Design of a Low-Cost Smart Solar-Powered Irrigation System

Kanyanta M. Makasa
Department of Electrical and Electronic Engineering
University of Zambia
Lusaka, Zambia
kanyanta.1makasa@gmail.com

Kangwa E. Mukuka
Department of Computer Science
University of Zambia
Lusaka, Zambia
kangwamuk3020@gmail.com

***Abstract*: This study proposes the design of a photovoltaic (PV) system to power agricultural activities in rural communities, with a focus on Sub-Saharan Africa. Considering the high costs of most PV systems for rural economies, the proposed design emphasises affordability. The system comprises a PV array converting solar energy to electricity and powering a DC water pump. To improve the efficiency of the system a step further, automation with an Arduino system optimises water usage. This automation not only conserves water but also extends the pump's lifespan and reduces maintenance costs. Also, efficient irrigation improves the quality and quantity of agricultural produce for the local communities. In the proposed design, a maize field with an estimated two-hectare size, located in Chisunka Luongo, Zambia, is used to check both the economic and technical feasibility of the irrigation system proposed in this paper. Weather data from PVGIS aided in assessing the design's technical feasibility, while an analysis of the life cycle cost-effectiveness and environmental benefits of the system is also presented. Affordability was a priority in the system design, catering to various farming communities. Results indicate that our proposed system is cost-effective compared to other solar energy irrigation solutions, effectively meeting the irrigation demand of surrounding farming communities.**

Keywords: Arduino (Uno), Irrigation, Photovoltaic Geographical Information System (PVGIS), Photovoltaic System (PV System), Thornthwaite Method (TH).

I. Introduction

In Zambia, a significant portion of farmers rely on rain-fed agriculture due to poor irrigation techniques, impacting crop productivity. The flood and bucket irrigation method, commonly used in rural areas near water bodies, tends to overwater fields, leading to nutrient loss and soil degradation [1, 2]. Climate change exacerbates these challenges, emphasising the need for improved irrigation practices.

The issue of irrigation in Zambia is crucial, especially in the face of droughts and poor rainfall patterns. Zambia's heavy reliance on rain-fed agriculture makes farmers vulnerable to climate shock [1]. Efforts to enhance irrigation for small-scale and rural farmers in Zambia and Africa are crucial due to the potential benefits for food security, poverty alleviation, and economic development.

This study introduces a solar-powered irrigation system that utilises the energy from the sun to pump water from a water body, in this case, groundwater, onto a raised tank, which is then used for irrigating crops. The method harnesses gravitational force to produce pressure, obviating the requirement for supplementary pumps needed for irrigation. The water pump is automatically deactivated when the tank reaches its maximum capacity in order to avoid excessive mechanical strain and wear on the pump motor. An Arduino Uno and temperature sensors are used to optimise irrigation efficiency by automatically providing water to crop areas when the evapotranspiration rate falls below a specific threshold [3, 4, 5]. This approach is advantageous because it leads to higher crop production and less soil erosion caused by flooding. The design emphasises optimising efficiency, minimising energy and water consumption, and guaranteeing cost-effectiveness for rural farmers. The system is subjected to technical testing and an economic study to verify its viability and integrity.

II. Literature Review

In the analysis and design of the solar systems, methods similar to those used in similar works were adopted. The connection from the irrigation system's sensor to the controller and actuator has been designed with inspiration from a similar design in [6]. In this design, a stepper motor is the controller of the system, and it receives an error signal proportional to the difference between the desired moisture content required by a given crop variety, in this case, maize. This error signal lets the stepper motor make an angle that either widens or narrows the irrigation valve, which is the actuator of the system.

In the analysis of the design, it was of the essence to have a thorough and compressive economic analysis of the system. To make sure the design not only works but is also cost-effective, making the project potentially self-supporting. The approach 'Life Cycle Cost' was employed in testing the cost-effectiveness, as it was with good reason applied in the test of a solar pumping system design and case study by [7]

Despite the similar control system in earlier literature [6], the model proposed in this paper is expected to have a lower cost as it uses fewer components than in previous works. The proposed pumping system is battery-less. Batteries were not needed, as the energy to irrigate the water will come from the stored gravitational potential energy that the solar pump will give to the water during the sun's hours.

III. System Design

In this paper, the viability of using solar energy to power agricultural activities in rural, Sub-Saharan Africa was

2024 IEEE PES/IAS PowerAfrica | 979-8-3503-8938-8/24/$31.00 ©2024 IEEE | DOI: 10.1109/POWERAFRICA61624.2024.10759498

explored. Utilising information from earlier studies that estimated the typical farmland use by the majority of rural farmers in Zambia, the idea's development involved calculating the irrigation load. The exact water requirements were estimated using the evapotranspiration rate from the Thornthwaite Method (TH) described in the literature of the EvapoTranspiration online calculator [8]. Once the load was specified, a PV system was sized to meet this demand using reliable PV sizing techniques.

A schematic of the overall system is shown in Fig. 1, with A = Water Tank, B = Water Pump, C = PV system, D = Automated System, and E = Irrigation Field

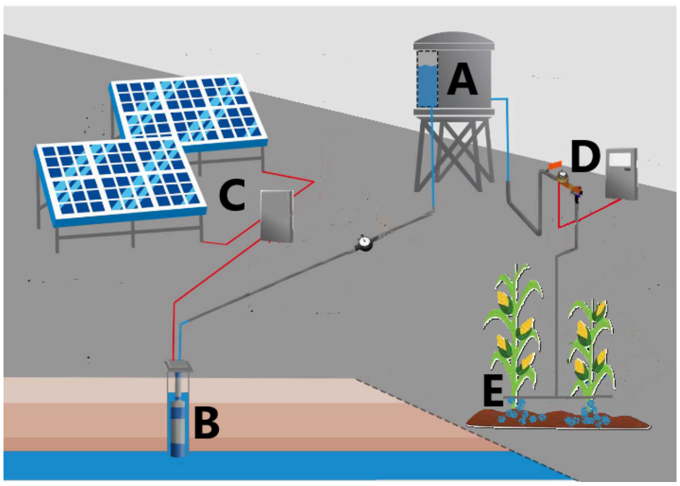

Fig. 1. Overview Diagram

A. *Tank size and elevation*

Maize as a crop requires between 2.6 mm and 2.9 mm of water for irrigation [9]. In this paper, a plot size of two hectares is used throughout the system design and analysis. The choice of two hectares comes from research that stated that the average plot size for a rural farm is about two hectares [10]. A farm plot of this size that only grows maize will need about 58,000 litres of water per day for irrigation. From the 58,000 litres of water, an appropriate tank size can be determined. To get an appropriate tank size, an emergency factor of about 1.38 is added, resulting in an 80,000-litre tank requirement for 2 hectares of maize farm.

Lastly, the tank is to be elevated to about 5 metres above the ground. The tank is given this level of elevation in order for it to have the potential energy needed for irrigation. This way, there won't be a need for a second pump, which would increase costs as well as energy conversion steps.

B. *Water Pump Design*

The system needs to be able to provide enough energy to fill the tank ten metres above the ground within a day. The potential energy required to pump this water is found as

$$E_{pump} = mgh \tag{1}$$

where m is the mass of the water in kg, g is the acceleration due to gravity assumed to be constant at 9.81 m/s2, and h is the height from the water table to the top of the tank.

Using (1), the following assumptions are made: The water table is 3 metres below the surface, and the pumping efficiency of the system is about 75%. The energy required by the pump in a day is about 5.3 kW. Because the system is battery-less, this power needs to be supplied during Chisunka Luongo's sun hours. To make sure the pump's power always meets the 5.3 kW energy need, calculations are based on the lowest sun hours available. The lowest recorded peak sun hours were taken from PVGIS's data on Chisunka Luongo.

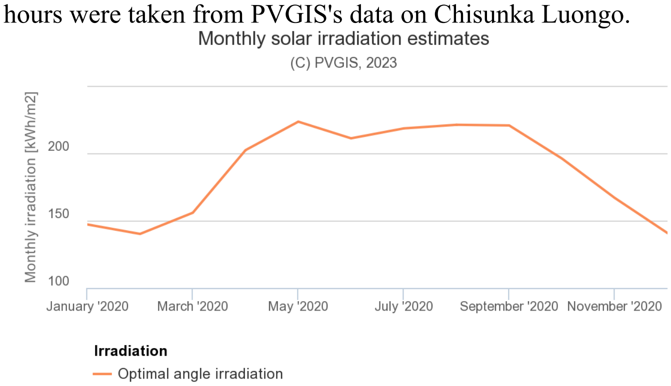

Fig. 2: PVGIS simulation chart (2023).

The month with the lowest mean irradiation was found to be the month of February, with a total direct irradiance of 118.3074 kW/m2. February has 28 days, so we can derive the Peak Sun Hours (P.S.H) for the lowest month using:

$$P.S.H = \frac{I_t}{1kW/hm^2 \times days} \tag{2}$$

From (2), the minimum available peak sun hours for Chisunka Luongo are rounded to 4.2 hours. Assuming the pump only works during the available sun hours, the estimated power rating of the pump should be 1.27 kW. Hence, a 1.5kW (2 hp) 12V DC centrifugal pump. If the DC centrifugal pump is not available, a similar-rated DC motor can be coupled to the centrifugal pump and perform almost as well.

C. *Photovoltaic System Design*

The pump uses a 48V motor; hence, the output of the array has to be 48V, with a power output of 1.5kW. The systematic approach we took to designing the system was first having it meet the power demand and then adjusting the arrangement of the strings so that the voltage specification of the load was met. To find the amount of energy needed for the PV array, the following formula was used:

$$P_{PV-system} = P_{pump} \times S_{fac} \tag{3}$$

where:

S_{fac} is a safety factor, taken as 1.2

P_{pump} is the power of the pump

According to (3), the PV system needs to be able to provide at least 1.8 kW of power. For this power output, 360Wp, 38V modules were selected. 5 of these modules were needed for the output to accommodate a 1.8 kW load. The modules are to be connected in parallel. The output electrical power of the PV system is then taken to a buck converter before going to power the DC pump.

The buck converter plays two key roles in this design. Firstly, it steps down the voltage from 38V DC to 12V DC needed by the pump; secondly, it increases the current supply, helping the pump start easily on load. Having a similar buck converter was proven to be sine qua non in a similar water pump design [6].

D. *Automated Irrigation System Design*

a.) Hardware Description: The physical design of the automated irrigation system is shown below:

i.) Microcontroller

In recent times, the Arduino Uno has gained popularity in many embedded systems because of its small size and affordable price [11]. In the scope of this project, the Arduino Uno will receive signals from the temperature sensors and forward control signals to the relay motor, which will in turn automatically turn on the valve.

ii) Temperature Sensor (LM35)

The LM35 sensor family is composed of precision integrated-circuit temperature sensors whose output voltage is linearly correlated to the temperature in degrees Celsius [12].

iii) Relay & Solenoid Valve

The regulated DC signal is used to drive a relay, which controls the AC motors. It can isolate one electrical circuit from another. The electromagnet's operating principle closes and opens the circuit. Wide-area electronics circuits like industrial control circuits, high-power amplifiers, phone exchanges, etc. use relays. The solenoid valve will be used to control the flow of water from the tank to the irrigation system [12, 13].

iv.) Buzzer (Sounder)

In this suggested work, a buzzer or beeper provides a warning signal when the motor is turning on or off. This can be mechanically, electrically, or electronically actuated to generate an auditory warning signal. An auditory signalling device, such as a buzzer or beeper, might be mechanical, electromechanical, or electronic [12].

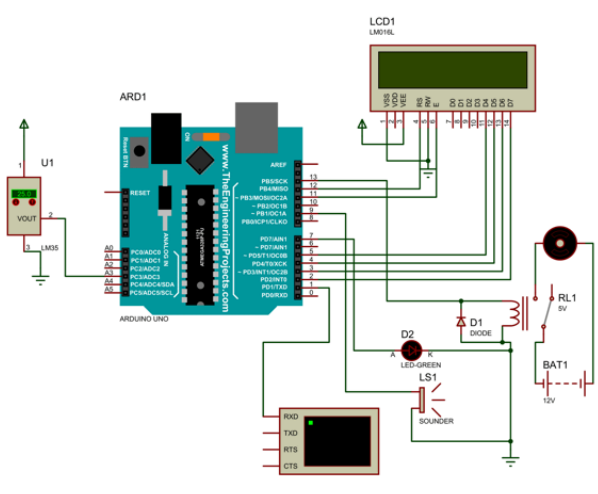

Fig. 3. Circuit Diagram

b.) Software Description: The Arduino Uno is a powerful tool for developing complex systems [11]. In this context, Proteus Design Suite 8.13, coupled with C++ programming and the Arduino IDE, was used to simulate the automation on a Windows 10 machine. The system's automation relies on the Thornthwaite Method (TH), a simple equation requiring only mean air temperature data [5]. Temperature sensors detect analogue values and display them on an LCD screen.

Fig. 4 below shows the mechanism used to automate the irrigation system, its dependencies, and the subsequent flow of data at a high level.

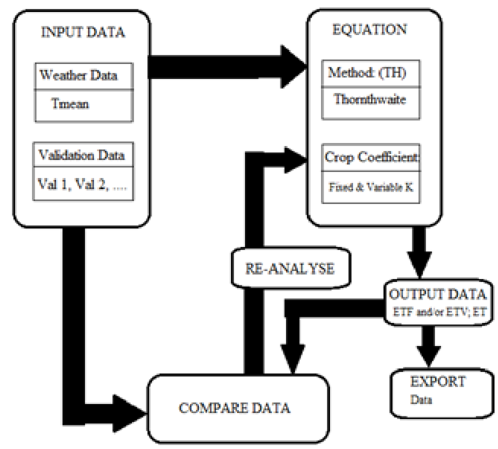

Fig. 4. Flow Diagram

Algorithm 1 Calculation of Daily Reference Evapotranspiration (ETR)

Input: T_{mean} (daily mean air temperature in °C), N (duration of the photoperiod in hours), T_{normal} (local normal climatic temperature in °C per month)

Output: ETR (daily reference evapotranspiration in mm)

Initialisation :
  $C \leftarrow N/360$
  $I \leftarrow \sum_{n=1}^{12} (0.2 \times T_{normal})^{1.514}$
  $a \leftarrow 6.175 \times 10^{-7} \times I^3 - 7.711 \times 10^{-5} \times I^2 + 1.7915 \times 10^{-2} \times I + 0.49239$
  $ETR \leftarrow 0$
Calculation of ETR :
if $T_{mean} \leq 0$ **then**
  $ETR \leftarrow 0$
else if $0 < T_{mean} \leq 26$ **then**
  $ETR \leftarrow 16 \times C \times (10 \times \frac{T_{mean}}{I})^a$
else
  $ETR \leftarrow C \times (-415.85 + 32.24 \times T_{mean} - 0.43 \times T_{mean}^2)$
end if
return ETR

where:

C - correction factor from converting from monthly to daily time scale

I - thermal index; a - exponent

n ranges from 1 to 12, representing each month of the year.

Algorithm 1 calculates the daily reference evapotranspiration using the mean air temperature taken from temperature sensors. This approach was chosen to reduce the number of sensors required for the irrigation system, thereby keeping costs low.

E. Irrigation Method Used

In this study, furrow irrigation was selected as the main irrigation method for two main reasons: the main crop of interest in the design of the system was maize, and over the years, it has been observed that grain crops produce good yields with furrow irrigation: Secondly, furrow irrigation systems have low installation and maintenance costs as compared to alternatives like drip irrigation [14].

IV. System Analysis

A. Technical Analysis

The proposed solar PV system in Chisunka Luongo, which is near a major natural reservoir, was tested with the EU's Photovoltaic Geographical Information System (PVGIS) [15]. The system's daily energy requirements are predicted to be 5.3 kWh, with a monthly energy production of more than 165 kWh. To be considered successful, the system must achieve these daily requirements, which total at most 165 kWh per month. PVGIS records the solar radiation database, PV technology, mounting position, slope, azimuth angle, and installed peak PV power. The estimations were based on the system's default losses.

After entering Chisunka Luongo's coordinates in PVGIS, the following data was entered to check the system's performance: Solar Radiation Database: PVGIS-SARAH2, PV technology: Crystalline, Mounting Position: Free-Standing, Slope: 10.6 degrees, Azimuth Angle: 0 degrees, Installed Peak PV Power: 1.8 kWp; the default system losses were used in the calculation of array system losses.

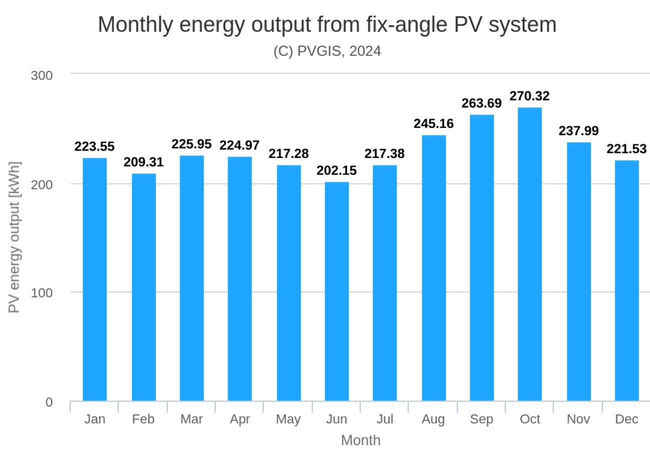

Fig. 5. The PV array meets the demand of the water pumps (PVGIS 2024).

The power output from the simulation surpasses the base requirement of 164 kWh/month. This means the proposed system can meet the irrigation load requirements throughout the year.

B. Life-Cycle Cost Analysis

The financial returns of a general irrigation system are highly dependent on the type of crop cultivated. Studies show that high-return, labour-intensive crops have higher returns when solar-powered irrigation systems are employed [16]. For this reason, financial returns to the customer are not the main area of focus in this paper. However, the actual capital expenditure of the system and the operations expenditure are what is used for the cost comparison of the proposed system. This comparison is done in two main stages: first, it is compared with the diesel-powered irrigation system as it is the main competitor to solar-powered irrigation as there is little to no access to main grid electricity in rural communities.

i.) Comparison with Diesel Irrigation Systems

Besides solar energy, fossil fuel generators like diesel generators can be used for crop irrigation. Diesel generators have a lower capital expenditure cost, while solar-powered systems have higher initial costs. However, diesel generators require more frequent maintenance, making solar-powered systems more cost-effective in the long run [16]. Additionally, solar-powered systems significantly reduce CO2 emissions and eliminate the need for ongoing fuel purchases.

ii.) Cost Comparison with Conventional Solar-Powered Irrigation System

The proposed system's automation reduces the operation period of the DC pump, which is the primary source of maintenance and replacements. The improved water efficiency leads to cost efficiency and conserves groundwater, preventing excessive extraction from the water table [3].

The initial cost of this design is slightly higher than conventional solar-powered irrigation systems. However, the addition of smart control to the irrigation system allows the DC pump to have a longer service life, thereby increasing the IRR (Internal Rate of Return) by reducing maintenance costs.

The cost of the system and maintenance costs are determined based on market prices and costs at the time of writing and may be due to fluctuations.

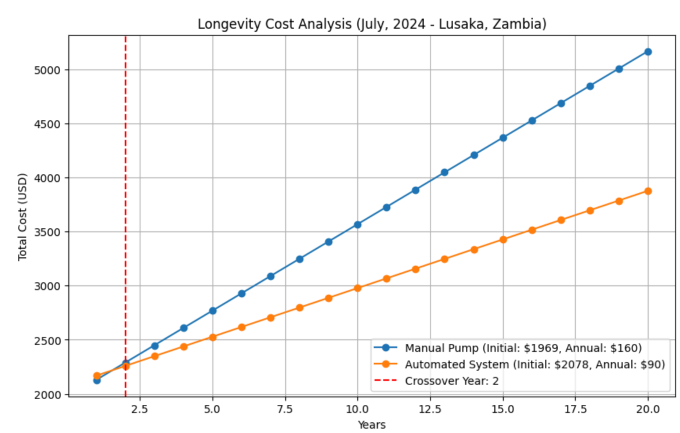

Fig. 6. Longevity Cost Analysis (July 2024, Lusaka, Zambia).

It can be seen from the results of the graph that the smart solar system has lower long-term operation costs as compared to the conventional solar-powered irrigation system. The automated irrigation system has a competitive advantage for the proposed system in 2 years (payback period), and in the longer twenty-year period, assuming ideal conditions, it costs about half the total cost of the conventional solar-powered irrigation system.

C. Socio-Economic Impact

Implementing improved irrigation systems, particularly solar-powered ones, in rural African communities can significantly enhance crop yields, leading to increased market value of produce, improved livelihoods for farmers, and heightened food security [17]. Solar irrigation not only introduces farmers to renewable energy but also exposes them to modern technologies like automation, potentially sparking interest in innovation among both adults and children, thereby fostering community-wide technological advancement [17].

Moreover, such projects align with various UN Sustainable Development Goals (SDGs) such as Zero Hunger, Clean Water and Sanitation (ensuring availability and sustainable management of water and sanitation for all), Affordable and Clean Energy, and Climate Action, contributing to comprehensive sustainable development by addressing key global challenges.

V. Conclusions

The purpose of this research was to build a solar irrigation system that is both intelligent and inexpensive. To assist with the design, the village of Chisunka Luongo was chosen as the region that was offered for the project. After that, the system was designed, and a PVGIS simulation was carried out to determine whether or not the proposed PV system was capable of satisfying the electric load that was required by the DC pump to elevate the water table and pump it into an elevated tank. Based on the findings of the PVGIS, it can be concluded that the design is capable of satisfying the electricity demand. Furthermore, an economic study was performed on the design that was proposed, and the primary concepts that were examined during the project were life cycle cost studies. However, the methods of determining the project's return on investment and payback period have been demonstrated. Though the annual savings could not be estimated due to restrictions, the methodologies have been proven.

References

[1] M. Mwape, H. Said, E. Phiri, M. Heiling, G. Dercon and C. Resch, “Understanding the interaction between maize water use efficiency and nutrient uptake in irrigated cropping systems, a basis for predicting and improving Zambia’s productivity in a changing climate,” *presented at EGU General Assembly 2023, Vianna, Austria,* April 24–28, 2023.

[2] M. Tuminetti, E. Byers, A. Vinca, G. Falchetta, M. A. Nevado Amell, J. Liu and M. A. Amir-Moezzi, *The benefits of rural electrification to improve water access and irrigation in Sub-Saharan Africa, a water-energy-land assessment framework applied to Zambia,* 2023.

[3] G. Shanmugasundaram, K. K. Prasanth, G. Magesh and B. Sriram, *Automated Irrigation System,* Podichery: 2019 IEEE International Conference on System, Computation, Automation and Networking (ICSCAN), 2019.

[4] A. R. Pereira and W. O. Pruitt, “Adaptation of the Thornthwaite scheme for estimating daily reference evapotranspiration,,” *Agricultural Water Management,* vol. 66, pp. 251-257, 2004.

[5] C. W. Thornthwaite, “An approach toward a rational classification of climate,” *Geographical Review,* vol. 38, pp. 55-54, 1948.

[6] S. I. Khan, M. M. R. Sarkar and M. Q. Islam, *Design and analysis of a low-cost solar water pump for irrigation in Bangladesh,* vol. 6, System, 2013, p. 1020.

[7] I. Imad, “Micro-Grid Solar Photovoltaic Systems for Rural Development and Sustainable Agriculture in Palestine,” *agronomy,* vol. 10, no. 10, 26 September 2020.

[8] HTS(Hydro Tools), “ETCalc - Evapotranspiration Calculator,” [Online]. Available: https://etcalc.hydrotools.tech/pageMain.php. [Accessed 20 June 2024].

[9] E. Mudenda, “Evaluation of Growth, Water Balance and Water Use Efficiency of Selected Maize Varieties under Rain-Fed Conditions in Zambia,” 30 November 2018. [Online]. Available: http://thesisbank.jhia.ac.ke/8447/. [Accessed 18 05 2024].

[10] J. D. Plessis, Maize Production, Pretoria: Department of Agriculture and obtainable from Resource Centre Directorate Agricultural Information Services, 2003.

[11] M. Tupac-Yupanqui, C. Vidal-Silva, L. Pavesi-Farriol, A. Sánchez Ortiz, J. Cardenas-Cobo and F. Pereira, “Exploiting Arduino Features to Develop Programming Competencies,” *IEEE Access,* vol. vol. 10, pp. pp. 20602-20615, 2022.

[12] R. N. Rao, *IoT based smart crop-field monitoring and automation irrigation system,,* B. Sridhar, Ed., Coimbatore: 2018 2nd International Conference on Inventive Systems and Control (ICISC), 2018, pp. 478-483.

[13] V. Ramachandran, R. Ramalakshmi and S. Srinivasan, *An Automated Irrigation System for Smart Agriculture Using the Internet of Things,* 2018, pp. pp. 210-215.

[14] G. D. Spencer, L. J. Krutz, L. L. Falconer, W. B. Henry, C. G. Henry, E. J. Larson, H. C. Pringle, C. J. Bryant and R. L. Atwill, *Irrigation Water Management Technologies for Furrow-Irrigated Corn that Decrease Water Use and Improve Yield and On-Farm Profitability,* Crop, Forage and Turfgrass Management, 2019.

[15] T. Huld, R. Müller and A. Gambardella, “A new solar radiation database for estimating PV performance in Europe and Africa,” *Solar Energy,* vol. vol. 86, no. issue 6, pp. 1803-1815, 2012.

[16] Powering Agriculture, “TOOLBOX ON SOLAR POWERED IRRIGATION SYSTEMS (SPIS),” in *Module 6 (Finance)*, Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH on behalf of BMZ, 2018, pp. 160-163.

[17] K. Sanogo, “Solar-based irrigation systems as a game changer to improve agricultural practices in sub-Saharan Africa: A case study from Mali,” 2 March 2023. [Online]. Available: https://www.frontiersin.org/journals/sustainable-food-systems/articles/10.3389/fsufs.2023.1085335/full. [Accessed 20 May 2024].