Renewable and Sustainable Energy Reviews 81 (2018) 1206–1225

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A review of sustainable solar irrigation systems for Sub-Saharan Africa

Saeed Mohammed Wazed[a,*], Ben Richard Hughes[a], Dominic O'Connor[a], John Kaiser Calautit[b]

[a] Energy2050, Mechanical Engineering, Faculty of Engineering, University of Sheffield, Sheffield, South Yorkshire S10 2TN, United Kingdom
[b] Department of Architecture and Built Environment, University of Nottingham, Nottingham NG7 2RD, United Kingdom

ARTICLE INFO

Keywords:
Solar energy
Solar water pumping
Photovoltaics
Concentrated solar thermal
Stirling engine
Irrigation

ABSTRACT

This investigation focused on the research undertaken on solar photovoltaic (PV) and solar thermal technologies for pumping water generally for irrigation of remote rural farms specifically considering the Sub-Saharan African region. Solar PV systems have been researched extensively for irrigation purposes due to the rise in Oil prices and the upscaling in commercialisation of PV technology. Based on the literature the most effective PV system is presented for the irrigation of a small scare remote rural farm with respect to the cost, pumping capacity and system efficiency. Similarly, solar thermal systems are reviewed and the most effective system described. Unlike PV technology, solar thermal technology for water pumping is lacking especially in small scale operations. However, with the possibility of local production, low investment cost, easy maintenance and lower carbon footprint, solar thermal water pumping technologies may be able to overcome the shortcomings of the PV technology that has stopped widespread use of the technology for irrigation applications. Taking into consideration recent developments in concentrated solar technologies using the Stirling engine, novel solar thermal water pumping systems may be developed. This review also highlighted the different methodologies such as modelling, used to investigate and optimise the performance of solar powered systems.

1. Introduction

Population growth and food insecurity necessitates an increase in farming and irrigation all over the world. The focus here is not only to produce more but to do so in a manner that protects the environment. Moreover, the impact on poorer nations, which are already struggling with food shortage, is far more adverse than others as more land and energy is required to meet the requirements of the future. This creates a need for the development of sustainable technologies that can be implemented to utilise the readily available local resources to drive the cost of the irrigation systems down.

The Sub-Saharan region in Africa is one such region that is marred by inconsistent supply of safe water supplies. Contaminated ground water and long dry spells means that the main source of water in these regions are the rich groundwater reserves. Only 10% of this region utilises groundwater and most of this stems from the lack of economic incentives [1]. The cost of harvesting the reserves are very high. Not only is the initial investment high for purchasing generators and pumps but also the ongoing inflation in fuel costs leads to a consistent increase in operational and maintenance costs [2]. Such costs are extremely high for remote small scale independent farmers to bear.

The focus of this review is to investigate affordable irrigation systems that will be portable and utilise the local resources for manufacture and maintenance. Emphasis is also provided on the use of renewable energy resources to negate the requirement of fossil fuel driven motors (generally diesel powered) and pumps to further reduce the running cost of irrigation. Severe draught, lack of rain and long dry spells provides the opportunity for the utilisation of solar power in Sub-Saharan Africa, with both solar thermal and Photovoltaic (PV) technologies [3], and hence, is considered the focus of this review.

In the review, solar thermal and PV technologies will be compared on the basis of cost, power output and flow generated. The above parameters have been selected in order to design a system that will be viable for the independent farmer for irrigation of remote small scale farms in the Sub-Sharan African region with average small scale farm size of 1 ha according to the Food and Agriculture Organisation (FAO) [4].

The research on solar thermal power has not been as prominent as PV panels in recent times for water pumping applications. However, major development in solar thermal technologies incorporating Stirling Engines warrants a review of solar thermal systems for irrigation because of it's potential to work at low temperatures and relatively simple construction. This review paper highlights major technological developments made in PV irrigation systems, solar thermal irrigation systems and new developments in solar thermal technology that could be utilised in irrigation, with focus on medium to low powered Stirling

* Corresponding author.
E-mail address: SMohammedWazed1@sheffield.ac.uk (S. Mohammed Wazed).

http://dx.doi.org/10.1016/j.rser.2017.08.039
Received 7 February 2017; Received in revised form 23 June 2017; Accepted 12 August 2017

cycle engines. The findings are summarised and the performance of the systems are compared to identify the key advantages and disadvantages of each technology.

2. Research methodology

A literature review is performed on PV and solar thermal irrigation systems. While there is numerous research on PV and Solar thermal technologies, the focus on this review is to study the implementation of the technology in irrigation. To obtain the research material for this literature review, keyword search has been utilised incorporating, “solar water pumps”, “solar irrigation”, “PV irrigation”, “solar thermal irrigation”, “PV water pumping systems”, “Stirling pumps”, “Rankine Cycle water pumps”, “ORC water pumps”, “ORC irrigation” and “Stirling Irrigation”. No location bias has been set. The University of Sheffield's “StarPlus Library Discovery” search tool, “Science-Direct” search engine and the “Google” search engine has been utilised.

PV system reviews have been divided in 4 sections:

- PV irrigation technology reviews – Contains reviews of papers which enlists the various PV technologies that have been studied in the years prior to the publication.
- PV irrigations systems – Contains reviews of papers which describe unique irrigation systems design.
- PV irrigation systems performance – Contains reviews of papers that discuss technologies and control systems that can be used to optimise PV irrigation systems
- PV irrigation technology in comparison to other technologies – Contains reviews of papers that compare PV irrigation technologies against other technologies including Diesel generated pump systems and Renewable energy generated pump systems.

Solar Thermal system reviews have been divided in 3 sections:

- Solar thermal irrigation technology reviews – Contains reviews of papers which enlists the various solar thermal technologies that have been studied in the years prior to the publication.
- Conventional solar thermal technologies – Contains reviews of papers discussing solar thermal technologies based on the Rankine cycle.
- Unconventional solar thermal technologies – Contains reviews of papers discussing solar thermal technologies based on Stirling cycle and other two stroke systems.

After the literature review was performed each solar powered technology (PV and Solar Thermal) is then individually analysed. A summary table of all the technology systems reviewed is presented and the best irrigation set-up has been established. Following this the future of solar irrigation technology is discussed.

3. PV irrigation systems

PV Technologies convert solar energy into electrical energy and then coupled with an electric motor is used to drive an electric pump. Fig. 1 depicts a typical PV irrigation set up. This system can be further enhanced depending on the output requirement, charge regulation based on the requirement of the pump (AC/DC) as well as the incorporation of a battery to counter the fluctuation of solar irradiation available throughout the day or even for irrigation at night, when lower water losses and higher irrigation uniformity is observed [5].

The water outlet from the irrigation system (depicted in Fig. 1) can be used either directly for irrigation or can be used to fill up a water storage tank. An advantage of the water storage tank is that it can be a substitute of the battery system, wherein the potential energy of the stored water can be utilised for drip irrigation.

Photovoltaic systems are generally very simple to implement, and an adequately designed system is efficient and can compete with other systems when operational and maintenance costs are considered. However, the initial investment is often identified as a major turn off [7]. While PV systems are easier to maintain than most other renewable energy systems, there are lots of factors that limit its use including, inconsistent solar irradiation, expensive tracking systems, reduction in efficiency due to overheating of panel systems, lower output due to energy conversion and one of the major issues identified in recent times is the large environmental impact in the production of PV panels [7–9].

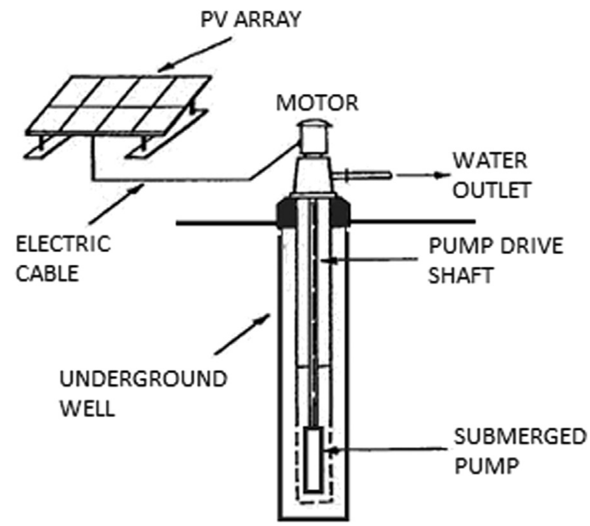

Fig. 1. Schematic of a simple PV irrigation set up for groundwater retrieval [6].

A decrease in the cost of PV technology has meant many rural developments have been keen on utilising the technology because of this, a great amount of research has been conducted on solar PV technologies for water pumping in the recent years so much so that photovoltaic irrigation systems have become synonymous with solar-powered irrigation. Significant research has been conducted on performance, feasibility and economic viability of various PV systems as detailed below.

3.1. PV irrigation technology reviews

Chandel et al. [10] reviewed technologies for irrigation and supply of drinking water to communities that utilises solar PV technology. The study focussed on new technology updates, efficiency, analysis of the performance, efficient sizing of panels, degradation of supplying power to the pump from the PV panels and the economic and environmental aspects of utilising PV technology. In comparison to diesel / conventional electric system, PV systems were identified to be more economically viable in urban and remote rural areas with a payback time of 4–6 years achieved. For shallow wells (10–20 m deep), AC motor pump systems showed similar water output levels when compared to DC motor pump systems, however, at higher depths (30–50 m) DC motor systems provide higher flowrates. The efficiency of different types of solar cells are as per indicated in Table 1 (as tabularised by Green et al. [11]) with Multijunction five-junction cells demonstrating the highest efficiency of almost 39%. Thin film CdTe cells, which are widely available commercially, are rated at an efficiency of 21%.

The efficiency of the system can be further improved using positive displacement pumps, diaphragm pumps and progressing cavity pumps were capable of pumping efficiencies of up to 70%. A Maximum Power Point Tracking [12] system could be utilised for further increasing the efficiency of the PV water pumping system by converting the high voltage from the DC output of the PV panels to a lower voltage for charging of batteries. The power degradation in PV modules was established to be 0.8% per year as a result of prolonged field exposure and requires further research [13]. While automatic tracking helped in increasing the efficiency, the cost was too high; instead double axis