environment for determining the required PV sizing to achieve the desired reliability of the system.

Keywords: PV sizing, Reliability model, Solar-powered center pivot

3.3 INTRODUCTION

There has been a reliance on fossil fuels for providing power to irrigation systems in remote areas with restricted electrical supplies. Escalating prices of fossil fuels as well as the associated environmental issues with their usage have raised the importance of consuming renewable energy resources such as solar, wind, and bio-fuel for irrigated agriculture. The potential for using solar energy is more attractive than other renewable energy options, due to the fact that the energy requirement (irrigation water required to meet the crop water demand) as well as energy production strongly depends upon the incoming solar irradiation.

A standalone Photovoltaic (PV) irrigation system may consist of a PV module (i.e. solar panels), a charge controller and/or inverter, batteries (for providing power in the absence of sun-light), a pump, a motor, and other mounting and wiring accessories. Several studies have been carried out for monitoring and improving the performance of individual components, for example, PV module (Lorenzo, 1994; Hansen et al., 2000; Abdallah, 2004; Vick and Clark, 2004; Huang and Sun, 2007), controller (Hohm and Ropp, 2003), battery (Copetti et al., 1993; Gergaud et al., 2003; Achaibou et al., 2012), solar pump (Vick and Clark, 2011), and pump motor (Bhat et al., 1987). The technology has been tested and design procedures have accordingly been developed for surface irrigation (Hamidat et. al., 2003; Glasnovic and Margeta, 2004; Vick and Clark, 2009; Cabral et. al., 2010), where water is pumped and stored into a storage tank using a low pressure pump and then applied to the field by gravity when needed. Because power is not required at the time of irrigation, a simple deterministic approach estimating water pumping potential based on the available average sunshine hours and comparing it with the crop water requirements can be used to design the PV system. In contrast, modernized irrigation systems such as a center pivot require special design considerations since their operation is directly related with the consumption of produced and stored energies when combined with a PV system.

In a center pivot irrigation system, power is required to pump and apply the water at a certain pressure for a pre-determined time based on the irrigable area, pivot system specifications and desired water application depth. The energy produced by the PV system varies with time due to its dependence on solar irradiation. However, the consumption of generated energy largely depends upon the pivot system operation (starting time and duration of irrigation). The exact timing of the irrigation events relative to peak solar-periods will strongly affect the reliability of the system. Therefore, a modeling approach is required for predicting and analyzing the energy production, storage, and the requirement over short time intervals (one hour) to precisely evaluate the PV system sizing for a center pivot irrigation system in a given environment. The evaluation may be carried out by adopting a loss of power supply probability (LPSP) technique (Borowy and Salameh, 1996) in which produced and stored energy are compared against the required energy to determine the probability for which production and storage systems fail to fulfill the load demands. An approach that combines center pivot system characteristics, crop water requirements, soil moisture monitoring, irrigation applications, PV array output, and battery performance is required for accurately estimating and analyzing system performance and, to design an appropriate PV system for center pivot irrigation system.

3.3.1 Objective

The purpose of this study is to develop a model for determining the reliability of the selected PV system under variable operating and meteorological conditions by combining interacting crop, soil, irrigation management, center pivot system, and climate variables. In addition, the developed model performance will be evaluated along with its application demonstration for a 1.4 ha solar powered center pivot irrigation system installed in Outlook, Saskatchewan Canada.

3.3.2 Conceptual Model

The reliability estimation for a PV powered center pivot irrigation system involves careful consideration of all the relevant system components. Figure 3.1 demonstrates the close interaction among the plant type, soil characteristics, irrigation management strategy, center pivot specifications, PV system components and climate variables. The instantaneous power required is primarily determined by the pivot system specifications (flow rate, operating pressure). However, the total energy required for a given time is influenced by the depth of water application. Irrigation scheduling determines the frequency and depth of water application, and is governed by the crop evapotranspiration, precipitation, crop sensitivity to the available soil moisture and soil water holding capacities (WHC). The term water holding capacity refers to the maximum amount of water that can be held in the soil (after the effects of gravity ceases) and available to plants for their use (Sommerfield, 2008). Available soil moisture is the amount of water the soil holds in between field capacity and permanent wilting point (PWP) where PWP is the soil moisture when plants ceases to extract water. The functioning of a PV panel is influenced by the climate variables i.e. incoming solar irradiation and temperature. The overall sizing the PV system (number of panels and batteries) required to achieve certain reliability is driven by the pivot specifications and irrigation scheduling practices. Overall, it can be said that there is a strong interaction among the driving variables of climate, crop type, irrigation system, and management practices. Therefore, a model combining sub-models for energy production, energy storage, and energy requirement considering all the interrelated variables, needs to be developed for predicting the performance of PV powered center pivot irrigation system.

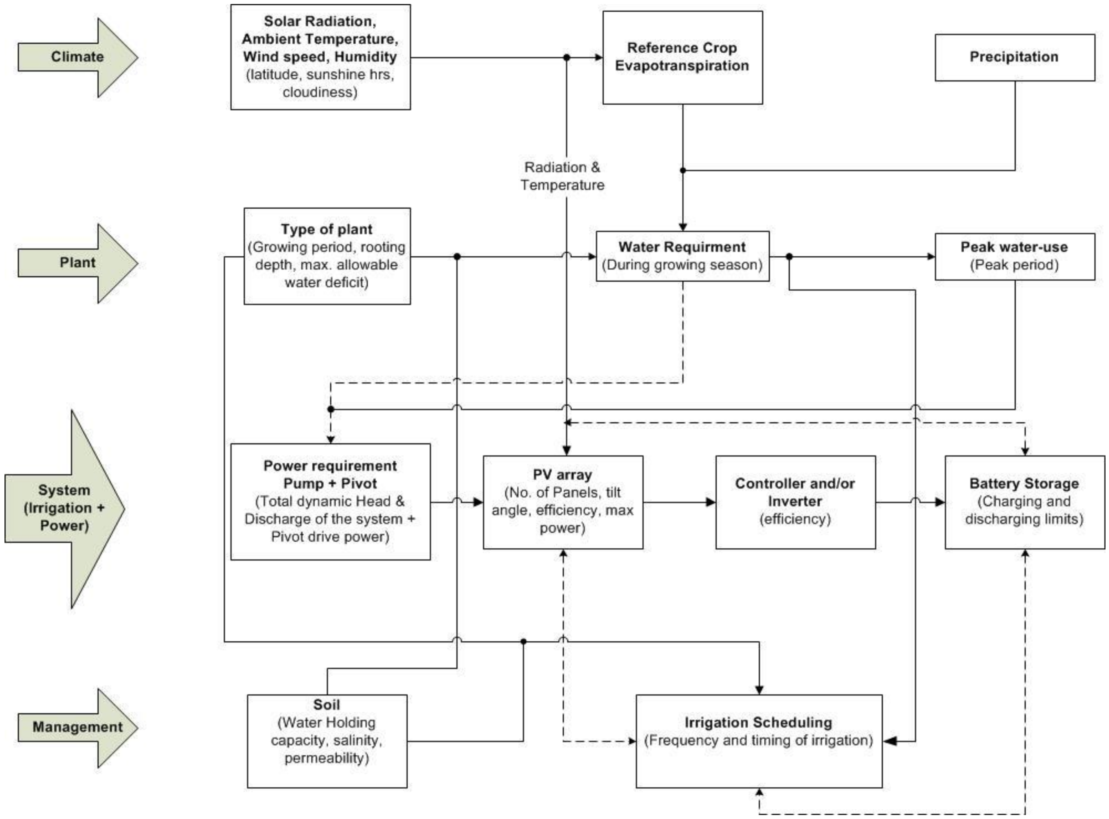


Figure 3.1. Conceptual model for solar-powered center pivot irrigation

3.4 MATERIALS AND METHODS

3.4.1 Model Development

3.4.1.1 Produced Energy

Power (P) produced by the PV module at any level of irradiance is the product of voltage (V) and current (I) of that module (Helikson, 1991). Voltage of the module remains practically constant unless adjusted by the charge controller and the current varies directly with irradiance. Open circuit voltage (V_{oc}) and short circuit current (I_{sc}) are the important characteristics of a PV module for monitoring its performance in any operating conditions, which represents the voltage when no current is flowing through the circuit and the current flowing in the absence of any load respectively (Florida Solar Energy Center, 1988). These are generally provided in the manufacturer's data sheet for the standard operating conditions (irradiance= 1,000 W m^{-2}). The voltage and current of an array (composed of two or more modules) can be increased by wiring the modules in series and parallel respectively. The current produced by the photovoltaic generator/ array at any irradiance (operating conditions), I_o^m can be estimated by representing the solar cell as an electrical equivalent one diode model (Lorenzo, 1994):

$$I_o^m = N_{pc}^m \, I_{sc,o}^c \left[1 - \exp\left(\frac{V_o^m - N_{sc}^m \, V_{oc,o}^c + \frac{I_o^m \, R_{sr}^c \, N_{sc}^m}{N_{pc}^m}}{N_{sc}^m \, V_{t,o}^c} \right) \right], \qquad (1)$$

where:

N_{pc}^m and N_{sc}^m = number of connected parallel and series cells in a module respectively,

$I_{sc,o}^c$ = short circuit current of the cell at operating conditions (A),

V_o^m = operating voltage of the module (V),

$V_{oc,o}^c$ = open circuit voltage of the cell at operating conditions (V),

R_{sr}^c = equivalent serial resistance of the cell (V A^{-1}),

$V_{t,o}^c$ = terminal voltage of the cell at operating conditions (V).

The characteristics of an example PV module (200W @ 12V) for standard operating conditions (ambient irradiance 1,000 Wm^{-2} and temperature 25°C) are derived using equation 1 and shown in figure 3.2. It can be seen from the I-V curve that at a given level of irradiance, there is a point (voltage and current) at which PV panel produces maximum power. Charge controllers equipped with maximum power point (MPP) tracking are used to enhance the energy use efficiency by forcing the PV panel operation at this point. This is achieved by adjusting the voltage and current of the module using a maximum power point tracking algorithm. It was assumed in the model that the system will be equipped with this type of controller.

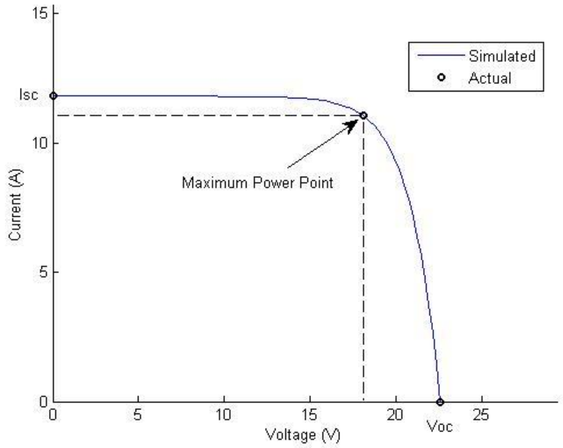


Figure 3.2. I-V Characteristics of a PV module

The parameters involved in equation 1 can be obtained given operating conditions from the manufacturers' provided specifications (Hansen et al., 2000). The short circuit current of the cell varies linearly with ambient irradiation, G_a ($I_{Sc,o}^{C} = C_1\ G_a$) where C_1 is the constant, ratio of short circuit current of the cell to the irradiation at standard conditions. The open circuit voltage of the cell varies with the cell temperature,T_c which depends upon the ambient temperature,T_a and irradiation ($T_c = T_a + C_2\ G_a$), where C_2 is the constant generally taken as 0.3 C m^2 W^{-1}. The equivalent serial resistance of the cell is a function of filling factor which is defined as the ratio of maximum power of the cell to the product of open circuit voltage and short circuit current at standard conditions. Terminal voltage of the cell depends upon the idealizing factor, m and cell temperature ($V_t^c = mK(273 + T_c)/e$) where $K\ and\ e$ are the Boltzmann's constant and electronic charges respectively. The idealizing factor could be estimated by matching the points on I-V curve given by the manufacturer with the simulated results using equation 1. An initial value between one and two may be assumed and then a solution could be obtained using an iterative technique.

PV Module specifications and climate variables (ambient temperature and irradiance) were the inputs required by the model to determine the maximum power produced by the module at any time t, which was then multiplied with the number of modules used in a given PV system for determining the power produced by the PV array (P_{pro}). Energy produced by the PV array E_p was calculated as:

$$E_p = \int_{t-1}^{t} P_{max}\, dt \qquad (2)$$

where P_{max} is the maximum power produced by the PV array.

3.4.1.2 Required Energy

The total instantaneous power required by the center pivot irrigation system (P_{load}) could be estimated by combining the power required for pumping water as well as for rotating the pivot via the electric motors on the tower. Power required for pumping (P_{pump}) is directly proportional to the system capacity (Q) and total dynamic head (TDH) (both were set as input variables in the model): $P_{pump} = C\ (TDH)\ Q$, where C is a constant for incorporating the water density, acceleration due to gravity, pump and motor efficiency factors. Total dynamic head is the sum of frictional head loss (lateral, mainline, and fittings), suction head, and pump operating pressure. Pivot drive power was provided as an input in the model and the average energy required during the operation of the system was calculated by the pivot percent timer settings (PTS). This is the setting which regulates the pivot machine motor to be turned on and off during the system operation time with respect to the desired amount of water to be applied. The percent timer setting was estimated based on the specified irrigation depth and the minimum pivot full rotation time, which depends upon the last tower travel speed and its distance from the pivot point. Both were provided as an input in the model.

The irrigation management strategy, which determines the frequency of irrigation, depth of water to be applied (IR), and starting time of irrigation was considered as the driving factors in distributing the required energy (E_l) during the crop growing season based on P_{load}. The irrigation management strategy is targeted to maintain the soil moisture at a desired level. Soil moisture status at any time t (SM_t) was estimated by considering the previously stored soil moisture in the effective root-zone of the crop, effective precipitation(EP), irrigation (IR), deep percolation/ seepage (DP) and crop water use also termed as crop evapotranspiration (ET_c) by a simple water balance method: $SM_t = SM_{t-1} + EP + IR - DP - ET_c$. Maximum available water capacity is determined from the soil texture, which is provided as an input in the model for the rooting depth of the crop. The effective rooting depth considering the crop uptake pattern may be provided in the model for soil moisture monitoring in the desired zone. It was assumed that 70% of the total precipitation would be effective i.e. stored in soil and remaining 30% will be lost in interception and runoff (Triana, 2008). However, this ratio may be altered for any site depending upon climate, intensity and duration of rainfall, slope and vegetation considerations. Initial soil moisture and precipitation for the season were provided as inputs of the model and crop water use was estimated as $ET_c = ET_{ref}\, K_c$, where K_c and ET_{ref} represents the crop coefficient or crop stage factor and reference crop evapotranspiration respectively. Crop coefficients for four main stages of a crop i.e. initial, crop development, maturity and late season were provided as an input which were used along with corresponding growing degree days to determine the crop coefficient for each day during the season by fitting a third-degree polynomial equation. The reference crop evapotranspiration was calculated by Penman-Monteith technique described by Allen et al. (2005) using equation 3:

$$ET_{ref} = \frac{0.408\, \Delta(R_n - G) + \gamma \frac{C_n}{T+273} \mathrm{U}_2 (e_s - e_a)}{\Delta + \gamma(1 + \mathrm{C}_d \mathrm{U}_2)}, \tag{3}$$

where:

R_n = incoming net radiation (MJ m^{-2} d^{-1}),

G = Soil heat flux density (MJ m^{-2} d^{-1}),

T = mean air temperature at 1.5 to 2.5 m height (°C),

U_2 = mean daily wind speed at 2 m height (m s^{-1}),

e_s = saturation vapor pressure at 1.5 to 2.5 m height (KPa),

e_a = mean actual vapor pressure at 1.5 to 2.5 m height (KPa),

Δ = slope of the saturation vapor pressure-temperature curve (KPa °C^{-1}),

γ = psychrometric constant (KPa °C^{-1}),

C_n = numerator constant that changes with reference type and calculation time step,

C_d = denominator constant that changes with reference type and calculation time step.

Climate variables (solar irradiation, temperature, wind speed, and relative humidity) as well as site attributes (elevation and latitude) were the required input parameters in the model for equation 3. Model flexibility allows the user to choose and later alter the irrigation management strategy according to the requirements. Irrigation depth (IR) derived from the irrigation management strategy was used along with the irrigable area and the system capacity to determine the required time for irrigation. The power requirement was then distributed according to the given starting time and pre-determined duration of irrigation for all irrigating days. The energy required (E_l) during the operation time of the system was calculated using equation 4. Since the irrigation system does not operate continuously throughout the season, self-discharge (depletion of stored energy) of the battery bank could not be neglected. Accordingly, an average load demand based on the system specifications could be assumed for the time when irrigation system is not operating and provided in the model to accommodate this feature.

$$E_l = \int_{t-1}^{t} (P_{pump} + P_{piv})dt \tag{4}$$

3.4.1.3 Stored Energy

A battery is one of the most critical components of a standalone PV system. It stores the excess energy when energy generated by the PV module is greater than required by the load, which can then be utilized to fulfill the deficit in cloudy days or at nights. State of charge (SOC) of the battery can be used to determine the energy stored at any time (t) for a known voltage system and battery capacity (Ah). Over charging or discharging reduces the battery life and efficiency significantly so it was assumed that a charge controller will restrict the battery operation within the desired limits ($SOC_{min} \leq SOC_t \leq SOC_{max}$). SOC_{min} and SOC_{max} were assumed to be 50% and 90% to ensure the safe operation of the battery banks with high efficiency. The Centro de Investigaciones Energeticas, Medioambientales y Technologicas (CIEMAT) model developed by Copetti et al. (1993) was selected for battery modeling and determining the state of charge (eq. 5):

$$SOC_t = SOC_{t-1} + \frac{I_{bat}\,\Delta t\,\eta_{bat}}{CB}\,, \tag{5}$$

where

I_{bat} = battery current (A),

η_{bat}= battery efficiency (%),

Δt = time duration (h),

CB = battery capacity, can be restored according to the average discharging current (Ah).

Battery efficiency was assumed to be 100% for the discharging mode and equation 6 was used for determining the charging efficiency of the battery, where I_{10} represents the normalized battery current with respect to rated battery capacity. The battery capacity in equation 5 was considered equal to the rated capacity of the battery (Gergaud et al., 2003) when $SOC_t \geq SOC_{max}$ and equation 7 normalized with respect to discharge current (I_{10}) corresponding to rated capacity for 10 hours (C_{10}) was employed otherwise.

$$\eta_{bat\_c} = 1 - exp\left[\frac{20.73}{\frac{I_{bat}}{I_{10}}+0.55}(SOC_{t-1} - 1)\right] \tag{6}$$

$$\frac{BC}{C_{10}} = \frac{1.67}{1+0.67\left(\frac{I_{bat\_d}}{I_{10}}\right)^{0.9}}(1 + 0.005\,\Delta T) \tag{7}$$

Discharging current of the battery is represented by I_{bat_d} in equation 7. Thus, by knowing the battery current, which is positive when going into the battery and negative when flowing from it, SOC could be determined at any time t. The battery current at any given time could be generated by dividing the battery power, P_{bat} to the battery terminal voltage, V_{t_bat} (Gergaud et al., 2003). Battery power was assumed to be zero when the power produced by the PV array was greater than the estimated load demand as well as the state of charge of the battery was higher than or equal to its maximum. Similarly, when SOC of the battery was below the lower limit and power required by the load was greater than that produced, battery power was assumed to be zero in the model. In all other cases, battery power was estimated by subtracting the load power from that produced by the PV array. Initial battery terminal voltage was provided as an input in the model and subsequent estimations for the given time steps were made with respect to pre-determined battery current and state of charge based on the battery operation mode, charging (eq. 8) and discharging (eq. 9).

$$V_{t\_bat\_c} = n_b(2 + 0.16\,SOC) + n_b\frac{I_{bat}}{C}\left[\frac{6}{1+{I_{bat}}^{0.86}} + \frac{0.48}{(1-SOC)^{1.2}} + 0.036\right](1 - 0.025\,\Delta T) \quad (8)$$

$$V_{t\_bat\_d} = n_b(1.965 + 0.12\,SOC) + n_b\frac{I_{bat}}{C}\left[\frac{4}{1+|I_{bat}|^{1.3}} + \frac{0.27}{(SOC)^{1.5}} + 0.02\right](1 - 0.007\,\Delta T) \quad (9)$$

Battery terminal voltage for charging, discharging modes are represented by $V_{t\_bat\_c}$ and $V_{t\_bat\_d}$ respectively, and n_b is the number of battery cells connected in series. The battery terminal voltage tends to display a sharp rise from when battery voltage reaches its gassing voltage, V_g (gaseous release of oxygen and hydrogen) during the charging regime (Gergaud et al., 2003) until it reaches the ending or final charge voltage (V_{ec}). The terminal voltage evolution during this phase can be estimated by means of an exponential law (eq. 10). The battery ending voltage, gassing voltage, and time constant (τ_g) required in equation 10 depends upon the battery current and were approximated by equations 10a, 10b and 10c respectively.

$$V_{bat\_oc} = n_b\,V_g + n_b(V_{ec} - V_g)\left[1 - exp\left(\frac{Ah_{restored} - 0.95\,BC}{I_{bat}\tau_g}\right)\right] \quad (10)$$

$$V_{ec} = \left[2.45 + 2.011\,\ln\left(1 + \frac{I_{bat}}{C_{10}}\right)\right](1 - 0.002\,\Delta T) \quad (10a)$$

$$V_g = \left[2.24 + 1.97\,\ln\left(1 + \frac{I_{bat}}{C_{10}}\right)\right](1 - 0.002\,\Delta T) \quad (10b)$$

$$\tau_g = \frac{1.73}{1+852\left(\frac{I_{bat}}{C_{10}}\right)^{1.67}} \tag{10c}$$

3.4.1.4 Reliability Determination

Borowy and Salameh (1996) defined the loss of power supply (LPS) at any time t as the deficit of energy produced when the available energy (generated and stored) is insufficient to meet the load demands (eq. 11), where E_{b_min} and $E_{b\ (t-1)}$ correspond to the energy stored in battery at SOC_{min} and the battery storage at time $(t-1)$ respectively. The loss of power supply probability ($LPSP$) was defined as the ratio of the energy deficit to the required load (Copetti et al., 1993), and was calculated using equation12. Its value ranges from zero to one, where zero represents a system always able to fulfill the load demands. The reliability of the system was determined by taking the inverse of loss of power supply probability $(1-LPSP)$. Thus, given combinations of solar panels and batteries can be analyzed in terms of their reliability under variable operating and meteorological conditions. The desired reliability of the PV system could be achieved by altering the PV panel sizing, the battery capacity, or the irrigation management strategy.

$$LPS_t = E_l - \left(E_p + E_{b\ (t-1)} - E_{b\_min}\right) \tag{11}$$

$$LPSP = \frac{\sum_{t=1}^{t} LPS_t}{\sum_{t=1}^{t} E_{l(t)}} \tag{12}$$

3.4.1.5Model Implementation

A model was developed by combining all the pre-described models for assessing the reliability of the PV system for providing power to the center pivot for its operation (MATLAB code is provided in Appendix A). Daily reference crop evapotranspiration was first calculated, based on the weather data input. Crop stage factor was determined and adjusted based on the soil moisture for each day and then the actual crop water requirement was estimated. The irrigation depth which could be applied was based on the prescribed soil moisture conditions (soil moisture reaches to pre-set percentage of maximum available water). Soil moisture was tracked by considering the previous storage in soil, precipitation, irrigation, and crop consumptive use. The system capacity, the depth of irrigation and the irrigated area ultimately determined the operating hours in a given day. The hourly simulation was then made based on the starting time of irrigation. The energy required for pumping and driving the pivot during an hour was then distributed based on the determined operating hours. The hourly energy stored and produced could be estimated using the models described in section 3.4. The hourly solar radiation based on the panel orientation and ambient temperature was provided as input for determining the produced energy. A soil moisture curve could be generated based on the reliability of the PV system. Alteration can be made in panel sizing, battery capacity and/or irrigation management strategy to attain the soil moisture in desired limits. A simplified flow diagram of the reliability assessment model is presented in figure 3.3.

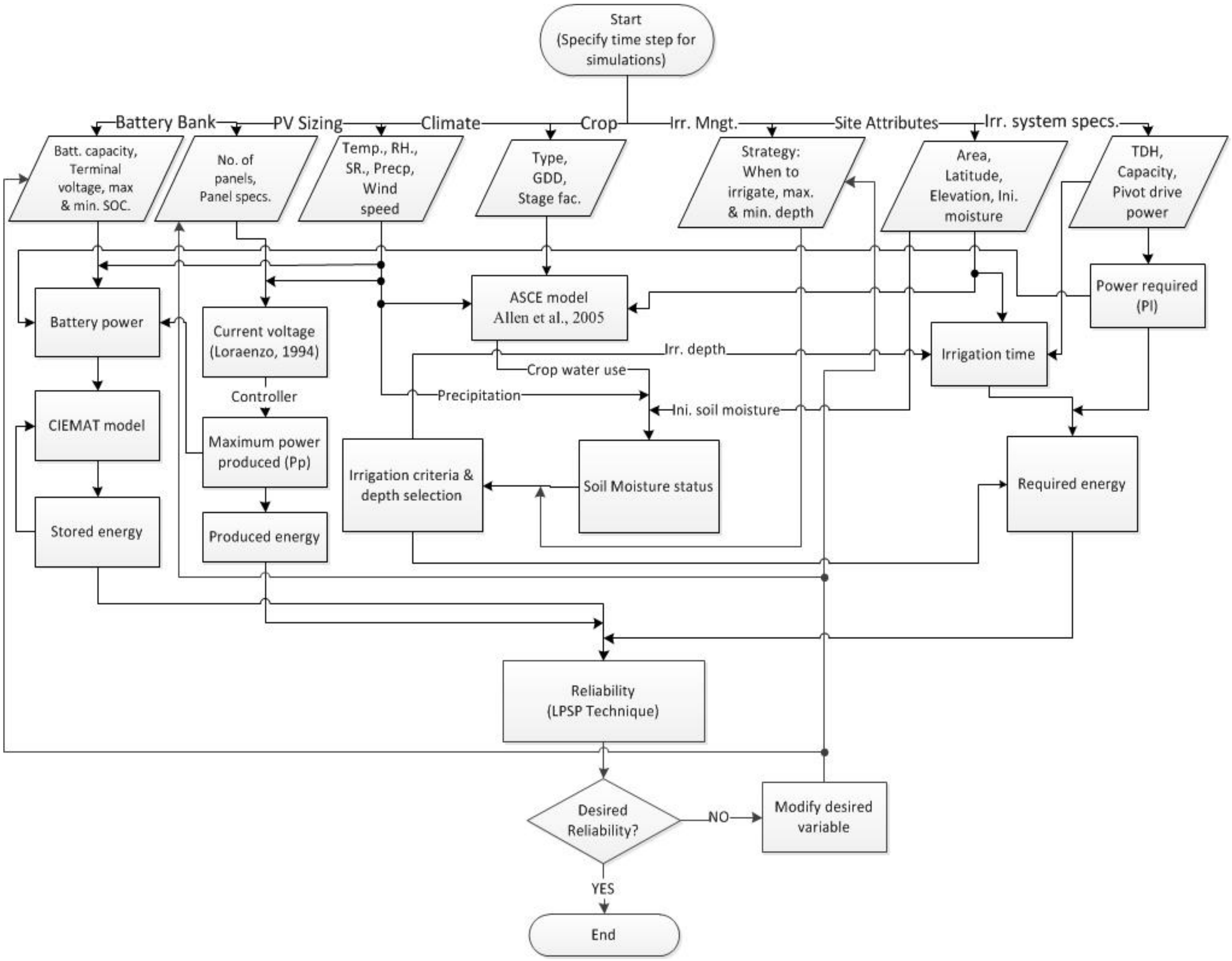


Figure 3.3. Simplified flow diagram of reliability model

3.4.2 Model Validation and Application Demonstration

A small, 67 m long (1.4 ha, two tower), 24V-DC solar powered center pivot irrigation system installed at Outlook, Saskatchewan, Canada (51° 30’ N, 107° 03’ W) was selected for validating the model and demonstrating its application. The system discharge was 112.5 L min^{-1} and was supplied by two Lorentz PS200 submersible solar pumps having their own parallel power production and storage systems. Each system was comprised of eight 200 W @ 12V solar panels connected in series with 35° slope and an array of eight 240 Ah @ 6V battery banks, arranged to yield banks of 480 Ah at 24V. A charge controller (Outback FLEXmax 80) equipped with a maximum power point tracking algorithm was installed to ensure the safe operation of the system by continuous monitoring of solar panel and battery voltages. The center pivot was equipped with spray nozzles operating at low pressure (70 kPa). The average power required for each solar pump was 275 W. The instantaneous power required to drive the pivot was 100 W. This power was supplied by a completely separate system comprised of four 40 W @ 12V solar panels connected in series to provide 160 W and eight 60 Ah @ 6V batteries. Figure 3.4 captures the installed solar-powered center pivot irrigation system displaying center pivot, solar array, lead-acid batteries, controller, data logger and other control switches. The application efficiency of the center pivot irrigation system was assumed to be 80%.

Figure 3.4. Installed system at Canada Saskatchewan Irrigation Diversification Center (CSIDC), Outlook, Canada: (a) Power production unit and center pivot (b) battery bank (iii) Controller and data-logger

The model was validated with the actual data obtained from the site. Transducers (DC current transducer CR5 200, and DC voltage transducer CR5 300) were used to measure the voltage and current of the array, battery bank voltage, the current going to/from the battery banks, the current used by the solar pumps and voltage and current going to center pivot drive motors. The monitored variables were logged using a Campbell Scientific CR23X data-logger for a five minute time interval. The hourly average was then calculated for validating it against the model predicted output.

The model application was demonstrated by evaluating the PV system performance for the selected site using 2012 weather data. Canola was the crop grown and the growing season was considered from May 16 to August 31. The required climate variables for modeling the crop water requirement and the power production were taken from the nearby weather station (approximately 200 m). A conventional irrigation management strategy was adopted, where 25-35 mm water was applied each time the soil moisture depletes to 65% to 70% of the maximum available water. Available moisture considering the root-zone depth (1.2 m) and soil texture (clay loam to loam) was estimated to be 220 mm. An hourly time step was used in the model for analyzing the energy produced and stored against the load demands.

3.4.3 Input Data Treatment

Measured solar irradiation is extremely sensitive to the accurate functioning of the instrument and its calibration. Furthermore, the modeled power production by a PV panel and the modeled crop water requirement depends on the high quality radiation data. The technique described by Allen (1996) was used for the purpose of assessing the integrity and quality of the measured and acquired radiation data. It was found that the collected daily average radiation data was not appropriate during 2009-12 for the study site. This is because recorded daily solar radiation remained well below (about 30%) the produced clear sky daily radiation envelop (considering the effect of atmospheric water vapor content and sun angle) throughout the period of interest (crop growing season i.e. May-September). However, rational results were attained for 2006-08 (Appendix B). The acquired solar radiation data was compared with two nearby sites for estimating the error: Brightwatercreek (BWC) and Agricultural Greenhouse Gas Program (AGGP) project site located at about 45 km south-west and 20 km north respectively. It was found that the acquired data was underestimated by about 30%. Accordingly, up-scaling was performed for the acquired daily and hourly radiation during 2009-12.

3.5 RESULTS AND DISCUSSION

3.5.1 Model Validation for Battery Current and Reliability

The modeled battery current compared with the measured current from July 30 to August 01, 2012 for one of the installed parallel pumping systems is shown in figure 3.4. Positive values in the figure indicate the current going to the battery bank whereas the negative values represent the current going from the battery bank. Normalized root mean square error (NRMSE) was estimated and found to be 0.027, indicating an excellent agreement between the modeled results and the recorded data. During this validation period, almost all possible scenarios were demonstrated. The regime A and E in the figure represents negligible battery current because battery at this stage was fully charged and power for irrigation was directly supplied by the PV array. The regime B and F represents the negative battery currents which means that produced power was less than the load demand and irrigations were applied by consuming the stored energy during these phases. The regime C and G represents the phases when irrigation was not practiced so battery current was just due to self-discharge of the battery bank. Regime D represents an early morning phase when irrigation was not started yet but produced current was used to charge the batteries. In contrast, regime H represents a phase where irrigation was started early in the morning so produced power was used for both supplying power for irrigation and charging the battery bank simultaneously. Battery current was chosen for validation because battery model considers the power production, load requirement and controller models for estimating the battery power and ultimately battery current. Thus validation of the battery model also endorses the accurate functioning of the other models.

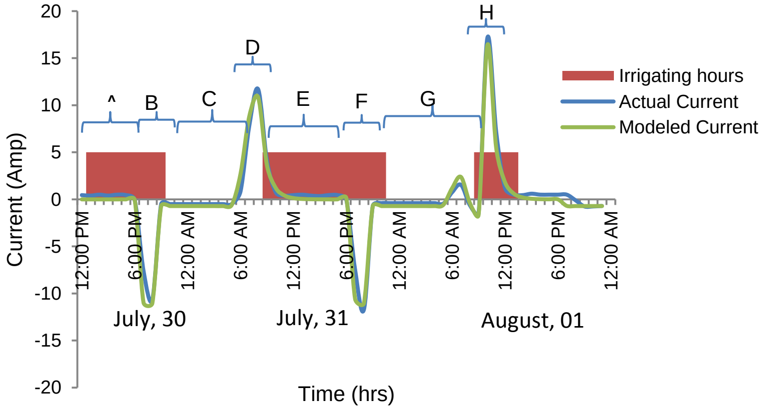


Figure 3.5. Modeled Vs. actual battery current

During the testing period of the model (July 30 – August 01, 2012), load demand was always fulfilled by the power production and storage systems (fig 3.5). The load demand was provided by the power production system except for a few hours when stored energy was consumed. However, the stored energy remained above its lower limit suggesting that the installed system is 100 % reliable for the selected testing period.

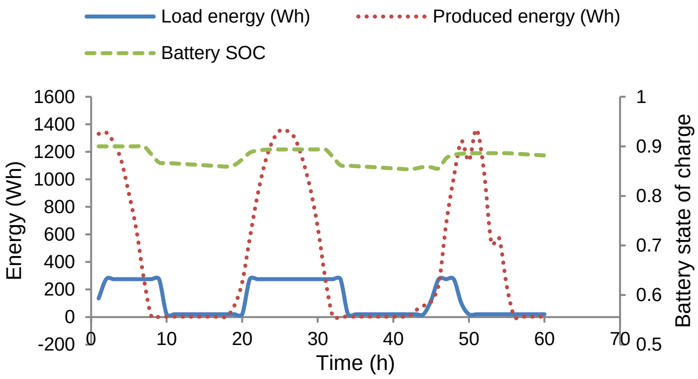


Figure 3.6. Monitoring of PV system performance

3.5.2 Model Performance Evaluation

The performance of the developed model was investigated by examining the energy production and storage profiles against the load demand for one of the parallel installed systems during two consecutive days considering high and low level of incoming solar irradiation (fig. 3.6). The two different selected scenarios (contrasting solar irradiation days) are used to explore the modeled energy production and storage profiles against the given load under variable weather conditions. The days in each scenario were selected in a way to represent the maximum and minimum radiation received for two consecutive days in the selected season (May-September, 2012). The lower limit of the battery state of charge was set to be 50%. The load demand was always supplied by the energy production and storage systems during high solar irradiation days as shown in figure 3.6 (a). The stored energy was used when produced energy was less than the load demand and battery capacity was restored otherwise. However, during low irradiation days, the produced energy was insufficient for the load demand except for a few hours during the second day of irrigation (fig. 3.6 b). Therefore, stored energy was used to power the system which was supplemented by the produced energy for the first day of system operation. The battery was drained to its minimum level at the end of the day due to continuous load and system operation was not possible for the second day till noon. The power production at this time was more than the required load (for a few hours), which was used to restore the battery capacity. During the end of the day stored battery capacity was not sufficient and power production remained less than the load demand, therefore, system operation was not possible. The model performs according to expectations during these two scenarios.

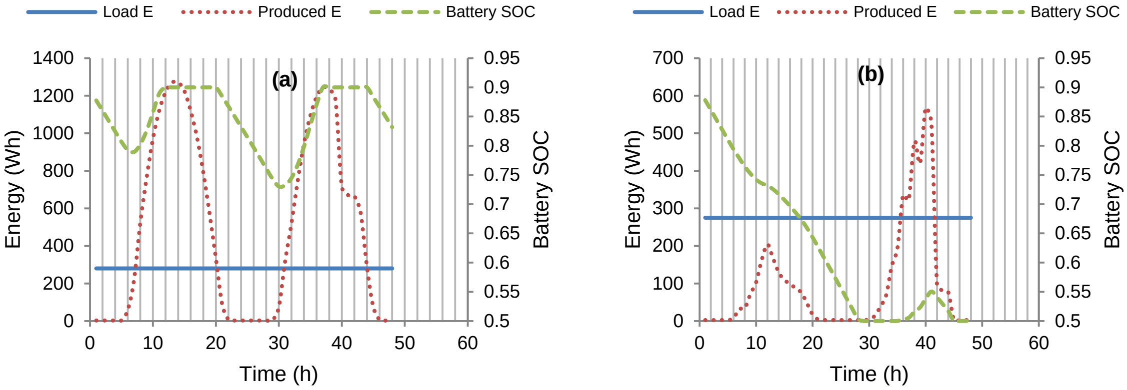


Figure 3.7. Modeled energy profiles for (a) 03-04 June 2012 at 31.0 and 28.3 MJ m^{-2} day^{-1} solar irradiation and (b) 15-16 July 2012 at 2.4 and 4.2 MJ m^{-2} day^{-1} irradiation

3.5.3 Application Demonstration

3.5.3.1 Reliability estimation and its sensitivity to management strategy

The usefulness of the developed model is demonstrated by evaluating the system described in previous sections using 2012 weather data. A large amount of effective precipitation (220 mm) was received during crop growing season, so only 180 mm water had to be applied through irrigation for maintaining the soil moisture above the threshold. The model predicted that the system is 90.1% reliable based on the currently installed battery capacities (960 Ah) and PV panel sizing (16 @ 200 W) for the traditional irrigation management strategy (30 mm water application when soil moisture depletes to 65% field capacity). When the irrigation management strategy was altered to 15 mm water application each time the soil moisture depletes to 65% field capacity, the same PV system becomes 98.4% reliable. This is because irrigation time decreases with the reduction in the depth of water application, lowering the energy requirement for the given day of irrigation. This implies that the irrigation management strategy may have a huge impact on reliability or PV system sizing. The simulated soil moisture for both the irrigation management strategies is shown in figure 3.7. The soil moisture remained within the desired limits (in between field capacity and threshold) even for 90.1% reliable PV system. This suggests that a system which is not designed at 100% reliability may avoid water stress conditions.

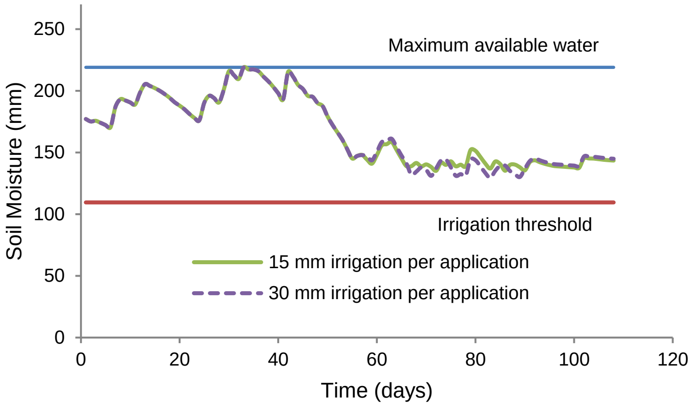


Figure 3.8. Simulated soil moisture profile

3.5.3.2 Reliability Variation with Panel and Battery Sizing

For conventional irrigation management strategies, PV systems may be designed at a moderate level of reliability (80-95%) to optimize the size of the PV system components. This is because the deficit of water caused by the loss of power supply may be fulfilled by applying irrigation during the following days of PV system failure since the irrigation system only operates for some days in the season if soil moisture drops down to its threshold. Figure 3.8 presents reliability curves for the selected irrigation management strategy and battery capacities. It can be seen from the figure that the panel sizing can be reduced from 16 to 10 if 80% reliability of the system is acceptable keeping the currently installed battery capacity. Similarly, 22 solar panels would be required to achieve the same reliability if the battery capacity is reduced to the half of the installed capacity (480 Ah). Thus considering the economics of the PV system components, the appropriate system can be selected.

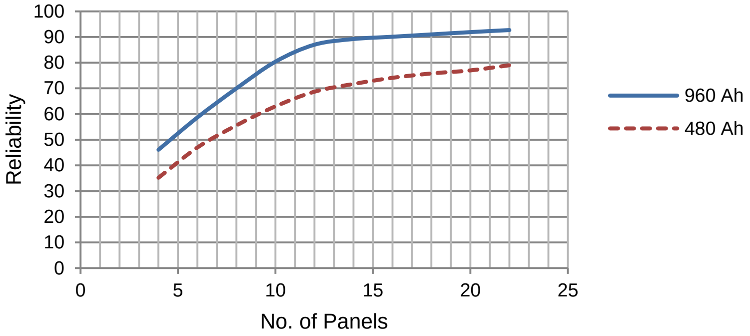


Figure 3.9. PV system performance for the selected site and management strategy

It has been demonstrated that the model can be used to determine the reliability of the selected PV system for the chosen irrigation management strategy in specified operating conditions provided the required input variables. In addition, desired reliability of the system can be achieved by altering the irrigation management strategy, panel sizing, and/or the battery capacity.

3.6 CONCLUSIONS

A model for assessing the reliability of a PV system for a center pivot irrigation system, under variable operating and meteorological conditions, has been developed. The modeled battery current was validated with the actual battery current and the normalized root mean square error was found to be 0.027 showing an excellent agreement between the modeled results and the actual data. The model performance was tested for different operating scenarios and satisfactory results were generated. The usefulness of the developed model was demonstrated by evaluating a 1.4 ha system installed at Outlook, Saskatchewan, Canada for the conventional irrigation management strategy (15-30 mm water application when soil moisture depletes 65% field capacity) using 2012 weather data. It was demonstrated that the PV system may be designed at moderate level of reliability for the conventional irrigation management strategy. The influence of irrigation management strategy, panel sizing and battery capacity were explored and the results suggest that a careful analysis considering all interacting crop, soil, management strategy, panel sizing, battery storage, pivot specifications, and the climate variables is required for appropriate selection of the PV system components.

3.7 REFERENCES

Abdallah, S., 2004. The effect of using sun tracking systems on the voltage–current characteristics and power generation of flat plate photovoltaics. *Energy Conversion and Management* 45: 1671-1979.

Achaibou, N., M. Haddadi., and A. Malek. 2012. Modeling of lead acid batteries in PV systems. *Energy Procedia* 18: 538-544.

Allen, R.G. 1996. Assessing integrity of weather data for reference evapotranspiration estimation. *Journal of Irrigation and Drainage Engineering*: 97-106.

Allen R.G., I.A. Walter., R. Elliott., T. Howell., D. Itenfisu., and M. Jensen. 2005. ASCE Standardized Reference Evapotranspiration Equation. ASCE-EWRI Task Committee Report: American Society for Civil Engineers.

Bhat, S.R., A. Pittet., and B. S. SONDE., 1987. Performance optimization of induction motor-pump system using photovoltaic energy source. *IEEE Transactions on Industry Applications* IA-23: 995-1001.

Boroway, B.S., Salameh, Z.M., 1996. Methodology for optimally sizing the combination of a battery bank and PV array in a wind/PV hybrid system. *IEEE Transactions on Energy Conversion* 11: 367-375.

Cabral, C. V. T., D.O. Filho., A. S. A. C. Diniz., J. H. Martins., O. M. Toledo., and B. M. Neto. 2010. A stochastic method for stand-alone photovoltaic system sizing. *Solar Energy* 84: 1628-1636.

Copetti, J.B., E. Lorenzo., and F. Chenlo. 1993. A general battery model for PV system simulation. *Progress in photovoltaic: Research and Applications* 1: 283-292.

Gergaud, O., G. Robin., B. Multon., and H. B. Ahmed. 2003. Energy modeling of a lead acid battery within hybrid

Glasovic, Z., J. Margeta. 2007. A model for optimal sizing of photovoltaic irrigation water pumping systems. *Solar Energ*y 81: 904-916.

Hamidat, A., B. Benyoucef., and T. Hartani. 2003. Small-scale irrigation with photovoltaic water pumping system in Sahara regions. *Renewable Energy* 28: 1081-1096.

Hansen, A.D., P, Sorensen., L.H. Hansen., and H. Binder. 2000. Models for a standalone PV system. Riso-R-1219 (EN)/ SEC-R-12.

Helikson, H.J., D.Z. Haman., and C.D. Baird. 1991. Pumping water for irrigation using solar energy. *Fact sheet EES-63. Florida*: University of Florida.

Huang, B.J. and F.S. Sun. 2007. Feasibility study of one axis three positions tracking solar PV with low concentration ratio reflector. *Energy Conversion and Management* 48: 1273-1280.

Lorenzo, E. 1994. Solar electricity engineering of photovoltaic systems. Artas Graficas Gala, Spain.

Sommerfield, S. 2008. Irrigation scheduling manual. Saskatchewan Ministry of Agriculture. Accessed at http://www.agriculture.gov.sk.ca/Default.aspx?DN=288f45ad-5bab-41b1-9878-80acf555e3bf on July 15, 2013.

Triana, E. 2008. A spatial decision support system for basin scale assessment of improved management of water quantity and quality in stream-aquifer systems. Colorado State University. Colorado: ProQuest. ISBN. 0549710558, 9780549710554.

Vick, B.D. and R.N. Clark. 2004. Effect of Panel Temperature on a Solar-PV AC Water Pumping System. ASES Solar 2004: A Solar Harvest Growing Opportunities. July 11-14. Portland.

Vick, B.D. and R.N. Clark. 2009. Determining the Optimum Solar Water Pumping System for Domestic Use, Livestock Watering or Irrigation. *In Proc.* of ASES National Solar Conference. New York. May 11-16.

Vick, B.D. and R.N. Clark. 2011. Experimental investigation of solar powered diaphragm and helical pumps. *Solar Energy* 85: 945-954.

4. IMPACT OF IRRIGATION MANAGEMENT STRATEGY ON SIZING OF A SOLAR-POWERED CENTER PIVOT IRRIGATION SYSTEM

4.1 PREAMBLE

Power production depends upon the climate variables for a PV system. Therefore, selection of an appropriate irrigation management strategy may be critical for effective usage of the produced energy while considering PV applications for center pivot irrigation systems. This paper evaluates alternate irrigation management strategies to identify the best management practice that leads to minimal sizing of the PV system for maintaining the soil moisture at desired limits. A small (1.4 ha) solar-powered center pivot irrigation system installed at Outlook, Saskatchewan, Canada was tested for the purpose. An optimal PV system can be designed by combining the modeling procedure described in chapter 3 with the identified irrigation management practice. Thus, this paper falls in the domain of developing an approach for a reliable and economically viable PV system design.

4.2 ABSTRACT

The potential for application of photovoltaic (PV) technology in irrigated agriculture has increased in recent years due to a wider availability of affordable PV modules, and a desire to reduce dependencies on conventional non-renewable energy resources. The irrigation management strategy determines the frequency and duration for which pumping is required, thus influencing the PV system sizing. The objective of this research is to investigate the variability of PV system sizing with alternate irrigation management strategies to identify a suitable management practice for minimum PV sizing. A model was used for determining the reliability of a selected PV system size under variable operating and meteorological conditions. The desired reliability of the PV system was achieved by modifying the PV system sizing. A small (1.4 ha) solar-powered center pivot irrigation system (79.3 L min^{-1} ha^{-1}) installed at Outlook, Saskatchewan, Canada was used to evaluate 2 irrigation management strategies: (1) moderate application depths (25-35 mm per application), and (2) frequent light irrigations (5-8 mm per application) in terms of their PV system sizing requirement. The use of frequent light irrigations required a significantly smaller PV system than the standard soil moisture threshold based strategy. For example, PV sizing reduced to 6 solar panels (200W @ 12V) with 360 Ah battery capacity from ten similar panels with 900 Ah battery capacity for altering irrigation management strategies to achieve an 85% reliable system (considering 2012 climate data). These results emphasize that the identified irrigation management strategy can have a significant impact upon the economic and technological feasibility of a PV irrigation system. The modeling tools demonstrated here can be used to determine the optimum size of the PV irrigation systems while taking into consideration the interrelated factors of irrigation management, soil water characteristics, and climatic variations.

Keywords: Best management practice, Center pivot irrigation system, Irrigation scheduling, PV sizing, Renewable energy

4.3 INTRODUCTION

Limited availability of conventional non-renewable energy resources and their associated environmental challenges pose barriers to expansion of irrigated agriculture. Therefore, adoption of renewable energy resources such as wind, bio-fuels and solar is crucial for sustainable growth of irrigated agriculture. Solar energy may feature more prominently than other resources in this context based on the inherent correlation of energy requirement (crop water need) and energy production through Photovoltaic (PV) technology with the solar irradiation. However, optimal sizing of the PV system components to assure the desired system reliability is critical for successful adoption of the technology. A reliable system can be designed by using the loss of power supply probability (LPSP) technique (Borowy and Salameh, 1996), which determines the probability of time for which the power produced by the PV panels and stored in the batteries fails to fulfill the load demands.

The pumping load requirement, a driving variable for the PV system sizing, is largely influenced by the irrigation management strategy. Therefore, selection of an appropriate irrigation management strategy may improve the feasibility of a solar-powered center pivot irrigation system. The irrigation management strategy determines the frequency and thus depth of irrigation to be applied for maintaining the soil moisture within desired limits. The frequency and depth of irrigation are inversely proportional. The operating time of a center pivot irrigation system depends upon the irrigation application depth for the given system discharge and irrigable area. Generally, crop yield or quality is not affected by the soil moisture status unless available water in the soil is less than the allowable depletion volume for the given crop (Evans et. al., 1996). Allowable depletion volume is generally represented as the percentage of the field capacity, which is the greatest amount of water present in the soil and available to crop for its use. It varies from crop to crop and through development stages: 40 to 70% for most of the crops (Al-Kaisi and Borner, 2009). Different irrigation management strategies may be adopted to maintain the soil moisture level above the threshold (allowable depletion). For example, the conventional irrigation management strategy in the Canadian prairies may be adopted in which relatively large depths (25-35 mm) are applied as required to maintain the soil moisture. However, the produced energy may not effectively be utilized under this strategy due to large number of non-irrigating days. In contrast, a frequent light irrigation (5-8 mm per application) management strategy may also be adopted to maintain the soil moisture within the desired level. This strategy may successfully be implemented by the modern irrigation technologies such as center pivot irrigation system. The frequent light irrigation management strategy is a requirement for light (sandy) soils and may also be adopted for the heavy soils (Trimmer and Hansen, 1994). The strategy is advantageous for effective use of precipitation, controlling drainage and maintaining nutrients, thus may have the potential to improve the quality and quantity of the produced crop (Hobbs and Krogman, 1978). Irrigation time and thus the load requirement during the operating days of center pivot irrigation system may largely vary for these altered management strategies due to different depth of water application. Therefore, variation in PV system sizing requirement may be significant for these altered strategies. Unfortunately, investigations of the variability of PV system sizing with alternate irrigation management strategies for solar-powered center pivot irrigation system are missing in the literature. Such an investigation may be very beneficial for identifying the best irrigation management strategy, for a given crop and climate, to minimize the sizing of PV system leading towards economically feasible system design.

4.3.1 Objective

The purpose of this study is to investigate the impact of two contrasting irrigation management strategies for identifying the best management practice for solar-powered center pivot irrigation: (i) less frequent moderate irrigations, (25-35 mm per application) and (ii) frequent light irrigations (5-8 mm per application), on PV system sizing for developing a minimal sizing design guideline. It is further planned to assess the effect of timing of irrigations (day time, day and night time) for the identified irrigation management strategies by varying the system flow rate.

4.4 MATERIALS AND METHODS

A reliability model was used for assessing the PV sizing requirements to achieve the desired reliability of the system under alternate irrigation management strategies. The mathematical development of the model has been discussed in chapter 3. However, a brief description of the model as well as the evaluated irrigation management strategies is described in the following sections.

4.4.1 Reliability Model

The reliability of a PV powered center pivot irrigation system was determined using loss of power supply probability (LPSP) technique (Borowy and Salameh, 1996). The ratio of the energy deficit to its demand, both with respect to load, is termed as LPSP (Copetti et al., 1993). The energy deficit was determined by comparing the simulated energy produced by the PV array and stored in the battery bank against the energy required by the pivot system for its operation during a given time period. The produced, stored, and required energies were estimated considering all the interactive involved variables by relevant sub-models. The inverse of LPSP was considered as a measure of the reliability of the PV system in a given environment and was expressed as percentage. A 100% reliable system specified that the load demand (energy required) was always met by the produced and/or stored energy of the selected PV system. A simplified flow chart for reliability assessment is presented in figure 4.1. Energy produced by the PV array and stored in the battery bank could be altered by varying their respective sizing whereas required energy could be redistributed during a given time span by changing the irrigation management strategy. This implied that the desired reliability of the PV system could be achieved by altering the PV panel sizing, the battery capacity, or the irrigation management strategy in the relevant sub-models of energy production, energy storage and energy requirement respectively.

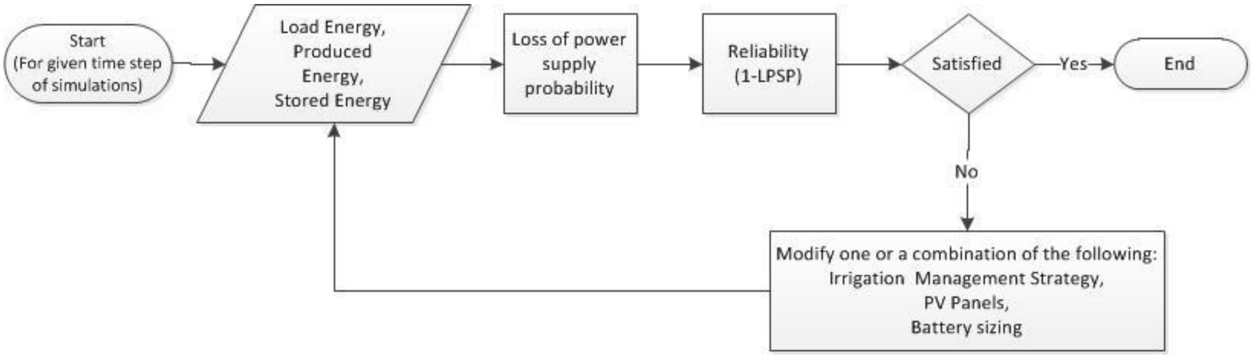


Figure 4.1. Simplified flow diagram for reliability assessment model for center pivot irrigation system

4.4.1.1 Sub-model of Produced Energy

Power (P) produced by a PV module is the product of voltage (V) and current (I) (Helikson, 1991). A range of voltages were passed through the model (Lorenzo, 1994) and corresponding current value were determined. The maximum of their product was taken as the power generated by the PV module at a given irradiance to incorporate the maximum power point tracking algorithm. A simplified flow diagram of the model is shown in figure 4.2. The required climate variables were ambient radiation and temperature whereas open circuit voltage, short circuit current, cell temperature, maximum power produced, standard irradiation, and number of cells connected in series and parallel could be obtained from the PV panel specifications. The energy produced for a given time interval was estimated by integrating the pre-determined maximum produced power for that time considering the total number of panels used.

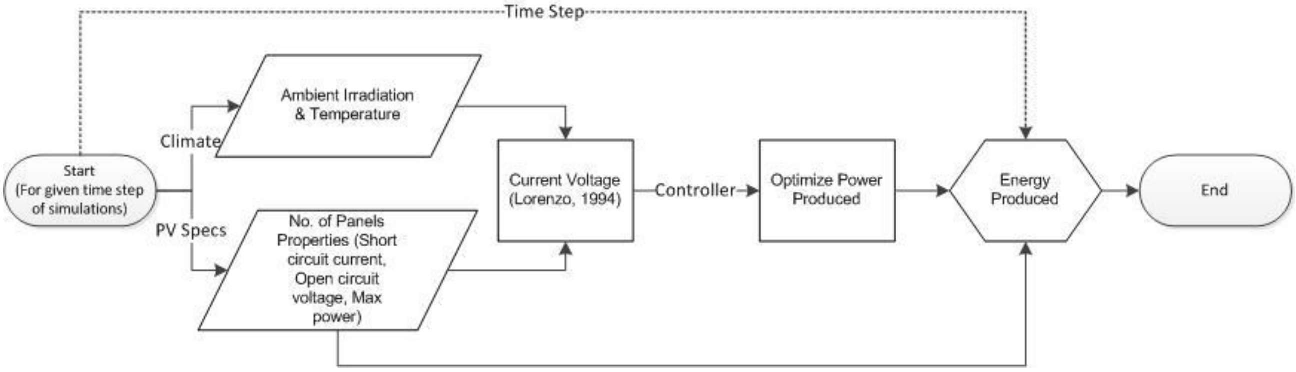


Figure 4.2. Simplified flow diagram for energy production model

4.4.1.2 Sub-model of Required Energy

A model considering irrigation system specifications, site attributes, irrigation management strategy (starting time, frequency, and depth of irrigation), crop characteristics and climate variables was used for estimating the required energy by the load for a given time (fig. 4.3). The total instantaneous power required by the center pivot irrigation system was estimated by combining the power required for pumping water and the power required for driving the pivot. The power required for pumping was assessed from the irrigation system discharge and the total dynamic head considering pump and motor efficiencies; both were provided as inputs in the model. Pivot drive power was also provided as an input and the average energy required during the operation of the system was calculated by the pivot percent timer settings. This is the setting which regulates the pivot drive motor to be turned on and off during the system operation time based on desired amount of water to be applied and pivot travel speed. The irrigation management strategy which determines the frequency of irrigation, depth of water to be applied, and the starting time of irrigation was considered as the driving variable in distributing the required energy during the crop growing season. The irrigation management strategy was finalized in a way to maintain the soil moisture within the desired limits. The soil moisture status at any time was estimated by subtracting the crop evapotranspiration from the net water supplied through irrigation and precipitation in addition to previously stored soil moisture assuming the runoff and deep percolations negligible. The initial water content (IWC) was provided as input in the model to start the simulations. Crop water use was determined by using the Penman-Monteith technique described in Allen et al. (2005). Thus a suitable irrigation depth could be selected and/or readjusted to maintain the soil moisture within the desired limits considering the predicted or recorded crop water use and precipitation. The duration of irrigation was then determined from the selected depth of irrigation, irrigable area and irrigation system discharge. The load energy demand was accordingly distributed for the pre-determined irrigation time based on the selected starting time of irrigation.

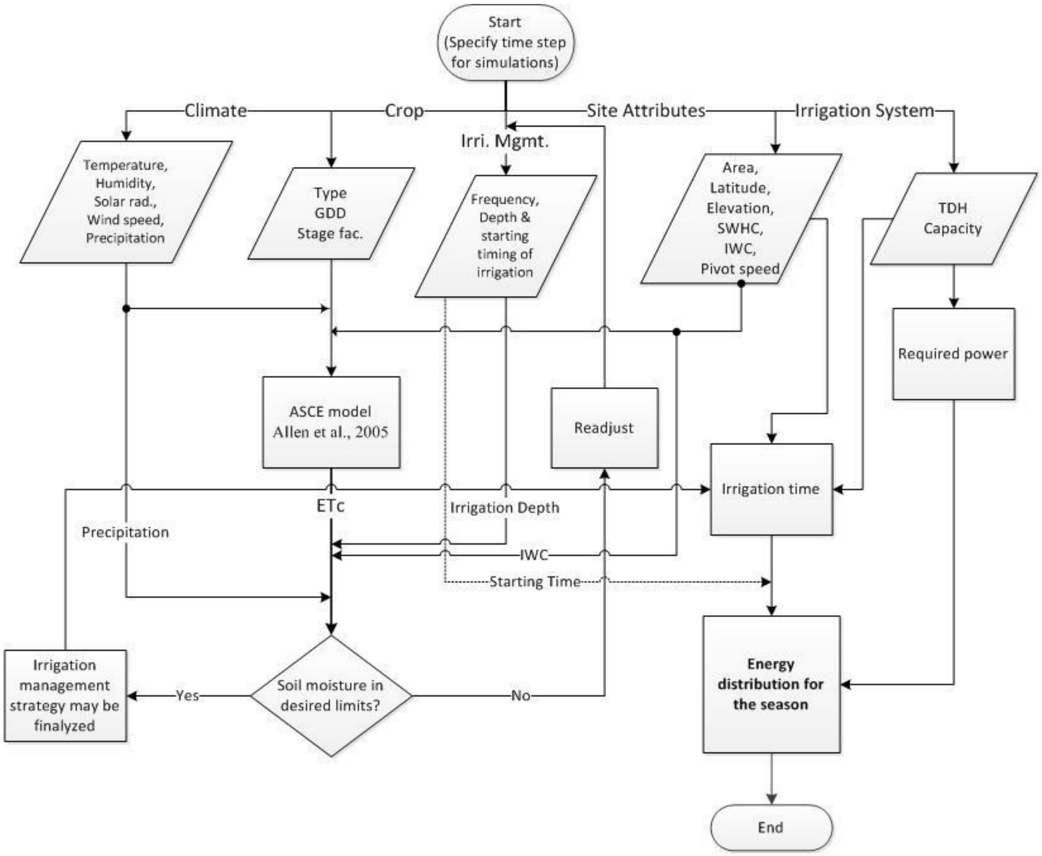


Figure 4.3. Load energy estimation model for a given environmental and operating conditions

4.4.1.3 Sub-model for Estimating Stored Energy

Energy produced by the PV panels and required by the load was incorporated with the battery specifications such as number of cells, maximum and minimum state of charge, and the battery capacity along with the climate variables (temperature) for the estimation of stored energy in the battery bank at a given time (fig. 4.4). The state of charge (SOC) of the battery was used to determine the energy stored in the battery bank at any time. The battery terminal voltage and the SOC were determined from the battery current using the Centro de Investigaciones Energeticas, Medioambientales y Technologicas (CIEMAT) model (Copetti et al., 1993). The battery current, positive when going into the battery bank and negative when flowing away from it, was determined by dividing the battery power by its terminal voltage. The battery power was assumed to be zero when the power produced by the PV array was greater than the estimated load demand and the state of charge of the battery was higher than, or equal to, its maximum. Similarly, when the SOC of the battery was below the lower limit and power required by the load was greater than the produced, battery power was assumed to be zero in the model. In all other cases, battery power was estimated by subtracting the load power from that produced by the PV array. Initial battery terminal voltage was provided as input in the model and subsequent estimations for the given time steps were made with respect to the pre-determined battery current using the CIEMAT model.

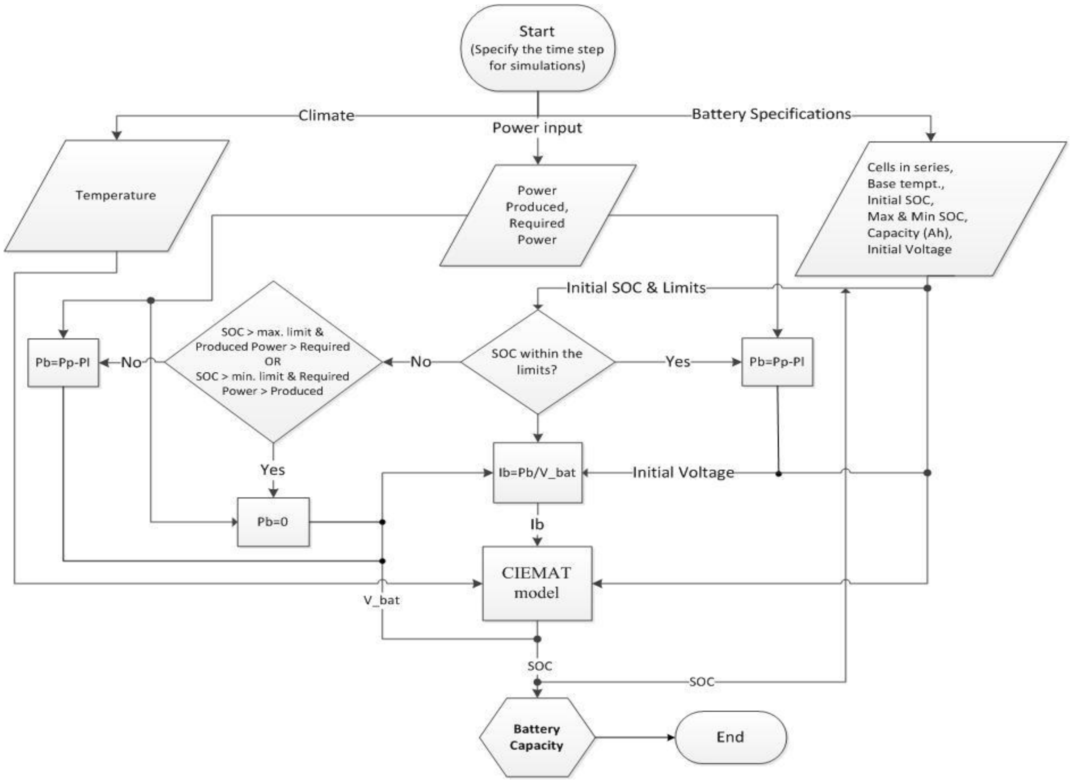


Figure 4.4. Simplified flow diagram for stored energy estimation model

4.4.2 Site Description

A 24V-DC solar-powered center pivot irrigation system installed at Outlook, Saskatchewan, Canada (51° 30’ N, 107° 03’ W) was selected as a test case for investigating the impact of irrigation management strategies on PV system sizing. The 67 m long (two tower) center pivot irrigation system could irrigate 1.4 ha area with a system discharge of 112.5 L min^{-1}. The average power required to pump the water for irrigation as well as to drive the pivot around the field was 660 W. The application efficiency of the installed irrigation system was assumed to be 80%. Each solar panel installed at the site was 200 W @ 12V and battery capacity was 240 Ah @ 6V. The panels and batteries were wired in series to produce the desired voltage of the system. The system was analyzed considering the crop water requirements of canola. The maximum available water for the soil was estimated as 220 mm based on its texture and root-zone depth of the growing crop. The growing season of the canola crop was considered from May 16 to August 31 and the initial soil moisture was assumed to be 65% maximum available water.

4.4.3 Irrigation Management Strategies and Battery Sizing

Two irrigation management strategies were evaluated in terms of PV system sizing requirement to achieve the desired reliability of the system for the study site using 2008 and 2012 weather data: (i) moderate depth with low frequency and (ii) light irrigations with high frequency. In the former strategy, 30 mm of water was applied each time that the soil moisture was depleted to 65% of maximum available water of the soil whereas in the later strategy 5-8 mm irrigation per application was planned, based on the daily crop water requirement, for the same soil moisture depletion level. The irrigation event could be linked with the availability of sufficient produced energy for both the strategies, which could be assessed by either evapotranspiration or directly through received solar irradiation. The selection of the evaluation years was based on exploring reliability variation potential for a wet (2012 with 220 mm effective precipitation during the crop growing season) and a relatively dry year (2008 with 90 mm effective precipitation). In the frequent light irrigation management strategy, the initial soil moisture was raised to the desired level by applying irrigations that exceeded the daily crop water requirements (6-7 mm against 2-3 mm) at the beginning of the season. The water application depths for both the strategies were chosen in order to explore a good extent of PV size difference for these altered irrigation management strategies, however, it may vary for different crop choices and locations considering various agronomic, irrigation system and environmental factors. In both strategies soil moisture was maintained within the desired limits for a certain level of reliability so it was assumed that the crop yield will remain the same for both the management schemes.

The energy storage (batteries) is the most expensive component of the PV system so it was planned to select the minimum possible battery capacities for both the strategies and panel sizing was varied to achieve the desired reliability of the system. Variation of the applied irrigation depth with time required for one pivot revolution for the installed system is explored in figure 4.5. It can be seen from the figure that the maximum irrigation depth application for the frequent light irrigation management strategy may require about 16 hours of system operation which could be carried out during the day when solar energy was available. Therefore, small battery capacity (360 Ah) was selected for this strategy, which was sufficient to supplement the produced energy during the day and to successfully operate the system for some hours in the absence of sunlight. The minimum time for full rotation time of the installed system considering its maximum rotational speed was estimated as 7.7 h in which 3.7 mm water could be applied. In the conventional irrigation management strategy, 25-35 mm water was applied when the soil moisture depleted to a certain level. The time required to apply this irrigation depth with the installed system discharge was about 3 days, indicating that night irrigations had to be practiced in this strategy. Therefore, larger battery sizing was required to ensure the successful operation of the system and battery capacity was elevated to 900 Ah for this strategy.

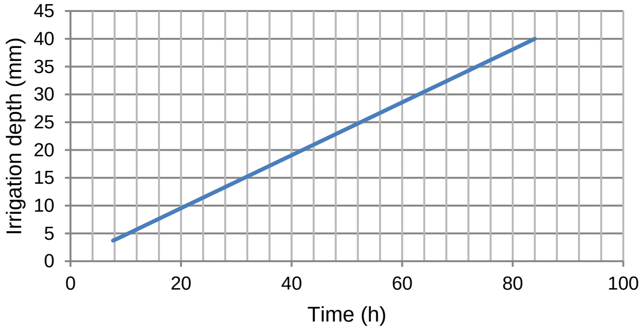


Figure 4.5. Center pivot operation time for applying desired depth of irrigation

The reliability assessment model was used for both selected irrigation management strategies to determine the required panel sizing for achieving the desired reliability. The required weather data for model simulations which includes temperature, relative humidity, wind speed, incoming solar irradiation, and precipitation for daily and hourly time steps was acquired from the nearby weather site (approximately 200 m). The hourly incoming solar irradiation, required to estimate produced power from the solar panels, was not available for the year 2008.

An estimate of hourly radiation was made from the average daily radiation using Shook and Pomeroy (2011). The measured solar irradiation, which is that received on a horizontal plane, was corrected for the slope of solar panels (35°) using the methods of Allen et al. (2006).

The installed center pivot had a system capacity of 79.3 L min^{-1} ha^{-1}. The system capacities are designed based on either seasonal irrigation depth or peak consumptive use considering soil moisture reserves, precipitation, irrigation period, additional water requirement (leaching), and water application efficiency. The calculated system capacity determines the minimum discharge for a unit area required to apply the estimated depth of water during the season. However, system discharge may be varied to apply the requisite depth of irrigation in the desired time span. Since the solar power production may significantly vary throughout the day, choosing the appropriate system discharge may be beneficial in applying required depth of irrigation during the preferred times of irrigation. Therefore, both the selected irrigations management strategies were further investigated with different combinations of irrigation system discharge to operate the system within a desired time (10-14 h, day time and 20-24 h, day and night time) for applying the desired depth and an appropriate choice was identified by exploring its impact on PV system sizing. The day time irrigation was started at 07:00 A.M.

4.5 RESULTS AND DISCUSSION

Simulated soil moisture status during the crop growing season for the selected irrigation management strategies using the 2008 and the 2012 weather data for a 100%, 90% and 80% reliable PV system are shown in figure 4.6. The top horizontal line in the figure indicates the maximum available water limit whereas the bottom horizontal line represents irrigation threshold which depends upon the maximum allowable deficit of the soil moisture for the selected crop. The soil moisture in between these two limits is considered as readily available to the plants for their consumption. The comparison of the soil moisture curves simulated for the conventional and the frequent light irrigation management strategies for both the years reveals that the soil moisture may be maintained within the desired limits even for an 80% reliable PV system under both the strategies for 2012. However, greater than 90% reliable PV system may be required to maintain the soil moisture within the desired limits for 2008 based on the prescribed operating conditions. The difference is caused by the larger seasonal irrigation depth required during the relatively dry 2008 growing season.

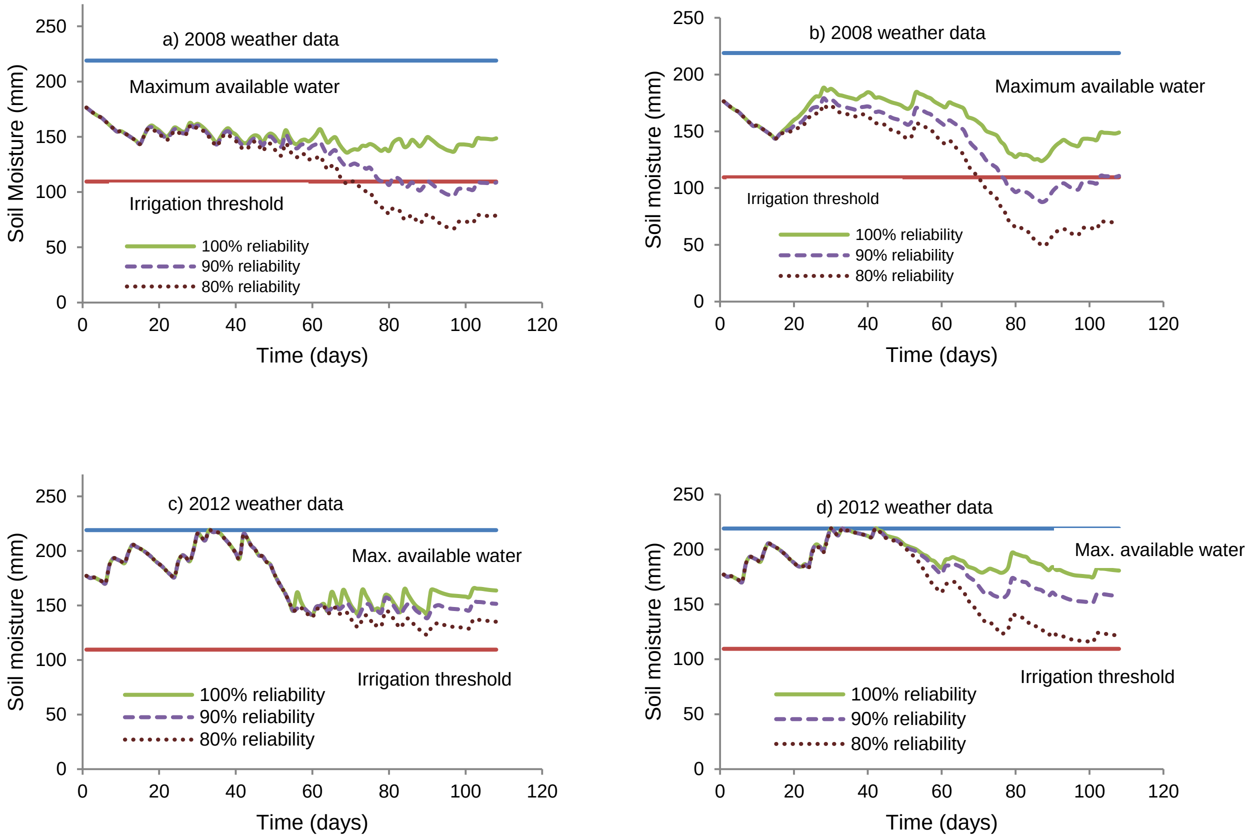


Figure 4.6. Soil moisture status with respect to PV system reliability for (a and c) conventional moderate depth, 25-35 mm (b and d) frequent light irrigations, 5-8 mm management strategies

The system reliability is determined based on its capability for providing power to the irrigation system during the suggested times of irrigation based on the adopted irrigation management strategy. Therefore, a 100% reliable system may still experience water stress if the crop’s consumptive use is not supplied by the irrigation system during its operating hours. Moreover, undesired circumstances such as repair and maintenance issues with irrigation, power production and/or the energy storage system may restrict the irrigation system operation for the pre-determined time which may cause the soil moisture to deplete below its lower limit. In contrast, it is also possible that a system with less than 100% reliability may be sufficient to maintain the soil moisture within the desired limits as shown in fig. 4.6. Therefore, a careful analysis should be carried out using historical climate data considering the irrigation system specifications and management strategy to identify and/or set the targeted system reliability. Overall, it can be said that these systems can be designed at a moderate level of reliability. The irrigation management strategy can be modified to prevent the soil moisture from falling below the threshold value. For example, in the conventional strategy, the system operates only for selected days throughout the season, so irrigation may be applied during the following days of system failure to elevate the soil moisture to the desired level. Similarly, the desired moisture level may be maintained for the frequent light irrigation management strategy by increasing the irrigation depth by modifying the system discharge to apply the increased depth during the same time of system operation.

4.5.1 PV Sizing for Selected Irrigation Management Strategies

The PV system sizing required to achieve the desired reliability for both the selected irrigation management strategies is presented in table 4.1. The system capacity (112.5 L min^{-1}) remained the same for both strategies. It can be seen that a significantly larger seasonal irrigation depth could be applied in 2008 as compared to 2012 with a similar (conventional strategy) or slightly larger (frequent irrigation management strategy) PV system sizing to achieve the desired reliability. The difference in irrigation depth may be associated with the lower precipitation received in 2008 as compared to 2012. Thus a range of seasonal irrigation depth can be applied with the same PV system depending upon the climate conditions and the adopted irrigation management strategy. A comparison of the PV system sizing requirement for both strategies indicates that a significantly smaller PV system is required for the frequent light irrigation management strategy. For example, 20 solar panels combined with a 900 Ah battery capacity are required for the conventional irrigation management strategy to achieve 100% reliability whereas a similar reliability may be achieved with only 14 solar panels combined with a 360 Ah battery capacity by modifying the management strategy with frequent light irrigations. The difference in solar panel sizing reduces for the selected strategies under moderate level of PV system reliabilities; however, battery sizing remains significantly larger for the conventional strategy. This suggests that the irrigation management strategy has a great impact on PV system sizing. Therefore, high frequent light irrigations management strategy should be adopted to optimize the PV system sizing.

Table 4.1. PV sizing requirement for the selected irrigation management strategies

Year	Targeted Reliability (%)	No. of panels		Battery Capacity (Ah)		Seasonal Irrigation Depth (mm)
		Conventional	Frequent light irrigation	Conventional	Frequent light irrigation	
2008	100	20	14	900	360	386
	90	12	10	900	360	337
	80	10	8	900	360	294
2012	100	20	12	900	360	212
	90	12	8	900	360	190
	80	10	6	900	360	156

4.5.2 PV Sizing Variation with System Capacity

The PV system sizing required to achieve the desired reliability for both the selected irrigation management strategies with the different irrigation system discharges using 2012 weather data is presented in Table 4.2. Changing the system discharge allows the irrigation system to operate within the desired time period for applying the required depth of irrigation. It can be seen from the table that the PV sizing is more sensitive to the timing of irrigation for the conventional strategy as compared to the frequent light irrigation management strategy. Battery sizing was increased when the irrigation system capacity was altered to operate the system during an entire day (20-24 h) for the conventional strategy. This is because an increase in the system discharge leads to an increase in the instantaneous power requirement and resultantly the energy requirement during times of low sunshine increases. Similarly, when the irrigation operation was restricted to day time (10-14 h) only, the battery capacity was reduced. The PV system sizing requirement for different combination of irrigation system capacities for both the strategies suggests that the optimum PV sizing can be achieved by adopting the frequent light irrigation management strategy (irrigation scheduling based on daily crop water requirement) in which water is applied during the day time system operation. When operating conditions limit the adoption of identified strategy, conventional practice may be adopted with low/minimum system discharge (system capacity) so that required irrigation depth may be applied in some consecutive days of system operation as it require considerably smaller PV sizing requirement than other choices.

Table 4.2. PV sizing comparison for alternate management strategies with different system capacities

System capacity (L min-1 ha-1)	Irrigating hours/ application	System Sizing	
		No. of Panels	Battery capacity (Ah)
Conventional (25-35 mm)			
i) 79.3	60-65	10	900
ii) 224.4	20-24	22	1200
iii) 420.1	10-14	28	480
Frequent low volume (4-8 mm)			
i) 56.1	20-24	6	420
ii) 79.3	10-14	6	360

Although the frequent light irrigations management strategy proved to be the most feasible option in terms of PV system sizing for the selected crop and climate yet its adoptability for other crops and environments needs careful consideration of the local circumstances. This is because of some crops may need very limited water during their some stages of growth, application of fertilizers, herbicides or insecticides during the growing season may restrict irrigation, and availability of resources for irrigation might not be the same for the whole season. Therefore, it is recommended to investigate different irrigation management strategies under the given climate considering any agronomic, social, managerial, cultural, and/or economic factors to identify the best irrigation management strategy for the reliable and economically viable PV system design.

4.6 CONCLUSIONS

A reliability assessment model based on the loss of power supply probability technique was employed to determine the PV system sizing requirements for conventional (moderate depth with less frequency) and frequent light irrigation management strategies. A small 1.4 ha solar powered center pivot irrigation system installed in Outlook, Saskatchewan, Canada was selected for evaluation of these strategies. Comparison of the two strategies demonstrates the significant impact of irrigation management strategy on PV system sizing. Irrigation scheduling based on daily crop water requirement (frequent light irrigations) and applying the required water during the day time proved to be most feasible choice for solar-powered center pivot irrigation system to optimize the PV system sizing. The results suggest that smaller system discharge should be used where conventional irrigation management strategy has to be adopted. However, it is recommended to consider agronomic, social, managerial, cultural and economic factors while assessing the PV system sizing for other crops and environments to finalize the suitable irrigation management strategy.

4.7 REFERENCES

Al-Kaisi, M. M., and I. Borner. 2009. Crop water use and growth stages. Colorado State University: 4.715. (http://www.ext.colostate.edu/pubs/crops/04715.html#top). Accessed on July 10, 2013.

Allen, R.G., I.A. Walter., R. Elliott., T. Howell., D. Itenfisu., and M. Jensen. 2005. ASCE Standardized Reference Evapotranspiration Equation. ASCE-EWRI Task Committee Report: American Society for Civil Engineers.

Allen, R.G., R. Trezza, and M. Tasumi. 2006. Analytical integrated functions for daily solar radiation on slopes. *Agriculture and Forest Meteorology* 139: 55-73.

Boroway, B.S., Salameh, Z.M., 1996. Methodology for optimally sizing the combination of a battery bank and PV array in a wind/PV hybrid system. IEEE transactions on energy conversion 11: 367-375.

Copetti, J.B., E. Lorenzo., and F. Chenlo. 1993. A general battery model for PV system simulation. Progress in photovoltaic: Research and Applications 1: 283-292.

Evans, R., D. K. Cassel., and R. E. Sneed. 1996. Soil, water, and crop characteristics important to irrigation scheduling. North Carolina Cooperative Extension Service: AG 452-1. (http://www.bae.ncsu.edu/programs/extension/evans/ag452-1.html).

Gergaud, O., G. Robin., B. Multon., and H. B. Ahmed. 2003. Energy modeling of a lead acid battery within hybrid wind/photovoltaic systems. SATIE- Brittany branch, ENS de Cachen- Ker Lan Campus: ISBN 90-75815-07-7.

Hobbs, E.H., and K.K. Krogman. 1978. Frequent light irrigation scheduling to improve efficiency of water use. *Canada Agricultural Engineering* 20: 109-112.

Lorenzo, E. 1994. Solar electricity engineering of photovoltaic systems. Artas Graficas Gala, Spain.

Shook, K., and J. Pomeroy. 2011. Synthesis of incoming shortwave radiation for hydrological simulation. *Hydrology Research* 42(6): 433-446.

Trimmer, W., and H. Hansen. 1994. Irrigation scheduling. Oregon State University Extension Service. http://ir.library.oregonstate.edu/xmlui/bitstream/handle/1957/15998/pnw288.pdf?sequence=1. Accessed on 20 August 2013.

5. ECONOMIC VIABILITY OF A SOLAR-POWERED CENTER PIVOT IRRIGATION SYSTEM

5.1 PREAMBLE

A model has been designed to size the PV system for a desired reliability in a given environment considering crop choice, site characteristics, irrigation system specifications, and management strategy for maintaining the soil moisture within the desired limits (chapter 3). The impact of irrigation management strategy has also been demonstrated on the PV system sizing and guidelines have been developed to identify a suitable irrigation management strategy for minimal sizing (chapter 4). The economic feasibility evaluation is considered as the integral component of any engineered design. This manuscript presents an approach for economic viability estimation and identifies the factors influencing economic feasibility. Thus, the manuscript addresses the third objective of the thesis. Therefore, a comprehensive design approach for a solar-powered center pivot irrigation system considering technical and economic feasibility evaluation has been presented by combining all the three chapters.

5.2 ABSTRACT

The economic feasibility of a solar-powered center pivot irrigation system can widely vary for different locations due to variable irrigation system specifications, crop production input and outputs, local availability of the system components, and climatic factors. Therefore, detailed investigations should be carried out for exploring its potential on a given site. The objective of this study is to demonstrate a procedure for determining the economic feasibility of a solar-powered center pivot irrigation system as well as to explore the factors influencing the system economics. A small (1.4 ha) system installed in Outlook, Saskatchewan, Canada was taken as a test case for this purpose. An appropriate PV system was designed for the selected site using a reliability assessment model and an economic analysis was conducted to determine its feasibility for different available crop choices with varying water requirements under the selected irrigation management scheme. The sensitivity of total dynamic head with PV system sizing was also studied. The results suggest that the sizing of the PV system components increases considerably for crops with higher water requirements. The PV system tends to be a more viable option for high value crops such as table potato. The total dynamic head proves to be a driving variable in influencing PV system sizing and consequently economic viability. Application of the demonstrated approach allows the economic feasibility of a PV irrigation system to be determined for any location.

Keywords: Economic feasibility, PV sizing, Reliability, Solar-powered center pivot

5.3 INTRODUCTION

The use of photovoltaic (PV) technology for generating power to utilize in sprinkler-irrigated agriculture has significant potential in areas where conventional power supplies are either unavailable or prohibitively expensive. This is because photovoltaic (PV) technology has precedent over other renewable energy resources since both power production and power requirement (crop water use) rely on solar irradiance. Photovoltaic (PV) technology has become increasingly affordable in recent decades (Pillai and McLaughlin, 2012). However, a PV system design must be shown to be reliable and economically feasible prior to its wide scale adoption. Several studies have been conducted for determining and comparing the economic feasibility of a solar-powered water pumping system with other alternate energy resources (Odeh et al., 2006; Meah et al., 2008; Kelly et al., 2010; Branker et al., 2011). However, no previous efforts have been made to determine the economic feasibility of a solar powered center pivot irrigation system.

The economic feasibility of a solar-powered center pivot irrigation system may largely vary for different locations due to variability in climatic conditions (which influences power production per panel and crop water use), crop agronomics, and market value of the selected crop. The system economics can also deviate from site to site because of factors influencing the total dynamic head (a driving variable for determining the required power), such as elevation head, friction losses in the water supply pipeline, and operating pressure of the sprinklers. Moreover, the economic viability of a solar powered pivot irrigation system may change significantly for different crop choices at the given site (due to varying crop water use as well as crop return). Therefore, a comprehensive modeling approach considering all of these factors is required for determining the economic feasibility of a solar powered center pivot irrigation system.

5.3.1 Objective

The purpose of this study is to demonstrate guidelines for evaluating economic viability of a solar-powered center pivot irrigation system using a small (1.4 ha) solar powered center pivot irrigation system installed at Outlook, Saskatchewan, Canada for growing alternative crops that have considerably different water requirements. It is further planned to explore the impact of total dynamic head on the PV system sizing and on the resulting economic viability of the system.

5.4 MATERIALS AND METHODS

5.4.1 Reliability Model

A model based on the loss of power supply probability (LPSP) technique (Borowy and Salameh, 1996) was used for assessing the reliability of the PV system sizing (panels and batteries) considering climate variables, crop water requirement, site attributes and pivot system specifications (described in chapter 3). Loss of power supply probability, an indicator of reliability of the PV system, was determined by analyzing the energy produced, stored and required assessed by the sub-models for an hourly time step for the whole growing season of the selected crop. Figure 5.1 shows the simplified flow diagram of LPSP and/or reliability estimation. Energy produced by the PV array for the given time step was estimated using a PV current and voltage model (Lorenzo, 1994) by providing solar irradiation and air temperature as an input. The instantaneous power required was estimated using the installed irrigation system specifications (total dynamic head, system capacity, and pivot drive power) and the energy requirement during the crop growing season was calculated based on irrigation system operation times. Irrigation management strategy determined the system operation timing, which is driven by the crop water requirement estimated by the Penman-Monteith approach (Allen et. al., 2005). The CIEMAT model (Copetti et. al., 1993) was used to monitor the energy storage in the battery banks. It can be seen from the figure 5.1 that the reliability of a PV powered system can be altered by varying the solar panel sizing, battery capacity and/or the irrigation management strategy inputs in the produced, stored and required energy sub-models respectively.

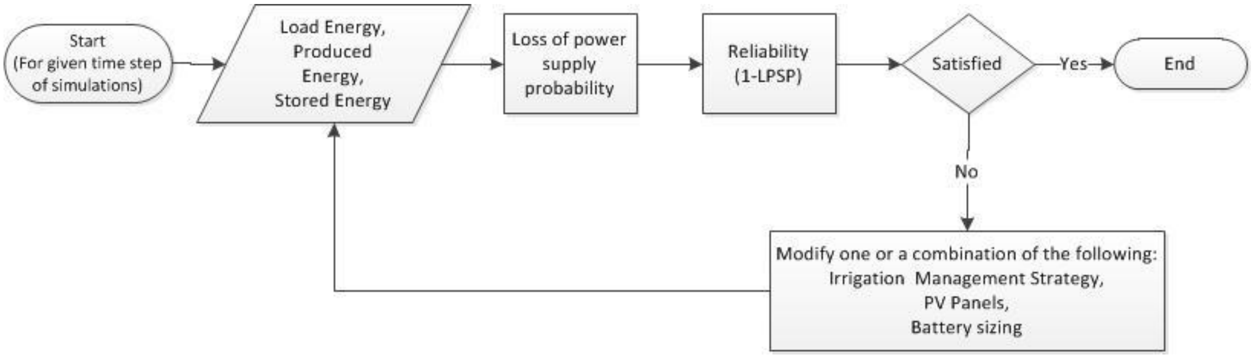


Figure 5.1. Simplified flow diagram for determining the reliability

5.4.2 Site Attributes

A 24V-DC solar-powered center pivot irrigation system installed at Outlook, Saskatchewan, Canada (51° 30’ N, 107° 03’ W), designed for the desired system reliability under given operating conditions, was selected for determining the economic feasibility of the PV system. The two tower center pivot irrigation system is designed to irrigate 1.4 ha area with a system capacity of 112.5 L min^{-1}. The average power required to pump the water as well as to rotate the irrigation system, was 650W. The application efficiency of the installed irrigation system was assumed to be 80%. Each solar panel installed at the site was 12V-200W and a total of 16 panels were installed. The total installed battery capacity was 980 Ah. However as part of the economic analysis, PV sizing will be varied depending upon the operating conditions to provide an optimum selection of system components.

5.4.3 Suitable Irrigation Management Strategy and Battery Sizing

The irrigation management strategy is a dynamic variable for distributing the load energy throughout the crop growing season for the given time step. Different strategies can be adopted to maintain the soil moisture within the desired limits i.e. in between field capacity and irrigation threshold. However, a management strategy of frequent light irrigations was demonstrated to be feasible choice for solar-powered irrigation (chapter 4). Accordingly, it was planned to maintain the soil moisture at 70% to 80% of field capacity by applying frequent low volume irrigations, based on the daily crop water requirement. For the installed system, the minimum depth that could be applied was 3.70 mm based on the maximum rotation speed. The irrigation starting time was set to be 07:00 A.M. and maximum depth was set to be 7.5 to 8 mm to restrict the system operation to less than sixteen hours i.e. till 11:00 P.M. Since batteries are the most expensive component of a PV system, night irrigations were avoided to keep the battery size at a minimum. The battery capacity was chosen as 360 Ah, which is sufficient to start the irrigation system early in the morning and to power the system for short period after sundown.

5.4.4 Operating Conditions / Procedure

Three crops with considerably different water requirements (canola, potato, soybean and/or alfalfa) were evaluated in terms of their economic viability to be irrigated with a solar powered pivot irrigation system at the selected site. This was accomplished by determining the appropriate PV system sizing requirement for each crop to provide a reliability of 80% to 90% and performing a comprehensive economic analysis on the basis of benefit-cost ratio. Seven years (2006-2012) of data was used for analysis of PV system sizing. The required climate data was taken from the nearby weather station, which includes air temperature, relative humidity, wind speed, radiation, and precipitation.

Total dynamic head is directly proportional to the power requirement for pumping and may largely influence the PV system sizing. It considers the operating head of the sprinklers, friction losses in the pipe, fitting losses, and elevation head. The sensitivity of total dynamic head to PV system sizing was evaluated at the selected site using 2012 weather data considering the crop water requirements for canola. The battery capacity for each combination of total dynamic head was chosen to store the sufficient energy for applying a few hours irrigation without sunshine.

5.4.5 Approach for Economic Analysis

A detailed economic analysis was conducted for the selected crops over the period of 20 years. The capital recovery factor (CRF) method was adopted for the purpose of amortization

(Jensen, 1980). In this approach, the single present worth value was used to determine the uniform series of annual values considering depreciation and interest over the analysis period. The annual value for the fixed cost is the product of present worth value and the CRF. Equation 1 was used to determine the CRF:

$$CRF = \frac{i\,(1+i)^n}{(1+i)^n - 1}\,, \tag{1}$$

where i is the interest rate and n is the number of years for which the cost will be incurred in the future. The present worth value for the components of a PV system that would need to be replaced during the period of analysis was estimated using equation 2:

$$PW_r = \frac{S}{(1+i)^n}\,, \tag{2}$$

where S is the present cost and other parameters have already been defined. Following the recent trend of reducing prices for PV system components, it was assumed that no escalation will occur over this analysis period. The annual cost was calculated based on present worth value of the investment for the PV powered system and the center pivot was then combined with the variable costs associated with the crop production (seed, fertilizer, insecticides, pesticides, herbicides, water charges, crop insurance). The price escalation effect in determining the variable costs was considered using equation 3 to determine the equivalent annual cost (EAC_r):

$$EAC_r = S\left(\frac{(1+r)^n - (1+i)^n}{(1+r)-(1+i)}\right)\frac{i}{(1+i)^n - 1}\quad, \tag{3}$$

where r represents the escalation factor.

5.4.6 Assumptions for Economic Analysis

The economic analysis was carried out based on 5% interest rate. The prices for different components were based on the current market prices near the installed site which has great potential for variation with time and location. The life of the PV system components such as solar panels, batteries, controller and pump was assumed to be 25, 8, 20 and 10 years respectively. The center pivot irrigation system life was assumed to be 30 years. The mounting and wiring accessories and transportation costs were assumed to be 10% and 5% of the PV system capital cost respectively. Salvage value for the PV system components as well as for the pivot system was determined by the straight line method. Annual inflation of 2% was assumed for the crop production variable inputs such as seed, fertilizers, pesticides, insecticides, fungicides, herbicides, water charges, equipment fuel, maintenance, and crop insurance. The system benefit was obtained from the revenue generated by the crop production based on its market price. Average and targeted crop yield along with their market prices as well as crop production input requirements were taken for the study site (Irrigation Crop Diversification Corporation, 2013). It was assumed that crop revenue will be increased by 3% annually.

5.5 RESULTS AND DISCUSSION

5.5.1 PV Sizing Variability with Crop Consumptive Use

Crop consumptive use depends upon climate variables and crop stage. Therefore, it varies with different crop choices under a given climate. The PV sizing (solar panels) variability with crop consumptive use to achieve 80% to 90% reliable system with a fixed battery capacity of 360 Ah is explored in figure 5.2 using 2012 climate data. It can be seen from the figure that the system sizing is proportional to the crop water requirement. For example, when crop consumptive use increased from 160 to 360 mm, PV sizing requirement increases from 6 to 10 solar panels. It should be noted that, in this example, the crop consumptive use was increased by altering the crop coefficient, while keeping the days for different growth stages the same.

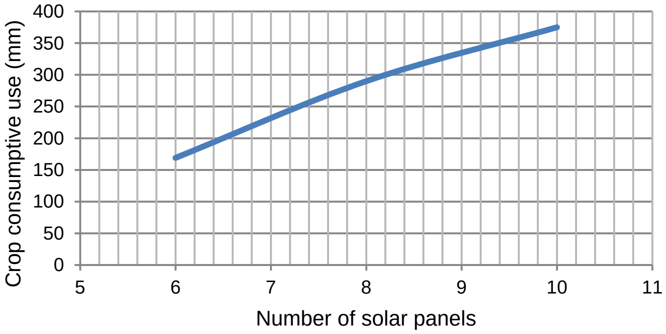


Figure 5.2. Solar Panel (200 W @ 12 V) sizing variation with crop consumptive use

5.5.2 PV System Sizing Variability with Total Dynamic Head

The system capacity and total dynamic head are the driving variables in determining the load demand thus their variability may have a large influence on the PV system sizing. System capacity may be kept constant for different locations but there is a great potential that total dynamic head will vary due to different water sources depth, frictional losses, operating pressure of the sprinklers, elevation head and fitting losses. The sensitivity of total dynamic head with respect to PV system reliability determined for canola using 2012 climate data for the selected site (six 200 W @ 12 V solar panels and 360 Ah battery capacities) is shown in figure 5.3. It can be seen from the figure that the total dynamic head has a significant effect on the PV system reliability. The reliability of the PV system reduces by about 5% to 10% with an increase in TDH by 10 m.

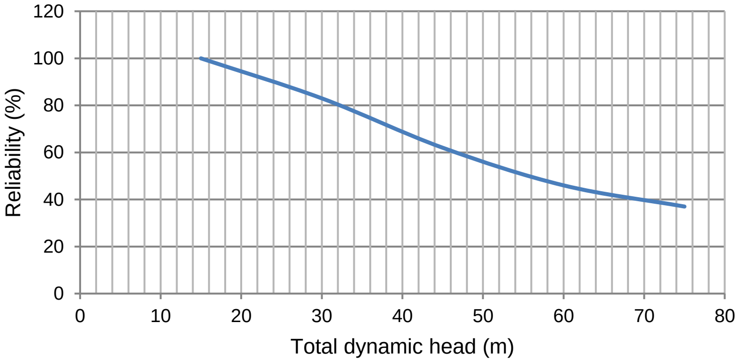


Figure 5.3. Reliability variation with total dynamic head

The PV system sizing required to achieve more than 90% reliability for different combinations of total dynamic head using 2012 weather data is shown in table 5.1. The instantaneous power requirement increases with increase in total dynamic head, therefore, battery capacity was increased to store sufficient energy to operate the system on battery storage alone for some hours. It can be seen from the table that the system size increases with the increase in TDH. For example, the increase in TDH from 15 m to 45 m results in about 2.6 times increase in PV sizing (both battery and panel sizing) to achieve the same reliability of the system.

Table 5.1. PV system sizing variation with total dynamic head

Total dynamic head (m)	Battery capacity (AH)	No. of panels (@12V-200W)	Reliability (%)
15	200	4	91.5
30	360	8	95.8
45	540	10	91.2
60	660	14	93.7
75	840	16	90.8

The great influence of TDH on PV system sizing suggests that attempts should be made to minimize it for economically viable system design. This can be achieved by using appropriate diameter of the pipeline for the given system capacity to minimize the frictional losses and selecting the sprinklers which are operated at minimum pressure.

5.5.3 Economic Analysis

The economic analysis carried out for the selected PV system, irrigation system and crop production factors considering canola is shown in table 5.2. The benefit-cost ratio for the targeted and averaged yield indicates that the system is economically viable over the period of twenty years operation. However, high capital investment is required at the beginning as can be seen from the fixed cost. The system will pay back the initial investment along with the crop production costs within 5-6 years for the targeted yield and 7-8 years for an average yield. Economic feasibility of the PV system can vary significantly from site to site due to climate variations and market prices for the produced crop. Therefore, a comprehensive economic analysis should be carried out for each individual site. In addition, the economic viability may vary for a given site with respect to the selected crop to be grown under a PV powered irrigation system. This is because PV system sizing and crop returns are the driving variables in determining economic feasibility and both vary from crop to crop (Appendix C) due to different water requirements and market value.

Table 5.2. Economic analysis for canola crop to be grown under solar powered pivot irrigation system in Outlook, SK

Particular	Unit	Quantity	$/unit	Net Price ($)
Fixed cost				
PV System				
PV panel (200W @ 12V each)	No.	8	350	2800
Solar battery (120 Ah @ 12V each)	No.	3	300	900
Battery replacement (2 times)	Lump sum	-	-	1218
Charge controller	No.	2	600	1200
Solar pump	No.	2	200	400
Pump controller	No.	2	150	300
Replacement (pump+controller)	Lump sum	-	-	335
Mounting and wiring accessories	Lump sum	-	-	715
Transportation	Lump sum	-	-	358
Salvage (panel, battery)	Lump sum	-	-	712
Annual solar system cost				603
Irrigation system				
Center pivot	No.	1	-	5000
Salvage (Pivot)	Lump sum	-	-	1667
sub-total				*10847*
Depreciation and interest on capital	Lump sum	-	-	870
Variable cost				
Seed (with treatment if required)	ha^{-1}	-	142	234
Fertilizer	ha^{-1}	-	321	529
Herbicide	ha^{-1}	-	15	24
Insecticide	ha^{-1}	-	0	0
Funjicide	ha^{-1}	-	62	102
Equipment (fuel+repairment)	Lump sum	-	-	33
Irrigation service/water charges	ha^{-1}	-	67	110
Crop insurance	Lump sum	37	35	57
Annual system cost				**1959**
Return				
Targeted yield	kg ha^{-1}	3963	0.2	4022
Average yield	kg ha^{-1}	3114	0.2	3010
Benefit-Cost Ratio				
Targeted yield				**2.1**
Average yield				**1.5**

5.5.4 Crop Variability and Economic Feasibility

The optimum PV system size and the benefit-cost ratio for the chosen crops is presented in table 5.3. It should be noted that the crop return was the highest for the table potatoes whereas it was slightly higher for the canola crop as compared to the soybean based on market research data. It can be seen from the table that the high value crops such as vegetables (table potato) provide the most economical solution for solar-powered pivot irrigation system. Comparison of economic feasibility for canola and soybean suggest that crops with less water requirements (canola, 444 mm) as compared to those with high water requirements (soybean, 630 mm) should be given preference for solar-powered irrigation if their returns are not varied significantly. This is because with increase in crop water requirement (from canola to soybean), PV sizing greatly increases (8 to 16 panels) to achieve the same reliable systems (85% to 95%) causing the system to become less economically viable.

Table 5.3. Economic feasibility for different crops for solar powered pivot irrigation system

Crop	Water requirement (mm)	No. of panels	Reliability (%)	Irrigation (mm)	Load energy (KWH)	Benefit-cost ratio
Canola	444	*8*	85-95	285	211	2.0
Table Potato	554	*12*	85-95	394	283	4.4
Soybean	630	*16*	85-95	471	344	1.2

5.6 CONCLUSIONS

A reliability assessment model considering climate conditions, crop choice, irrigation management strategy, irrigation system specifications, site attributes, and PV system sizing was used to design a solar-powered center pivot irrigation system in Outlook, Saskatchewan, Canada. An approach for determining the economic feasibility of the PV powered center pivot system was described. The PV system, center pivot, and crop production parameters which need to be considered in the economic analysis were presented. The impact of different crop choices with variable water requirements on PV system sizing was investigated and it was found that the capital requirement increases considerably for crop having high water requirements (500-600mm). However, economic feasibility is also largely influenced by the crop return. Therefore a vigilant economic analysis considering different available crop choices should be conducted for solar-powered pivot irrigation at the location of interest. The results suggested that the PV sizing is also very sensitive to total dynamic head. Thus appropriate measures should be taken to keep it at minimum for an economically viable PV system design.

5.8 REFERENCES

Allen R.G., I.A. Walter., R. Elliott., T. Howell., D. Itenfisu., and M. Jensen. 2005. ASCE standardized reference evapotranspiration equation. ASCE-EWRI Task Committee Report: American Society for Civil Engineers.

Boroway, B.S., Salameh, Z.M., 1996. Methodology for optimally sizing the combination of a battery bank and PV array in a wind/PV hybrid system. *IEEE Transactions on Energy Conversion* 11: 367-375.

Branker, K., M.J.M. Pathak., and J.M. Pearce. 2011. A review of solar photovoltaic levelized cost of electricity. *Renewable and Sustainable Energy Reviews* 15: 4477-4482.

Copetti, J.B., E. Lorenzo., and F. Chenlo. 1993. A general battery model for PV system simulation. *Progress in photovoltaic: Research and Applications* 1: 283-292.

Jenson, M.E. 1980. Chapter 3: Farm resources and system selection. In *Design and Operation of Farm Irrigation Systems*, 55-69. J.A. Basselman. Michigan: American Society of Agricultural Engineers.

Kelly, L.C., E. Gilbertson., A. Sheikh., S.D. Eppinger., S. Dubowsky. 2010. On the feasibility of solar-powered irrigation. *Renewable and Sustainable Energy Reviews* 14: 2669-2682.

Lorenzo, E. 1994. Solar electricity engineering of photovoltaic systems. Artas Graficas Gala, Spain.

Meah, K., S. Fletcher., S. Ulah. 2008. Solar photovoltaic water pumping for remote locations. *Renewable and Sustainable Energy Reviews* 12: 472-487.

Odeh, I,. Y.G. Yohanis., and B. Norton. 2006. Economic viability of photovoltaic water pumping systems. *Solar Energy* 80: 850-860.

Pillai, U. and J. McLaughlin. 2012. Polysilicon price declines and solar grid parity. College of Nanoscale Science and Engineering: University at Albany, SUNY. http://www.industrystudies.pitt.edu/pittsburgh12/documents/7.2%20-%20Pillai%20(Slides).pdf (accessed on May 12, 2011).

6. DISCUSSION

The main purpose of the study is to develop an approach for determining the technical and economic feasibility of a solar-powered center pivot irrigation system in a given environment. Three chapters have been presented which individually address the different aspects of a solar-powered center pivot irrigation system design and provide a holistic approach to achieve the pre-defined goal of the study, when combined. The first manuscript (chapter 3) defines an approach for determining the technical feasibility of the selected PV system. A reliability assessment model is developed for the purpose and demonstrated for a site located at Outlook, Saskatchewan, Canada. The PV system sizing (solar panels and battery capacities), climate data, pivot specifications, selected crop information, site characteristics, and irrigation management strategy are provided as input in the model and PV system reliability is predicted. The PV sizing is adjusted to achieve a certain level of reliability for designing a technically feasible system. The second manuscript (chapter 4) identifies a suitable irrigation management strategy for reducing the PV system size. Thus, an optimum PV system can be designed for a given environment, by adopting the procedures and guidelines presented in these two manuscripts. The third manuscript (chapter 5) demonstrates an economic feasibility evaluation technique which considers the irrigation system (center pivot), power production through PV technology, and crop production factors. Therefore, a technically feasible and economically viable PV system for powering a center pivot can be designed by combining all of these manuscripts. The results pertaining to each manuscript have been discussed in depth in their respective sections. However, since the results were derived from the selected study site (1.4 ha), a general discussion is still needed for identifying the technological constraints associated with up-scaling of the systems as well as for recognizing the factors influencing the application of the technology in other locations.

6.1 UPSCALING CONSTRAINTS

It has been identified that the frequent light irrigations management strategy, in which water is applied during the day light hours (10-14 h) is the best choice for optimum sizing of a solar-powered center pivot irrigation system (chapter 4). A small irrigation system of 1.4 ha was evaluated for demonstration. The increase in irrigable area will result in increasing volume of water required for an irrigation event to apply the desired irrigation depth. Therefore, the system flow rate will have to be increased for scheduling the irrigation event within the desired time (10-14 h), which will lead to higher power requirements for pumping water. Figure 6.1 demonstrates the linear relationship between the irrigated area and system flow rate. Since the pumping power requirement is largely depend upon the irrigation system flow rate and total dynamic head so a linear increase in power requirement may be anticipated with increase in area assuming the total dynamic head constant. The total head can be kept in desired range by varying the pipe diameter.

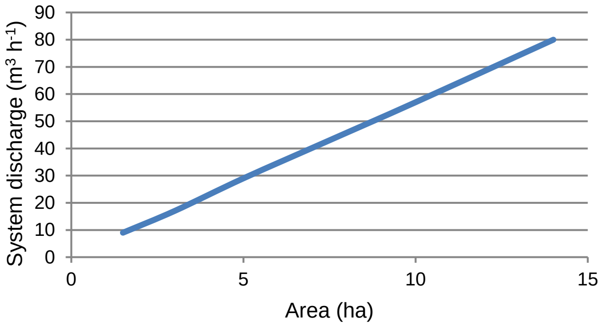


Figure 6.1. System discharge and irrigated area

Solar water pumps with DC power input may be used for moderate level of system flow rates (up to 80 m^3 h^{-1}). The further increase in system flow rate may require utilizing solar powered AC pumps due to higher power requirements. Inverters are used to convert PV DC supply into AC, and 10% to 20% power may be lost in this conversion. Alternatively DC parallel pumping systems having their own power production and storage systems may be used for the given center pivot. However, it may result in increasing system cost and complexity. Battery capacity requirement for larger irrigated areas will also increase to ensure safe operation of the system which may lead to uneconomical system design. This discussion shows that up-scaling of the system may raise several constraints; however, their significance may vary from site to site.

6.2 TECHNOLOGY TRANSFER

The potential of photovoltaic (PV) technology for operating a center pivot irrigation system is determined by its economic feasibility or profitability, which can be quantified by the benefit-cost ratio determined for the period of analysis. The economic viability is greatly influenced by the input cost associated with the power generation, center pivot, and crop production system components as well as by the crop return. Therefore, a significant variation in application potential of the technology may be observed for different regions around the world. The following sections describe some of the major factors that may influence the application potential of the PV technology with center pivot irrigation system.

6.2.1 Factors Affecting Power Generation Cost

Meteorological Variation

Power produced by the PV panel is exclusively driven by the climate variables such as solar irradiance and ambient temperature. The solar irradiance integrated for a given time is most commonly quantified as sun-hours. One sun-hour represents 1 KWH m^{-2} day^{-1}. The potential for solar powered pivot irrigation is directly proportional to the sun-hours. Since the sun-hours vary considerably for different seasons (summer and winter), for example, the average daily sun-hours for Saskatchewan vary from 10.3 to 2.9 hours for the month of July and December respectively (fig. 6.2).

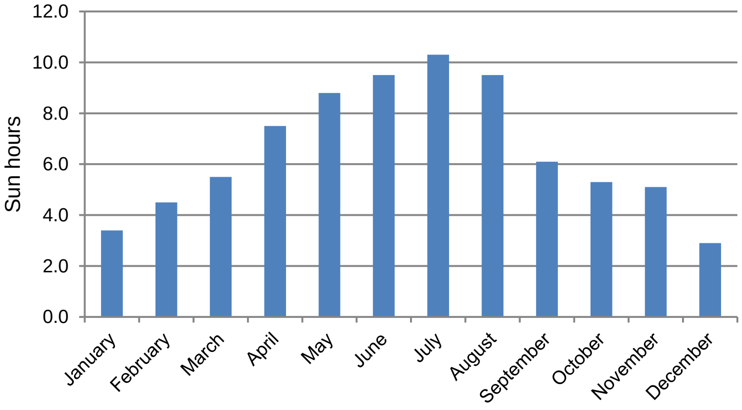
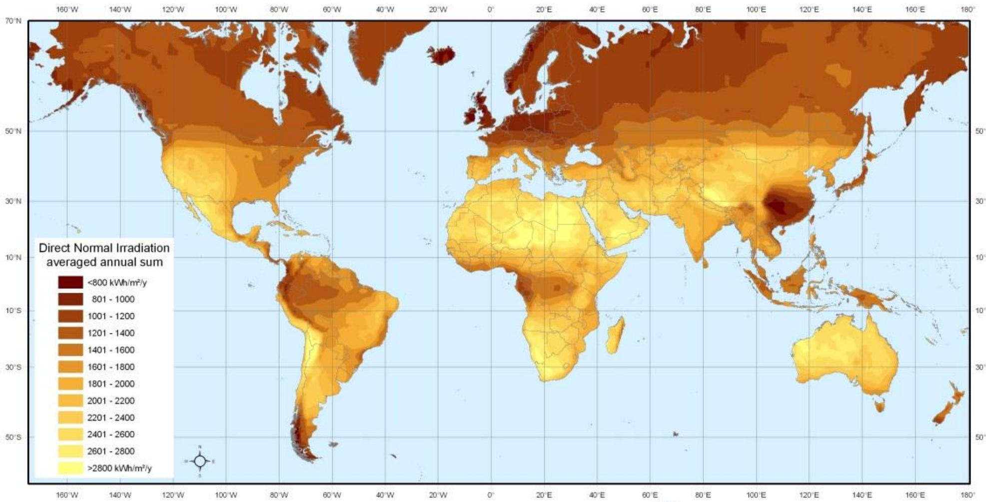


Figure 6.2. Average daily sun-hours for Saskatchewan based on 1970-2000 climate data

(http://www.currentresults.com/Weather/Canada/Saskatchewan/sunshine-annual-average.php Accessed on September 17, 2013)

The incident solar irradiation varies significantly in different parts of the world (fig.6.3). Therefore, power produced by the selected panels will vary substantially resulting in varying economic viability in the regions where favorable weather conditions exist and different crops are grown throughout the year. Low water requirement crops may be chosen during the winter and moderate to high water requirement crops for the summer in order to efficiently utilize the PV technology. The comparison of average annual irradiation (fig 6.3) indicates that South Asia has more solar-powered irrigation potential than Canadian prairies as it receives 1800-2200 KWh m^{-2} y^{-1} against 1200-1400 KWh m^{-2} y^{-1}.



Data based on NASA SSE 6.0 dataset for a 22-year period (July 1983 - June 2005)
(http://eosweb.larc.nasa.gov/sse/)

Map created and map layout by DLR 2008
(http://www.dlr.de)

Figure 6.3. Average annual irradiation world map (source: NASA 2008)

Selection of Power Production Components

Various techniques have been identified and developed to improve the performance of a solar panel. Some of the techniques include tilting the fixed panels at some suitable angle or utilizing tracking algorithms. Tracking systems have been further classified as single and dual axis. The power collection efficiency of a panel can be improved by 5% to 10% using fixed tilt approach and by 10% to 40% by using trackers. The general recommendation for the tilt angle is the site latitude plus 15° in winter and latitude minus 15° for the summer season, facing south if the site is in Northern hemisphere. Trackers are relatively new technology and fairly expensive, therefore, a careful economic analysis should be carried out for deciding whether adding more panels or utilizing tracking technology is more economical.

6.2.2 Load Management

Since power production by the PV panels is characterized by the climate, it cannot be controlled for the given site. However, the overall potential of the PV powered pivot irrigation can be increased by reducing the power requirement through adopting appropriate load management strategies. The instantaneous power determined from the system capacity, total dynamic head, and pivot drive motor specifications, is distributed in a given time frame according to selected irrigation management strategy. The total dynamic head and thus the power requirement can be reduced by using low pressure sprinklers and appropriate diameter pipelines. The results suggest that the frequent light irrigation management strategy requires a much smaller PV system as compared to the conventional, less frequent high volume management strategy (chapter 4). Therefore, the potential of the technology will vary depending upon the possibility of adopting the identified irrigation management strategy. Several site specific issues such as water accessibility, soil characteristics, crop water demand and sensitivity to different stages of growth, application of fertilizers, insecticides, fungicides, herbicides, and availability of labor may act as barriers in implementation of the identified strategy. However, it is suggested to adopt as frequent light irrigation management strategy as possible with the day time irrigations to efficiently consume the produced power.

6.2.3 Cropping Pattern

Cropping choices for the given site is one of the main factors influencing the potential for adoption of solar powered center pivot irrigation system. It has been demonstrated (chapter 5) that the economic viability can substantially be improved by considering high value crops with low water requirements for solar powered irrigation based on the identified frequent light irrigations management strategy. Therefore, low value crops with relatively high water requirements should be given least preference. The technology may particularly be well suited to areas where multiple crops can be grown in the same year.

6.2.4 Financial Feasibility

In the economic feasibility evaluation, the project cost is distributed uniformly for the analysis period whereas in the financial feasibility evaluation actual annual cost and expected returns are compared. Therefore, a project may be economically feasible but financially unviable based on the development cost and cash flow considerations. In the case of solar powered pivot irrigation, high investment is required initially which curtails its financial feasibility. For example, installing a 1.4 ha solar-powered pivot irrigation system in Outlook, Saskatchewan, Canada; designed to meet the crop water requirements for canola and similar crops requires about $ 12,000 (chapter 5). Based on the targeted crop yield, 5 to 8 years may be required by the system including the variable costs to payback the investment. However, a decrease in crop yield may be observed due to undesired conditions, thus lengthening the total payback time. It should be noted that the economic feasibility of the system may be improved by the increase in irrigated area as the pivot cost reduces substantially for larger areas. Conversely, financial feasibility may become a more serious issue due to increase in initial capital investment caused by the subsequent increase in PV power production and storage system components. Available finance resources such as bank loans, government subsidies, and other profit sharing business opportunities along with their policies may be considered as the crucial factor in determining the financial feasibility of a solar-powered center pivot irrigation system in a given region. Therefore, the potential for application of the technology may considerably vary for different locations based on the available options for financing the project.

7. CONCLUSIONS

A comprehensive approach, for simulating an off-grid irrigation PV powered system (solar panels and storage batteries) is needed to accurately evaluate the potential of solar-powered center pivot irrigation system in a given environment. Accordingly, a model has been developed for assessing the reliability of the PV system to provide the required power considering variable operating and meteorological conditions (objective 1, chapter 3). The variability of the PV system sizing was studied for alternate irrigation management strategies using the developed model for achieving the desired reliability in order to identify the best management practice (objective 2, chapter 4). A procedure describing the economic feasibility evaluation was also presented with a case study to demonstrate the appropriate process (objective 3, chapter 5).

The developed reliability assessment model requires climate data (solar irradiance, ambient temperature, wind speed, maximum and minimum relative humidity, and precipitation), crop information (days of maturity, growing degree days, crop stage factor, and root-zone depth), soil profile (water holding capacity, initial soil moisture), irrigation system specifications (system capacity, total dynamic head, pivot drive power), irrigation management strategy (frequency, depth and starting time of irrigation), and PV system sizing characteristics (panels with power rating, and battery bank capacities) as an input and predicts the system reliability based on loss of power supply probability. The functioning of the model was validated with the actual data acquired from the site installed at Outlook, Saskatchewan, Canada and an excellent agreement was found (NRMSE= 0.027 for battery current).

The PV system sizing requirement for two alternate irrigation management strategies, conventional and frequent light irrigations, was determined and compared on the study site. In conventional irrigation management strategy, 25-35 mm water was applied when soil moisture depleted to 65% of maximum available water whereas 5-8 mm was applied in frequent light irrigations management strategy. The results suggest that significantly larger PV sizing (panels and batteries) is required for the conventional irrigation management strategy. This may be associated with greater power requirement for applying larger depths. Therefore, attempts should be made to adopt the frequent light irrigations management strategy based on daily crop water requirement for minimizing the sizing and increasing the potential for adoption of the PV technology in irrigation sector. However, any agronomic, soil, environmental and managerial constraints ought to be taken into account for selecting the irrigation depth for this strategy.

An economic feasibility evaluation technique using the capital recovery factor was described that considers capital investment costs and variable costs associated with power and crop production system components (chapter 5). The potential of solar-powered pivot irrigation for three crops that have varying water requirements (canola, table potato, and soybean) was determined using the developed reliability assessment model and described economic feasibility estimation method. The results suggest that the potential of solar powered pivot irrigation can be dictated by the crop choice. Hence, high value crops should be selected for solar-powered irrigation and preference should be given to crops with low water requirements for choosing a crop of similar return. Furthermore, it has been demonstrated that the increase in total dynamic head may significantly escalate the PV system sizing. Therefore, efforts should be made to minimize the total dynamic head which can be achieved by using the appropriate water pipeline and choosing the sprinklers operated at minimum pressure.

A solar-powered center pivot irrigation system may be precisely evaluated in terms of its reliability and economic viability for any given location using the developed reliability assessment model customized for the site specific operating (PV sizing, irrigation system specifications, management strategy chosen in the light of recommendations i.e. frequent light irrigations) and meteorological conditions considering the crop selection and minimizing the total dynamic head guidelines. The holistic approach has a great potential for its worldwide adoption due to ever growing interest in replacing conventional non-renewable energy resources application in irrigation sector with environment friendly PV technology, which is becoming increasingly affordable. Since the potential of a solar-powered pivot irrigation system is limited by the high initial cost causing financial difficulties during the payback period of the system. Therefore, policies for providing loans on easy conditions and installments, insuring crops, and giving subsidies by the government agencies may prove very beneficial to cope with the challenge. The financial support by the government will help in rapidly promoting the long lasting, environment friendly, and reliable renewable energy technology application in irrigation sector.

8. RECOMMENDATIONS

Long term historical climate data should be used in assessing the technical feasibility of a solar-powered center pivot irrigation system. The developed reliability model may be used in evaluating the technical feasibility of the system. Considering the significant influence of an irrigation management strategy on PV system sizing (chapter 4), efforts should be made to adopt frequent light irrigations for optimum selection of PV system components. The system should be designed at moderate level of reliabilities aiming to maintain the soil moisture at 65% to 75% of maximum available water for appropriate sizing and keeping the soil moisture in desired limits. System discharge should be selected for the suggested irrigation management strategy in a way to apply the desired depth during the sun-shine hours (day time). The minimum instantaneous power can be selected by reducing the total dynamic head at the minimum level possible. Therefore, low pressure sprinklers should be chosen. In addition, high value crops with low water requirements should be selected to grow under solar-powered irrigation for generating more benefit.

The appropriate sizing of a PV system for providing power to a center pivot irrigation system is tied in with considering long term climate variations. The PV system performance may either be evaluated for each year of historical climate data or only one simulation can be made by providing the predicted climate variables based on the historical data treatment. Currently, data treatment for predicting the climate variables based on probability distribution is not incorporated in the model. However, induction of such models may further improve the performance or easiness and resultantly adaption of the reliability model. Therefore, further work may be carried out in this direction to include accurate models for predicting the involved climate variables based on the analysis of historical data.

Appendix-A

Reliability estimation model for PV powered center pivot

Table of Contents

Written by "Hafiz F Ahmed" on November 1, 2012 Last updated July 15, 2013
Reliability Determination model for PV system

Input Parameters

```
%INPUT PARAMETERS FOR DETERMINING THE LOAD ENERGY
load('ET_data.mat');

%{
This file includes Day, Month, Year,temperature & humidity(max and min), solar
radiation, and wind speed.
Elements name as: Day, Month, Year, Tmax, Tmin, U, RHmax, RHmin, Precp and SR
temperatures = C, Solar radiation = KJ/m2/day, wind speed = km/day
%}

Cn(1:length(Tmax),1)=1600;
Cd(1:length(Tmax),1)=0.38;
%{
These constants depend upon the crop type
Alpha Alpha
Cn=1600 Cd=0.38
Grass(small)
Cn=900
Cd=0.34
%}
z(1:length(Tmax),1)=482; % elevation of the site in m
Latitude(1:length(Tmax),1)=51.91; % degrees
GDDC=[0;90;610;850;1100];
%{
Growing degree days required by the crop for its maturity, first two entries are
for initial stage, followed by crop development, middle, and late or harvest
stage, similarly Kc values are given below
%}
Kc=[0.35;0.35;1.15;1.15;0.35];
CWi(1:length(Tmax),1)=zeros; %Initial water content array is generated
CWi_rel(1:length(Tmax),1)=zeros; %for moisture monitoring based on reliability
CWi(1)=180; % initial water content in mm
CWi_rel(1)=180;
E_I=0.80; % efficiency of irrigation system in decimal
I(1:length(Tmax),1)=zeros; % irrigation column is created
A_R=6; %Average expected irrigation depth

%{
Available water maximum (AWM)depends upon the soil type and rooting depth

based on soil type, choose and input maxmum moiture avialble below for
different rooting depths
source:Irrigation Scheduling Mnaual by Saskatchewan ministry of agriculture

Loamy sand (LS)= 0.71 mm/cm
Sandy loam (SL)= 1.41 mm/cm
```

```
Fine sandy loam (FSL) = 1.55 mm/cm
Very fine sandy loam (VL) = 1.70 mm/cm
Silt loam (SL) = 1.70 mm/cm
Loam (L) = 1.69 mm/cm
Clay loam (CL) = 1.87 mm/cm
Clay (C) = 2.54 mm/cm
%}
D_30=1.87; %depth 0-30 cm
D_60= 1.87; % depth 30-60 cm
D_90= 1.69; % depth 60-90 cm
D_120= 1.87; % depth 90-120 cm
MAD=50; % management allowable deficit in %
MAD=MAD/100;

A=1.4; % area of the field in hectares
Q=8.5; % system capacity in USgpm/acre
E_pump=95; % pump efficiency in %
E_motor=90; % motor efficiency in %
TDH_f=31; % total dynamic head m
P_piv= 100; % Power required to drive pivot in Watt
P_SD=20; % Self discharging power of the batteries in Watt
DPPLT= 220; %distance from pivot point to last tower in ft
LTTS_100= 2.99; %Last tower travel speel at 100% timer setting

S_h_i=7; % starting time for irrigation

%{
If time of irrigation is expected to be 24 h or more in a day, then h must
be equal to zero (0)
%}


% INPUT PARAMETERS FOR DETERMINING THE ENERGY PRODUCED BY THE SOLAR PANELS

load ('Panel_input'); % Ga will be in Mj/m2 and Tc in C (hourly)
P_no(1:length(Ga),1)=6; % No of solar panels


% INPUT PARAMETERS FOR DETERMINING THE ENERGY STORED IN BATTERIES(LEAD-ACID)

Battery_c_s=12; % No. of battery cells connected in series
Battery_b_t=25; % Battery base temperature
Battery_t_s=1; % time step of calculations, its 1 hr in this case
SOC_initial=0.87; % initial state of charge
SOC_maximum=0.9; % maximum state of charge
SOC_minimum=0.5; % minimum state of charge
Battery_c=360; % Total Battery capacity in A-hr
Battery_tv_i=25.8; % initial terminal voltage of the battery
```

CALCULATIONS

```
[ T ] = Tavg( Tmax, Tmin ); % average temperature function
Tmax_K=Tmax+273.16; % degree C is converted into K
Tmin_K=Tmin+273.16;
[ P ] = mean_atmospheric_pressure( z ); % pressure function
Gama=0.000665.*P;
[ Delta ] = Slope_SVP_curve( T );
e_Tmax= 0.6108.*exp((17.27.*Tmax)./(Tmax+237.3));
```

```
e_Tmin= 0.6108.*exp((17.27.*Tmin)./(Tmin+237.3));
[ es ] = saturation_vp( e_Tmax, e_Tmin );
ea=((e_Tmin.*RHmax./100)+(e_Tmax.*RHmin./100))./2;
SR=SR./1000;
Rns=0.77.*SR;
fi=3.14./180.*Latitude;
J=(Day-32)+(round(275.*Month./9))+(2.*round(3./(Month+1)))+(round(Month./100-
mod(Year,4)./4+0.975));
dr=1+(0.033.*cos(2.*3.14.*J./365));
small_delta= 0.409.*sin((2.*3.14.*J./365)-1.39);
ws=acos(-tan(fi).*tan(small_delta));
Ra=7.64.*4.92.*dr.*(ws.*sin(fi).*sin(small_delta)+cos(fi).*cos(small_delta).*sin
(ws))
Rso=(0.75+2*10^-5.*z).*Ra;
fcd=(1.35.*SR./Rso)-0.35;
Rnl= 4.901.*10.^-9.*fcd.*(0.34-0.14.*(ea).^0.5).*(((Tmax_K).^4+(Tmin_K).^4)./2);
Rn=Rns-Rnl; % Net radiation
U_ms=U.*.011; % unit conversion, km/day to m/s
G=0; % Ground heat flux,for daily cycle it is zero
[ ET_ref ] = Reference_ET( Rn, Cn, Cd, U_ms, Delta, G, Gama, T, es, ea );
%function for estimating reference evapotranspiration

E_time(1:length(ET_ref),1)=zeros; % elapsed time in days
E_time=1:1:length(ET_ref);
E_time=E_time';
Tbase(1:length(T),1)=5;
GDD_int(1:length(T),1) = 1;
GDD_int=T-Tbase;
GDD_int(T<Tbase) = 0;
GDD = cumsum(GDD_int);
Coeff=polyfit(GDDC,Kc,3);
Coeff=Coeff';
P1=Coeff(1,1); P2=Coeff(2,1); P3=Coeff(3,1); P4=Coeff(4,1);
Kc_C=P1.*GDD.^3+P2.*GDD.^2+P3.*GDD+P4;
Kc_C(Kc_C<0)=0.05;
D_30=D_30.*30; D_60=D_60.*30; D_90=D_90.*30;
D_120=D_120.*30;
AWM(1:length(Kc_C),1)=zeros;
AWM(1)=D_30(1)+D_60(1)+D_90(1)+D_120(1); % maximum available water
AWM([2:1:end])=AWM(1);
EP=Precp.*0.75; % Effective precipitation
Kc_adj(1:length(Kc_C),1)=zeros;% adjusted Kc based on soil moisture
Kc_adj(1)=(Kc_C(1).*log((CWi(1)./AWM(1)).*100+1))./log(101.0);
ET_C(1:length(Kc_C),1)=zeros; Pp_C(1:length(ET_C),1)=zeros;
Pl_C(1:length(ET_C),1)=zeros; ET_C(1)=ET_ref(1).*Kc_adj(1);
CWf(1:length(Kc_C),1)=zeros; %{final water content in a day%}
CWf_f(1:length(Kc_C),1)=zeros;% final water content based on system reliability
CWf(1)=CWi(1)+EP(1)-ET_C(1);
I(1)=0;
CWf_f(1)=CWf(1)+I(1);
CWf_f(CWf_f>=AWM)=AWM(1);

%Irrigation management strategy may be defined and modified here
for i=2:15(Kc_C);
CWi(i,1)= CWf_f(i-1,1);
Kc_adj(i,1)=(Kc_C(i,1).*log((CWi(i,1)./AWM(i,1)).*100+1))./log(101.0);
ET_C(i,1)= ET_ref(i,1).*Kc_adj(i,1);
CWf(i,1)= CWf_f(i-1,1)+EP(i,1)-ET_C(i,1);
I(i,1)=0; % Irrigation is not recommended for canola crop for first
fifteen day
CWf_f(i,1)=CWf(i,1)+I(i,1).*E_I;
CWf_f(CWf_f>=AWM)=AWM(i,1);
```

```
end

for i=16:93(Kc_C);
CWi(i,1)= CWf_f(i-1,1);
Kc_adj(i,1)=(Kc_C(i,1).*log((CWi(i,1)./AWM(i,1)).*100+1))./log(101.0);
ET_C(i,1)= ET_ref(i,1).*Kc_adj(i,1);
CWf(i,1)= CWf_f(i-1,1)+EP(i,1)-ET_C(i,1);
if CWf(i,1)>CWf_f(i-1,1)| CWf(i,1)>=AWM(i,1).*0.65 && CWf_f(i-1,1)-CWf(i,1)<3.7
I(i,1)=0;
elseif CWf(i,1)>=AWM(i,1).*0.65 && CWf_f(i-1,1)-CWf(i,1)<7.6 && CWf_f(i-1,1)-
CWf(i,1)> 3.7;
I(i,1)= CWf_f(i-1,1)-CWf(i,1);
else
I(i,1)=7;
end

CWf_f(i,1)=CWf(i,1)+I(i,1).*E_I;
CWf_f(CWf_f>=AWM)=AWM(i,1);
end

for i=94:108(Kc_C);
CWi(i,1)= CWf_f(i-1,1);
Kc_adj(i,1)=(Kc_C(i,1).*log((CWi(i,1)./AWM(i,1)).*100+1))./log(101.0);
ET_C(i,1)= ET_ref(i,1).*Kc_adj(i,1);
CWf(i,1)= CWf_f(i-1,1)+EP(i,1)-ET_C(i,1);
I(i,1)=0;
CWf_f(i,1)=CWf(i,1)+I(i,1).*E_I;
CWf_f(CWf_f>=AWM)=AWM(i,1);
end

IT(1:length(Kc_C),1)=zeros;
IT=AWM.*MAD; % IT stands for irrigation threshold
V=(I./1000).*A.*10000;
%{
Irrigation depth is in mm so I is divided by 1000 to convert mm into
m,
A is the area in ha which needs to be converted in m2 so multiplied
with 10000
%}
A_ac=A.*2.47; % area in acre
Q=(Q.*3.78.*A_ac)./(1000.*60); % unit conversion USgpm into m3/s
t_rev=(V./Q)./3600; % time required for pivot to apply selected amount of water
t_rev_rel(1:length(t_rev),1)=zeros;
V_rel(1:length(t_rev),1)=zeros; % actual volume applied based on reliability
I_rel(1:length(t_rev),1)=zeros;
%{
t_rev value should be equal to or greater than pivot full rotation
time
 (which is minimum time) calculated later as variable PFRT, if its not then
either increase the depth of irrigation or reduce the system capacity
untill it is achieved
%}
t_rev_d=t_rev./24; % time required for one revolution in days
E_pump=E_pump./100;
E_motor=E_motor./100;
TDH=TDH_f;
P_R= (Q.*1000.*9.8.*TDH)./(E_pump.*E_motor); % power required by load in Watt
Irr_t(1:length(t_rev),1)=zeros;

for i=1:length(Irr_t);
Irr_t(i,1)=t_rev(i,1);
end

daily_mod(1:length(t_rev),1)=0; x_hr=24; % No of hours in a day
```

```
for i=1:length(t_rev);
if Irr_t(i,1)>x_hr;

for i=1:length(daily_mod);
if t_rev(i,1)>x_hr;
daily_mod(i,1)=x_hr;
g=t_rev(i,1); % just to fix the t_rev value in the cell
while g>=daily_mod(i,1).*m;
i=i+1;
if g-daily_mod(i-1,1).*m>=24;
daily_mod(i,1)=24;
else
daily_mod(i,1)=g-daily_mod(i-1,1).*m;
g=-1;
end
m=m+1;
end
end
end

for i=1:length(t_rev);
t_rev(i,1)=daily_mod(i,1);
end

end
end

rev_hours(1:length(t_rev)*24,1) = 0;
rev_hours_I(1:length(t_rev)*24,1) = 0;
k=1;

for i=1:length(t_rev)
rev_hours_1(1:24,1) = 0;
S_h=S_h_i;
if t_rev(i,1)>0;
if t_rev(i,1)>=23 && t_rev(i,1)<24;
rev_hours_1(S_h+1:floor(t_rev(i,1)),1) = 1;
rev_hours_1(S_h+floor(t_rev(i,1))+1,1) = (t_rev(i,1)) - floor(t_rev(i,1));
elseif t_rev(i,1)==24;
rev_hours_1(S_h+1:S_h+floor(t_rev(i,1)),1) = 1;
else
if S_h==0;
S_h=1;
end
rev_hours_1(S_h:S_h+floor(t_rev(i,1))-1,1) = 1;
rev_hours_1(S_h+floor(t_rev(i,1)),1) = (t_rev(i,1)) - floor(t_rev(i,1))
end
end
rev_hours(k:k+23,1) = rev_hours_1;
S_h=S_h_i;
k=i*24+1;

end

Pl= P_R.*rev_hours; % Power of the load or power required
PFRT= (2.*3.14.*DPPLT)./ (LTTS_100.*60); % Pivot full rotation time in hrs
TR_1_inch= ((((25.4./E_I)./(1000)).*A.*10000)./Q)./3600; % time required for 1"
application
PTS= (25.4.*PFRT)./(TR_1_inch.*A_R); % Percent timer setting
P_piv_eff(1:length(Pl),1)=zeros;
for i=1:length(P_piv_eff)
P_piv_eff(i,1)=PTS.*P_piv;
end
```

```
for i=1:length(Pl)

if Pl(i,1)>0;
Pl(i,1)=Pl(i,1)+P_piv_eff(i,1);
end end
for i=1:length(Pl)

if Pl(i,1)==0;
Pl(i,1)=P_SD;
end end

Ga=(Ga.*10^6)./3600; % unit conversion MJ/m2 into W/m2/hr
for i=1:length(Ga)
[ P_max(i,1), Vmp(i,1), Imp(i,1) ] = Maximum_power( Ga(i,1), Tc(i,1));
%maximum power is a function to estimate max. power produced incorporating
current model
end

P_PVmax=Vmp.*Imp.*P_no; % power produced by the panel in Watt
Pp(1:length(P_PVmax),1)=P_PVmax;


NB_s(1:length(Pp),1)=Battery_c_s; % number of cells in battery connected in
series
TB_r(1:length(Pp),1)=Battery_b_t;
t_Hr(1:length(Pp),1)=Battery_t_s;

SOC_I(1:length(Pp),1)=SOC_initial; % Initial state of charge
SOC_Mx(1:length(Pp),1)=SOC_maximum; % Maximum state of charge
SOC_Mn(1:length(Pp),1)=SOC_minimum; % minimum state of charge

CN_10(1:length(Pp),1)=Battery_c; % nominal capacity of the battery
IN_10(1:length(Pp),1)=CN_10./10; % nominal current of the battery
Pb(1:length(Pp),1)=0; % battery power
if SOC_I(1,1)>=SOC_Mx(1,1) && Pp(1,1)>Pl(1,1);
Pb(1,1)=0;
elseif SOC_I(1,1)<=SOC_Mn(1,1) && Pl(1,1)>Pp(1,1);
Pb(1,1)=0;
else
Pb(1,1)=Pp(1,1)-Pl(1,1);
end

VB_t(1:length(Pp),1)=0; % terminal battery voltage
IB(1:length(Pp),1)=0; % battery current
IB_d(1:length(Pp),1)=0; % average discharging battery current
CB(1:length(Pp),1)=0; % battery capacity calculated against
discharging current
SOC_B(1:length(CB),1)=zeros; %battery state of charge
E_C(1:length(CB),1)=zeros; %efficiency of charge

VB_ini(1:length(Pp),1)=Battery_tv_i;
IB(1,1)=Pb(1,1)./VB_ini(1,1); % Battery current

if IB(1,1)>=IN_10(1,1);
IB(1,1)=IN_10(1,1);
elseif IB(1,1)<IN_10(1,1);
IB(1,1)=IB(1,1);
end

if IB(1,1)<0; % this is average discharging current
IB_d(1,1)=-(IB(1,1));
elseif IB(1,1)>=0;
IB_d(1,1)=0;
end
```

```
if SOC_I(1,1)>=SOC_Mx(1,1);
CB(1,1)=CN_10(1,1);
elseif SOC_I(1,1)<SOC_Mx(1,1);
CB(1,1)= ((1.67./(1+0.67.*(IB_d(1,1)./IN_10(1,1)).^0.9)).*(1+0.005.*(Tc(1,1)-TB
end

if IB(1,1)<0;

SOC_B(1,1)=SOC_I(1,1)+((IB(1,1).*t_Hr(1,1))./CB(1,1));

elseif IB(1,1)>=0;
E_C(1,1)=1-exp((20.73.*(SOC_I(1,1)-
1))./((IB(1,1)./IN_10(1,1))+0.55));
SOC_B(1,1)=SOC_I(1,1)+((IB(1,1).*t_Hr(1,1).*E_C(1,1))./CB(1,1));
end

if SOC_B(1,1)<=SOC_Mn(1,1);
SOC_B(1,1)=SOC_Mn(1,1);
elseif SOC_B(1,1)>=SOC_Mx(1,1);
SOC_B(1,1)=SOC_Mx(1,1);
end

Vbat_D(1:length(IB),1)=zeros; %battery discharging terminal voltage
Vbat_C(1:length(IB),1)=zeros; %battery charging terminal voltage
Vbat_OC(1:length(IB),1)=zeros; %battery overcharging terminal
voltage
V_G(1:length(IB),1)=zeros; %battery gassing voltage
V_EC(1:length(IB),1)=zeros; %battery final charge voltage
ta_G(1:length(IB),1)=zeros; % time constant

if IB(1,1)<0;
Vbat_D(1,1)=(NB_s(1,1).*(1.965+0.12.*SOC_B(1,1)))+(NB_s(1,1).*IB(1,1)./CN_10(1,1
)).*4./(1+(-(IB(1,1))).^1.3))+(0.27./SOC_B(1,1).^1.5)+0.02).*(1-0.007.*(Tc(1,1)-
TB_r(1,1)));
Vbat_C(1,1)=0;
V_G(1,1)=0;
elseif IB(1,1)>=0;
Vbat_D(1,1)=0;
Vbat_C(1,1)=(NB_s(1,1).*(2+0.16.*SOC_B(1,1)))+(NB_s(1,1).*IB(1,1)./CN_10(1,1)).*
((6./(1+IB(1,1).^0.86))+(0.48./(1-SOC_B(1,1).^1.2))+(0.036)).*(1-
0.025.*(Tc(1,1)-TB_r(1,1)));
V_G(1,1)=(2.24+1.97.*log(1+IB(1,1)./CN_10(1,1))).*(1-0.002.*(Tc(1,1)-
TB_r(1,1)));
end


if Vbat_C(1,1)>NB_s(1,1).*V_G(1,1);
V_EC(1,1)= (2.45+2.011.*log(1+IB(1,1)./CN_10(1,1))).*(1-0.002.*(Tc(1,1)-
TB_r(1,1));
ta_G(1,1)= 1.73./(1+852.*(IB(1,1)./CN_10(1,1)).^1.67);
Vbat_OC(1,1)= NB_s(1,1).*V_G(1,1)+NB_s(1,1).*(V_EC(1,1)-V_G(1,1)).*(1-
exp(((IB(1,1).*t_Hr(1,1)-(0.95.*CB(1,1)))./IB(1,1).*ta_G(1,1))));
elseif Vbat_C(1,1)<=NB_s(1,1).*V_G(1,1);
Vbat_OC(1,1)=0;
end

if Vbat_OC(1,1)==0;
Vbat_OC(1,1)=Vbat_C(1,1);
end

VB_t(1,1)=Vbat_D(1,1)+Vbat_OC(1,1);

for i=2:length(Pp);

if SOC_B(i-1,1)>=SOC_Mx(i,1) && Pp(i,1)>Pl(i,1);
```

```
Pb(i,1)=0;
elseif SOC_B(i-1,1)<=SOC_Mn(i,1) && Pl(i,1)>Pp(i,1);
Pb(i,1)=0;
else
Pb(i,1)=Pp(i,1)-Pl(i,1);
end

IB(i,1)=Pb(i,1)./VB_t(i-1,1);
if IB(i,1)>=IN_10(i,1);
IB(i,1)=IN_10(i,1);
elseif IB(i,1)<IN_10(i,1);
IB(i,1)=IB(i,1);
end

if SOC_B(i-1,1)>0.875 && SOC_B(i-1,1)<SOC_Mx(i,1) && IB(i,1)>0.5;
IB(i,1)=IB(i-1,1)/3;

else
IB(i,1)=IB(i,1);
end
if IB(i,1)<0;
IB_d(i,1)=-(IB(i,1));
elseif IB(i,1)>=0;
IB_d(i,1)=0;
end

if SOC_B(i-1,1)>=SOC_Mx(i,1);
CB(i,1)=CN_10(i,1);
elseif SOC_B(i-1,1)<SOC_Mx(i,1);
CB(i,1)= ((1.67./(1+0.67.*(IB_d(i,1)./IN_10(i,1)).^0.9)).*(1+0.005.*(Tc(i,1)-
TB_r(i,1)))).*CN_10(i,1);
end

if IB(i,1)<0;
SOC_B(i,1)=SOC_B(i-1,1)+((IB(i,1).*t_Hr(i,1))./CB(i,1));

elseif IB(i,1)>=0;
E_C(i,1)=1-exp((20.73.*(SOC_B(i-1,1)-1))./((IB(i,1)./IN_10(i,1))+0.55));
SOC_B(i,1)=SOC_B(i-1,1)+((IB(i,1).*t_Hr(i,1).*E_C(i,1))./CB(i,1));
end

if SOC_B(i,1)<=SOC_Mn(i,1);
SOC_B(i,1)=SOC_Mn(i,1);
elseif SOC_B(i,1)>=SOC_Mx(i,1);
SOC_B(i,1)=SOC_Mx(i,1);
end

if IB(i,1)<0;
Vbat_D(i,1)=(NB_s(i,1).*(1.965+0.12.*SOC_B(i,1)))+(NB_s(i,1).*IB(i,1)./CN_10(i,1
)).*4./(1+(-(IB(i,1))).^1.3))+(0.27./SOC_B(i,1).^1.5)+0.02).*(1-0.007.*(Tc(i,1)-
TB_r(i,1)));

Vbat_C(i,1)=0;
V_G(i,1)=0;
elseif IB(i,1)>=0;
Vbat_D(i,1)=0;
Vbat_C(i,1)=(NB_s(i,1).*(2+0.16.*SOC_B(i,1)))+(NB_s(i,1).*IB(i,1)./CN_10(i,1)).*
((6./(1+IB(i,1).^0.86)))+(0.48./(1-SOC_B(i,1).^1.2))+(0.036)).*(1-
0.025.*(Tc(i,1)-TB_r(i,1)));
V_G(i,1)=(2.24+1.97.*log(1+IB(i,1)./CN_10(i,1))).*(1-0.002.*(Tc(i,1)-TB_r(i,1))
end

if Vbat_C(i,1)>NB_s(i,1).*V_G(i,1);
V_EC(i,1)= (2.45+2.011.*log(1+IB(i,1)./CN_10(i,1))).*(1-0.002.*(Tc(i,1)-
TB_r(I,1)));_
ta_G(i,1)= 1.73./(1+852.*(IB(i,1)./CN_10(i,1)).^1.67);
```

```
Vbat_OC(i,1)= NB_s(i,1).*V_G(i,1)+NB_s(i,1).*(V_EC(i,1)-V_G(i,1)).*(1-
exp(((IB(i,1).t_Hr(i,1))-0.95.*CB(i,1)))./IB(I,1).*ta_G(i,1))));
elseif Vbat_C(i,1)<=NB_s(i,1).*V_G(i,1);
Vbat_OC(i,1)=0;
end

if Vbat_OC(i,1)==0;
Vbat_OC(i,1)=Vbat_C(i,1);
end

VB_t(i,1)=Vbat_D(i,1)+Vbat_OC(i,1);

end

E_bat_min(1:length(Pb),1)=SOC_minimum.*Battery_c.*Battery_c_s.*2;
E_bat(1:length(Pb),1)=zeros;
for i=1:length(E_bat);
E_bat(i,1)=SOC_B(i,1).*Battery_c.*Battery_c_s.*2;
end

E_load(1:length(Pl),1)=zeros;
for i=1:length(E_load);
E_load(i,1)=Pl(i,1);
% power should be multiplied with time to get WH but time is 1 hr
here
end

E_p(1:length(Pp),1)=zeros;
for i=1:length(E_p);
E_p(i,1)=Pp(i,1);
end

LPS(1:length(E_p),1)=zeros;
LPS(1,1)= E_load(1,1)-(E_p(1,1)+(SOC_initial.*Battery_c.*Battery_c_s.*2)-
E_bat_min(1,1));
for i=2:length(LPS);
LPS(i,1)=E_load(i,1)-(E_p(i,1)+E_bat(i-1,1)-E_bat_min(i,1));
end
for i=1:length(LPS);
if LPS(i,1)<0;
LPS(i,1)=0;
end
end

for i=1:length(E_load);
if E_load(i,1)==P_SD;
E_load(i,1)=0;
end
end
LPSP=sum(LPS)./sum(E_load);

Gross_d= sum(I); % Total irrigation depth
Gross_EL=sum(E_load)./1000; % Energy in KWH
Gross_EP=sum(EP);

Reliability=1-LPSP;


o=1;
for i=1:length(Pp_C);
Pp_C(i,1)=sum(Pp(o:o+23,1));
o=i*24+1;
end

Pp_C=Pp_C./1000; %Produced daily energy in KWH
```

```
z=1;
for i=1:length(Pl_C);
Pl_C(i,1)=sum(Pl(z:z+23,1));
z=i*24+1;
end

Pl_C=Pl_C./1000; %Required daily energy in KWH

for i=1:length(rev_hours_I);
rev_hours_I(i,1)=rev_hours(i,1);
end

for i=1:length(rev_hours_I);
if E_load(i,1)>E_p(i,1)+E_bat(i,1)-E_bat_min(i,1);
rev_hours_I(i,1)=0;
else
rev_hours_I(i,1)= rev_hours_I(i,1);
end
end

j=1;
for i=1:length(t_rev_rel);

t_rev_rel(i,1)=sum(rev_hours_I(j:j+23,1));
j=i*24+1;
end

V_rel=t_rev_rel.*3600.*Q;
I_rel=V_rel./(A.*10);
CWf_rel(1:length(Kc_C),1)=zeros; %{final water content in a day%}
CWf_rel(1)=CWi_rel(1)+EP(1)+I_rel(1).*E_I-ET_C(1);
for i=2:length(CWf_rel);
CWf_rel(i,1)=CWf_rel(i-1,1)+EP(i,1)+I_rel(i,1).*E_I-ET_C(i,1);
CWf_rel(CWf_rel>=AWM)=AWM(i,1);
end

Gross_d_rel=sum(I_rel);
% plot (E_time,CWf_f,'b',E_time,CWf_rel,'k',E_time,
IT,'r',E_time,AWM,'g');
% title('Scheduling');
% xlabel('Elapsed Time (days)');
% ylabel('Water content (mm)');
% legend('Current water content in soil', 'Irrigation threshold',
'Maximum water holding’);
% ylim([ 0 300 ]);
```

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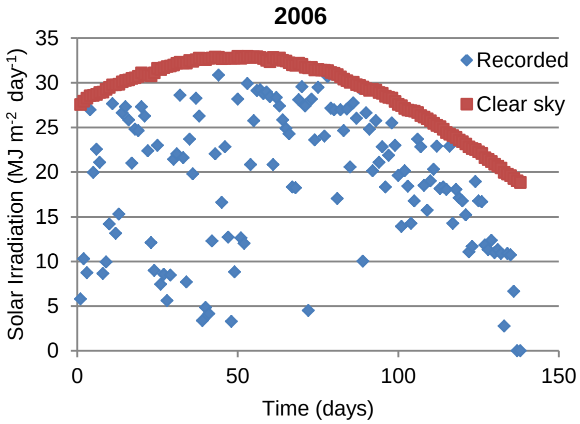
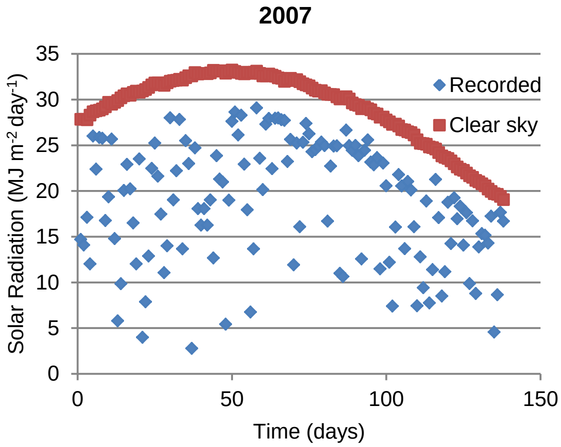
Appendix-B (Radiation data analysis)

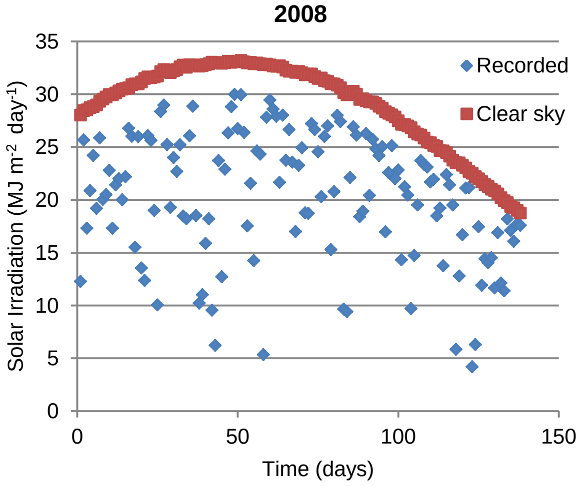
The recorded daily average solar radiation from 1st May to 15 September are plotted against the predicted clear sky radiation envelop for 2006-12. It can be seen from the figures that recorded data seems accurate for 2006-08; however, underestimation of the recorded radiation can be observed for rest of the years. The comparison of maximum solar radiation recorded during the peak period indicates that radiation reduced from 31-32 to 24 MJ m^{-2} day^{-1} for 2009-12, which suggests up-scaling of the data may be required during these years to adjust the error in recording.



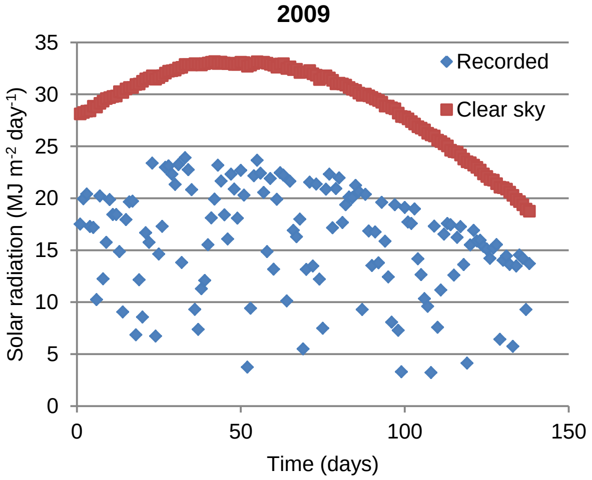
2006



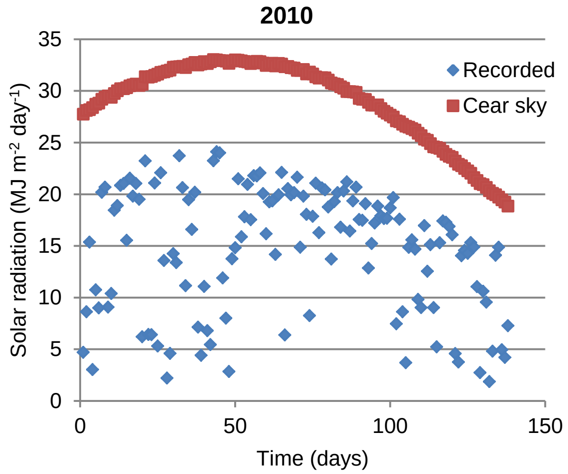
2007

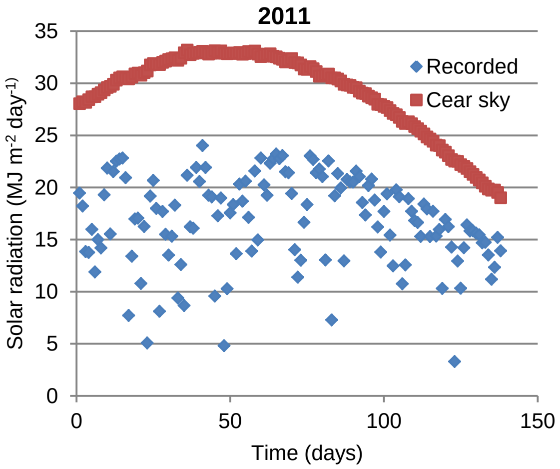


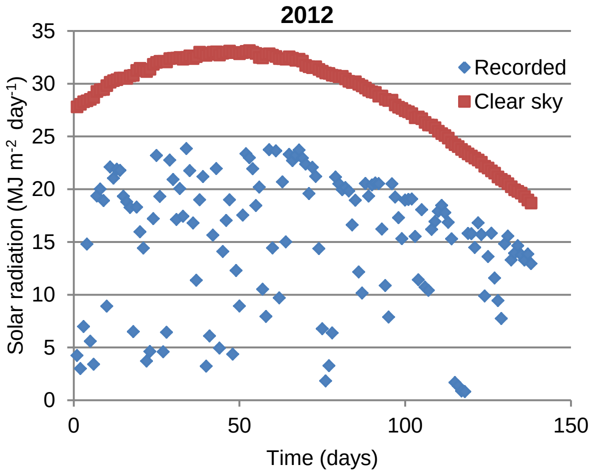
2008



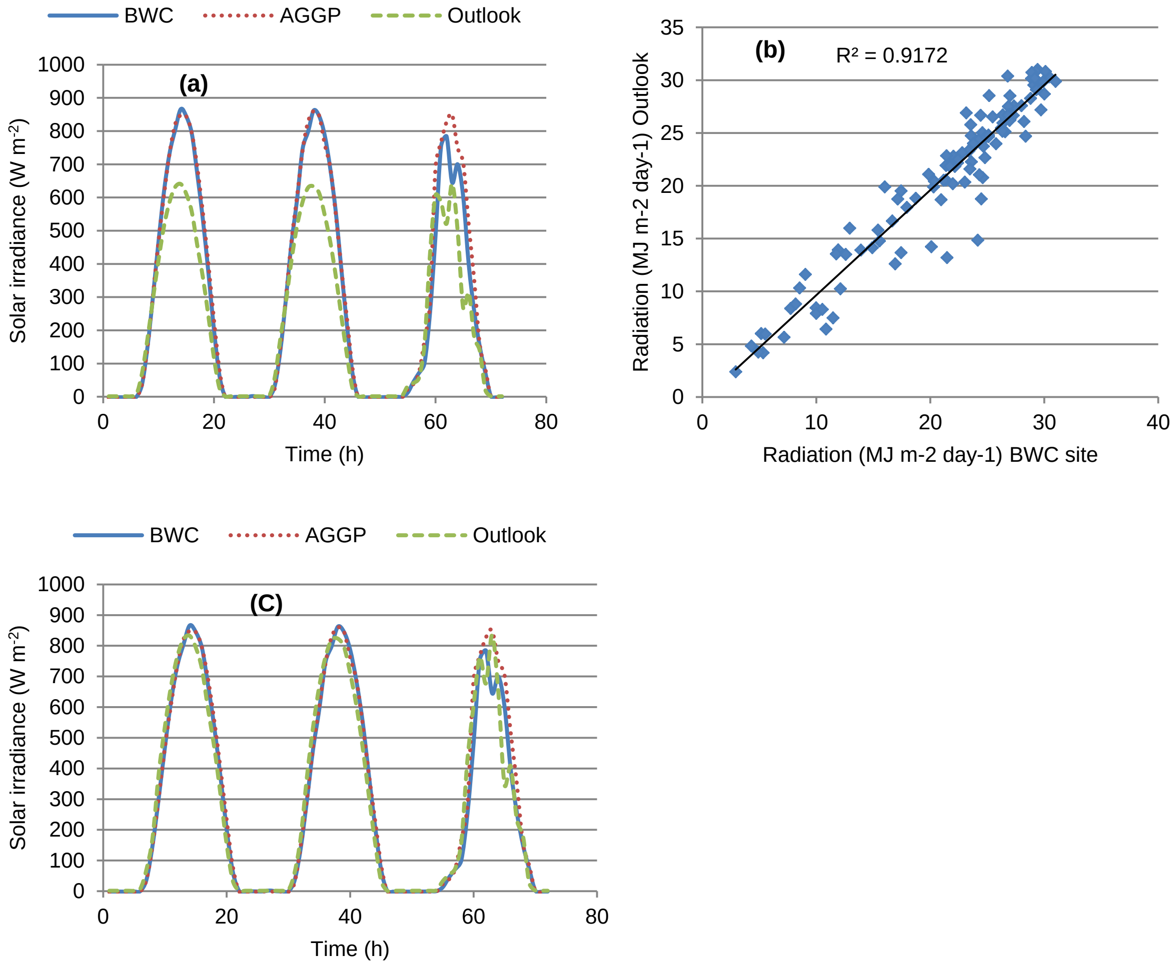
2009





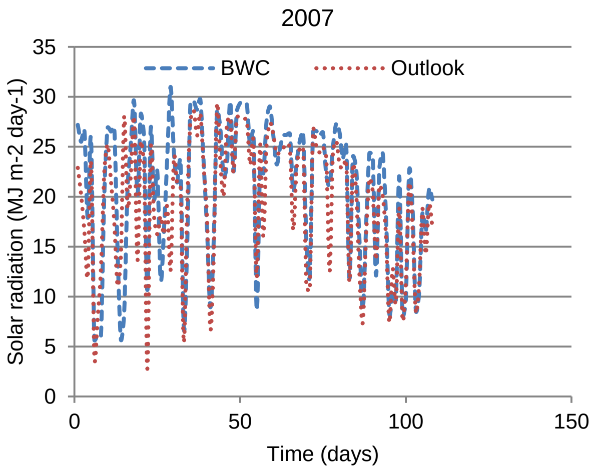


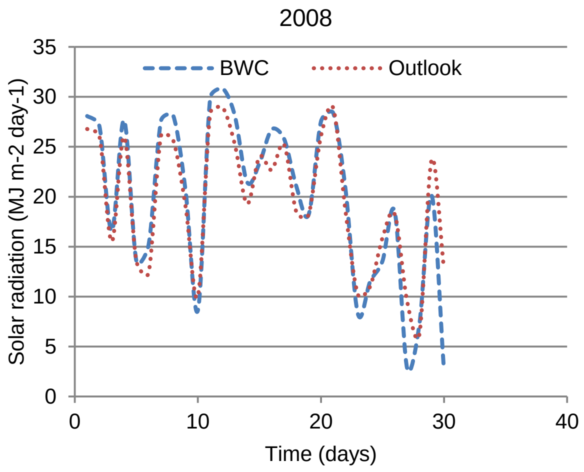
Solar radiation acquired for the study site was compared with the two nearby sites for the selected model validating period (July 30 to August 01, 2012). Solar radiation should not vary significantly for the sites with little spatial variations on a clear sky day. However, significant difference in the recorded radiation on the study site can be observed in the figure (a). The average daily solar radiations were increased by 15%, 20%, 25%, 30%, 35% and 40% for 2012 at the study site when it was less than the radiation recorded at BWC site. The 30% increase in radiation generated the most reliable results, R^2 =0.917 (fig. b), therefore, up-scaling was performed accordingly. It can be seen that the data quality was significantly improved (figure c). The preference was given to upscale the study site data rather than using the radiation received on the nearby site to accommodate spatial variation effect especially on cloudy days.

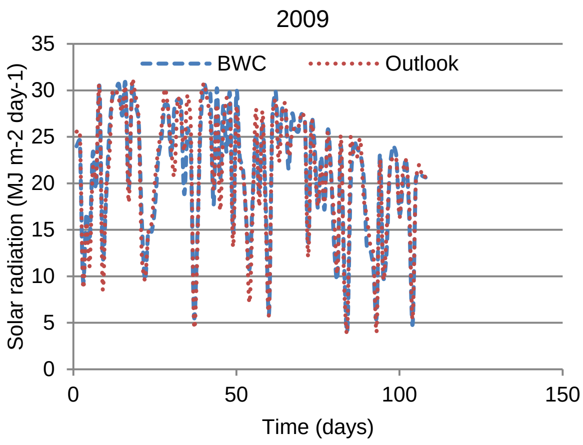


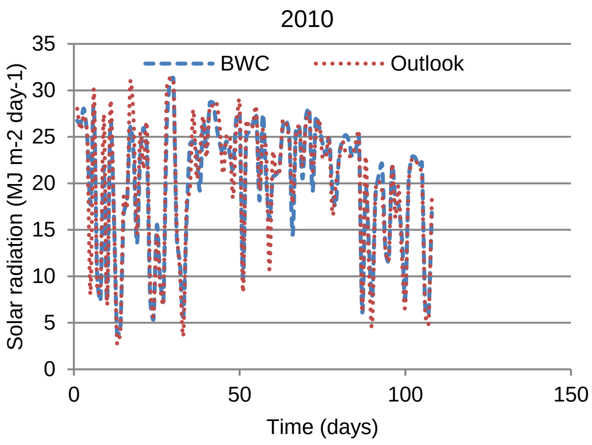
The acquired average daily radiation data for the study site was found to be adequate for 2007-08. This was compared with the BWC site data to see the relative variation. The little variation may be justified with spatial variation causing to change the cloudiness factor. The radiation data for 2009-12 was increased by 30% and then compared with the BWC data. The BWC radiation data was missing from July 11 to July 26, 2012, which was provided from the AGGP site. Similarly the missing daily radiation (23 to 26 August, 2012) for the study site

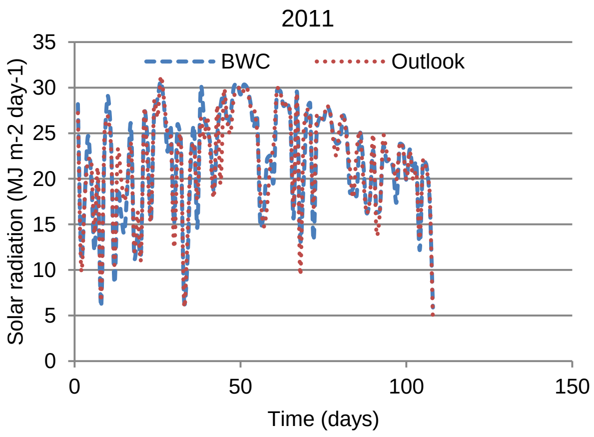
(Outlook) was acquired from the AGGP site. It can be seen from the figure that the adjustment in the radiation data yields suitable estimates with respect to the close by site (BWC).

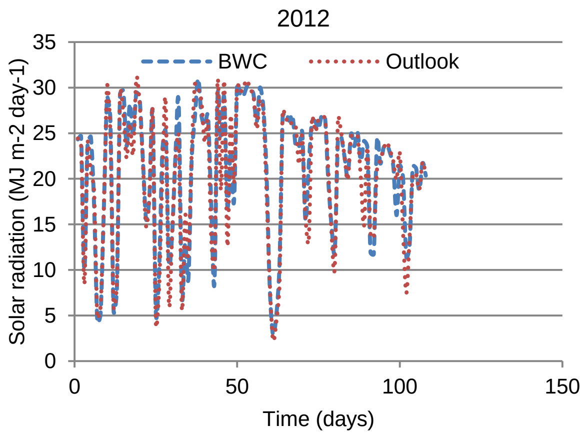












Appendix C (Economic Analysis)

Table C1: Economic analysis for Potato crop grown under solar-powered center pivot at Outlook

Particular	Unit	Quantity	$/unit	Net Price ($)
Fixed cost				
PV System				
PV panel (200W @ 12V each)	No.	12	350	4200
Solar battery (120 Ah @ 12V each)	No.	4	300	1200
Battery replacement (2 times)	Lump sum	-	-	1624
Charge controller	No.	2	600	1200
Solar pump	No.	2	200	400
Pump controller	No.	2	150	300
Replacement (pump+controller)	Lump sum	-	-	335
Mounting and wiring accessories	Lump sum	-	-	926
Transportation	Lump sum	-	-	463
Salvage (panel, battery)	Lump sum	-	-	1043
Irrigation system				
Center pivot	No.	1	-	5000
Salvage (Pivot)	Lump sum	-	-	1667
sub-total				*12939*
Depriciation and interest on capital	Lump sum	-	-	1038
Variable cost				
Seed (with treatment if required)	$acre^{-1}$	-	455	1874
Fertilizer	$acre^{-1}$	-	122	502
Herbicide	$acre^{-1}$	-	50	206
Insecticide	$acre^{-1}$	-	21	0
Funjicide	$acre^{-1}$	-	154	634
Equipment (fuel+repairment)	Lump sum	-	-	865
Irrigation service/water charges	$acre^{-1}$	-	27	111
Crop insurance				688
Annual system cost				**5919**
Return				
Targetted yield				25830
Average yield				22601
Benefit-Cost Ratio				
Targetted yield				**4.4**
Average yield				**3.8**

Table C2: Economic analysis for Soybean crop grown under solar-powered pivot at Outlook, SK

Particular	Unit	Quantity	$/unit	Net Price ($)
Fixed cost				
PV System				
PV panel (200W @ 12V each)	No.	16	350	5600
Solar battery (120 Ah @ 12V each)	No.	4	300	1200
Battery replacement (2 times)	Lump sum	-	-	1624
Charge controller	No.	2	600	1200
Solar pump	No.	2	200	400
Pump controller	No.	2	150	300
Replacement (pump+controller)	Lump sum	-	-	335
Mounting and wiring accessories	Lump sum	-	-	1066
Transportation	Lump sum	-	-	533
Salvage (panel, battery)	Lump sum	-	-	1323
Irrigation system				
Center pivot	No.	1	-	5000
Salvage (Pivot)	Lump sum	-	-	1667
sub-total				*14269*
Depriciation and interest on capital	Lump sum	-	-	1145
Variable cost				
Seed (with treatment if required)	acre^{-1}	-	45	185
Fertilizer	acre^{-1}	-	125	515
Herbicide	acre^{-1}	-	6	25
Insecticide	acre^{-1}	-	21	0
Funjicide	acre^{-1}	-	24	99
Equipment (fuel+repairment)	Lump sum	-	-	95
Irrigation service/water charges	acre^{-1}	-	27	111
Crop insurance				45
Annual system cost				2220
Return				
Targetted yield				2691
Average yield				2201
Benefit-Cost Ratio				
Targetted yield				1.2
Average yield				1.0