GSJ: Volume 11, Issue 3, March 2023, Online: ISSN 2320-9186
www.globalscientificjournal.com

DESIGN OF PHOTOVOLTAIC WATER PUMPING SYSTEM: CASE STUDY GASABO DISTRICT

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Keywords: evapotranspiration, rainfall, infiltration rate, moisture, irrigation, pump, pv modules.

Abstract

This project intended to design a small scale PVWPS to be implemented in Kajevuba marshland of Gasabo District in Kigali city for irrigation of one hectare maize crop.

In the current work, a solar irrigation system was sized according to the quantity of water required in all growing stages of maize for the site of interest.

The site meteorological data, solar radiation and reference evapotranspiration were obtained from Kigali station using CLIMWAT software.
By entering those data in combination with site soil and plantation date of chosen into the CROPWAT 8.0 software, the Effective rainfall and the crop Irrigation water requirement were determined.
The highest average daily reference evapotranspiration and solar irradiation were obtained for the month of August with respective values of 4.65mm and 19.0MJ/m^2.
The highest water demand and maximum number of sun hours are found in the month of July with respective value of 52.6mm/dec and 7.5.

This month having the lowest ratio between daily solar radiation and water demand was chosen for designing the size of the system. For proper irrigation of 1 hectare of maize crop in kajevuba site, for the month of July the everyday requirement of water has been 52.6m^3corresponding to the flow rate of 117LPM. The total dynamic head in this research was estimated to be 20m.

From the water demand and TDH, the required hydraulic energy, pump system power required and PV rating KWpeak were calculated and the respective values found are 2.87KWh pr day, 1.27KW and 1.637KWp.
By using a GRUNDFOS sizing tool, SQF-5A-7 pump was selected and the corresponding solar modules was proposed. Six modules were connected in series to supply the electrical power of 1.62KW.

1. Introduction

Gasabo, one of Districts of city of Kigali, owns a lot of number of cultivated marshlands but the production is still poor because of traditional irrigation methods used during multiple droughts [1]. Even some farmers are not practicing any kind of irrigation which results in shortage and high price of vegetables in Kigali city.

PV systems remain the most charming choices for renewable by reason of its basic characteristics which make it very attractive; some of them are: direct conversion process, little or no maintenance problems of the system, applicability in remote and isolated area, pollution free system, availability of abundant solar energy and simple to operate by lay users [2].

Its use has increased in recent years as the energy from fossil-fuel based sources has contributes to global change of climate [3]. Over the past decade, prices of PV modules have fallen significantly while that of competing fuels has increased.

SPVWP has been proven to be the cheapest option for continuous pumping purposes like municipal supply of water and animal troughs, as well as for for irrigation water pumping [4].

Solar pumps are being promoted and used not only for reducing the consumption of diesel and greenhouse gas emission, but also to address the deficiency of grid connectivity and provide the better life to poor farmers.

2. Background of the Project

Solar water pumping systems are a reliable mean to provide sustainable water access for households in off-grid communities [5].

Solar resources and water scarcity have a close relationship: In the period of intense sun shines there is ability to provide much water for irrigation. On the other hand, irrigation on rainy days is not necessary [6]. The price of PV systems is now competitive with other conventional systems like diesel. However, it is still a significant challenge to make them affordable for the communities living in low-income areas [7].

Rwanda is known for its abundant water resources due to its climate but these resources are not distributed equally across the country. [8]

Using irrigation to strengthen rain fed agriculture can play a significant role in stabilizing or increasing food production and reducing poverty. [9]

The availability of water is another factor to be considered for field irrigations.

The principal resources of irrigation water in Rwanda are rivers, lakes, water dams, groundwater resources and wetlands. [5]

Some researches for impact of irrigation on reduction of poverty in Rwanda have been done basing on diesel, electrical and hand pumping systems. The application of PVWPS pilot projects has started in Rwanda but till now, only a small number of solar water pumps are operating in the whole country. [7]

3. Problem statement

According to the World Bank, agriculture is the hugest economic sector in Rwanda, contributing to the country's national income and enabling employment for a big number of the country's population.

Irrigation is an established practice on several fields and is applied at different levels at the earth for enabling diversification of crops and increasing in yields [13].

It is a method that provides the required quantity of water in the cultivated area and contributes to the increase in agricultural production by allowing diversification of crops and increasing crop yields [14]. Most of times, It is impossible to connect the water pump system to the nearby power grid, as expanding the mains network is expensive. By the use of diesel pumps to bring water to the destination point, many problems are faced from both a profit and environmental point of view. High diesel prices increase the operating costs of diesel pumps and reduce revenues. Also, the use of diesel pumps emits large amounts of CO2, which contributes to global warming. The answer to these challenges is to adopt energy from solar to run the water pump. This is not only a friendly and free source of energy, but also saves power by consuming less mains power.

Although the possibilities or motivations of using solar pumps attracted a big number of farmers initially, this quickly faded, and only then in recent years, a wide range of stakeholders have increasingly turned their attention to solar pumping solutions.

For finding solutions to the effects of erratic rainfall patterns and drought that limit the growth of agricultural production, the Rwandan government has just increased investment in development of irrigation [15].

Gasabo, one of Districts of city of Kigali, owns a lot of number of cultivated marshlands but the production is still poor because of traditional irrigation methods used during multiple droughts. Even some farmers are not practicing any kind of irrigation which results in shortage and high price of vegetables in Kigali city. Furthermore, selecting the best option of SWPS technology is a challenge to find appropriate solution.

4. Objectives of the study

4.1. Main Objectives

The principal objective of this work is to design a small scale photovoltaic and water pumping system for replacing the existing irrigation pumping systems using either the electricity from the mains or fossil fuel based pumps.

The increase of the number of solar water pumping systems in Rwanda is a key factor for development of a sustainable agriculture and Rwanda, as a member of ISA, has a big interest to adopt this technology.

4.2. Specific Objectives

- Find the appropriate crops for the study area.
- Estimate the water requirement.
- Estimate the appropriate hydraulic energy and the corresponding electrical power needed for satisfying the load demand.
- Propose the Pumping Equipment Manufacturer and use his sizing tool to select and simulate the equipment in question.

5. Literature Review

This part covers the theoretical knowledge of different fields related to this research. The focus was put on the identification of the findings from different researchers and related gaps.

"SWPS for irrigation: A review" Showed that SWPS have been identified to be the greatest alternative irrigation techniques. Variations in the temporal and spatial distribution of water present for the purposes of irrigation impose great demands of technologies on saving of water that contribute to economic and social development. SIS has been found to be a solution to the Indian farmer's energy crisis as it reduces the consumption of the grid power, its implementation is easy and it brings environmentally clean solutions for irrigated farms.
The principal benefits over other alternatives are long service life, no maintenance, no fuel, no pollution and easy installation. Another important feature is that the maximum water demand period coincides with maximum insolation periods [21].
Technical and Economic assessment of SWPS in villages of Ethiopia have been analyzed and showed that the direct SIS is the cheapest and simplest system to adopt [22].

A rapid grow of SIS was found in a review of recent research and conclude that the adoption of SWPS is increasing worldwide due to their ease of adoption, profitability to stimulate socio-economic improvement and its cost-effectiveness [23,24]. A study on usage of PV energy for HEI published the results of a field study conducted to assess the impacts of high-efficiency solar-powered system of irrigation across Pakistan's Punjab province, where nearly half of the rural population is living by farming.
It showed that the implementation of PVWPS has resulted in a decrease in the high operation and maintenance costs registered while using fossil-fuel based pumps [25].
A research on the small scale irrigation technology adoption in Rwanda showed that the decisions are based on farm size, education, counseling services, gender, group membership access to credit, access to weather forecast information and rainwater harvesting techniques. [26].

6. Research method

In this part, a number of steps need to be taken to ascertain whether a stand-alone solar system meets the required water demand from the selected water source. These steps are: Description of the case study site, crop water-demand assessment and design period, calculation of total dynamic head, pump and PV module size estimation, orientation of solar panels, Size and location of water storage tank and Computer-Based System Sizing.

To determine the crop water requirements, the models CLIMWAT and CROPWAT are used.

The data are extracted from Kigali climate and entered in CROPWAT for further details calculations [27]. The sizing and simulations are performed basing on the average daily water demand. The pump and solar panels are selected from the GRUNDFOS software database to meet the corresponding water demands. In this project, a field with total size of one hectare is selected for maize plantation.

6.1. Description of the Site

The proposed SIS will be sited in Kajevuba marshland of Gasabo district of the city of Kigali in Rwanda. Kajevuba marshland covers an area of 65ha in Gikomero, Rutunga and Bumbogo sectors.

6.1.1. Geographic location

The geographic coordinates of Kajevuba marshland are:

- Latitude :1° 53' 5" South (or-1.8847)
- Longitude : 30° 8' 53" East(or 30.13141)
- Height above sea level:1511 m. [28]

6.1.2. Crop production

The “A” agricultural season starts in September and ends in February, “B” is between starts in March and July, and last season “C” is specially for marshland crops and lies between August and September [29]. The country landscape conditions its climate: The temperature is warmer for lower altitudes.

From June to August there is a dry season and between March and May a heavy rainfall is registered. There is a third season for agricultural in Rwanda for of rice and vegetables cultivation in regions with abundant water especially in marshlands taking place in the dry season [30].

From 2016 Kajevuba marshland has been used by farmers to grow horticultural crops including green beans (also known as French beans), beetroots, tomatoes, and sweet pepper, maize, cabbage, and egg plants among others [31]. It is important to design an SPIS that is affordable and profitable. Profitability depends on the yield or income from the sale of the crop. The choice of crops to grow is therefore critical. Maize is the used by Rwandans for prevention from famine and therefore it is selected as the crop of interest in this project.

6.2. Assessment of crop water demand

Once the selected crop types are chosen, the first step in designing SPVWPs is to calculate daily crop water requirement. The rainfall and/or irrigation must fully satisfy the sum of the water which is to be consumed by the crop and loss by evaporation, together referred as evapotranspiration (ET) of the crop. The knowledge of Crop Water Requirement (CWR) is essential for the design of SIS. It depends on various factors like crop type, soil type, climatic conditions of the site, irrigation methods cropping pattern etc.

6.2.1. Calculation of the reference evapotranspiration (ET0)

Crop evapotranspiration (ETc) is the sum of all processes by which water enters the atmosphere from the surface. That is, the release of water is water vapor from plant leaves by evaporation of water from the capillary edges of the water table, evaporation from terrestrial bodies of water, and transpiration [34]. Evapotranspiration from a water-rich reference area is named reference evapotranspiration ETo. Accurately indicates the evapotranspiration of alfalfa grass based on physical, physiological and aerodynamic parameters. His concept was introduced to study the need for atmospheric evaporation regardless of crop type, crop development, and management methods. A reference area is a theoretical grass reference culture with specific properties. The only factor affecting reference evaporation is climatic parameters. Baseline evapotranspiration is therefore depending to the climatic conditions and it is calculated using meteorological data. It represents the location and time atmosphere evaporative power without taking into account plant characteristics or soil parameters [35]. The FAO Penman-Monteith method is used for the computation of evapotranspiration from meteorological data. (fao.org)

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

The Crop water requirement ET_c calculation is done by using the crop coefficient K_c and corresponding reference evapotranspiration ET_o.

$$ET_c = CWR = K_c\, ETo \quad (2)$$

CWR is Crop water requirement.

The Figure 1 shows climate data input and reference evapotranspiration output from Cropwat8.0. The weather data are exported from CLIMWAT software database and fed as input into CROPWAT system.

Monthly ETo Penman-Monteith - F:\KIGALI.pen

Country: Location 2 — Station: KIGALI

Altitude: 1497 m. — Latitude: 1.96 °S — Longitude: 30.11 °E

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	°C	°C	%	km/day	hours	MJ/m²/day	mm/day
January	15.1	26.5	78	173	5.6	17.8	3.75
February	15.2	26.8	76	173	5.6	18.2	3.91
March	15.3	26.5	79	173	5.3	17.8	3.76
April	15.6	25.8	83	156	5.2	17.0	3.42
May	15.7	25.5	80	173	5.6	16.5	3.37
June	14.8	26.0	69	181	7.1	17.9	3.83
July	14.5	26.6	61	207	7.5	18.8	4.34
August	15.4	27.6	61	225	6.9	19.0	4.65
September	15.3	27.7	69	216	6.0	18.6	4.36
October	15.3	26.9	76	216	5.7	18.3	4.06
November	15.1	25.8	81	190	5.1	17.0	3.54
December	15.0	26.0	80	181	5.3	17.1	3.56
Average	**15.2**	**26.5**	**74**	**189**	**5.9**	**17.8**	**3.88**

Figure 1: Climate data input and reference evapotranspiration output from Cropwat 8.0

6.2.2. Monthly rain data and calculation of Monthly mean effective rainfall

During rains, some of the rainwater runs off and another seeps out. The rest of the water stored in the root zone is called available precipitation. [36]

USDA Soil Conservation Services (SCS) formula is used to calculate available precipitation [1].

$$Peff = \frac{P_{total}(125 - 0.26P_{total})}{125} \quad \text{for } P_{total} \leq \left(\frac{250}{3}\right) \text{mm} \tag{3}$$

$$Peff = \frac{125}{3} + 0.1 * P_{total} \quad \text{for } P_{total} > \left(\frac{250}{3}\right) \text{mm} \tag{4}$$

With P_{eff} : the monthly mean effective rainfall, P_{total} is the monthly mean rainfall.

Monthly rain - F:\KIGALI.cli

Station: KIGALI   Eff. rain method: USDA S.C. Method

	Rain	Eff rain
	mm	mm
January	70.6	62.6
February	92.4	78.7
March	113.8	93.1
April	168.4	123.0
May	103.3	86.2
June	27.6	26.4
July	12.8	12.5
August	36.3	34.2
September	77.1	67.6
October	96.3	81.5
November	120.8	97.5
December	90.2	77.2
Total	**1009.6**	**840.5**

Figure 2: Monthly effective rain calculation by using Cropwat 8.0 software

6.2.3. Crop data

For Kajevuba marshland the most appropriate time to plant maize is June-October.

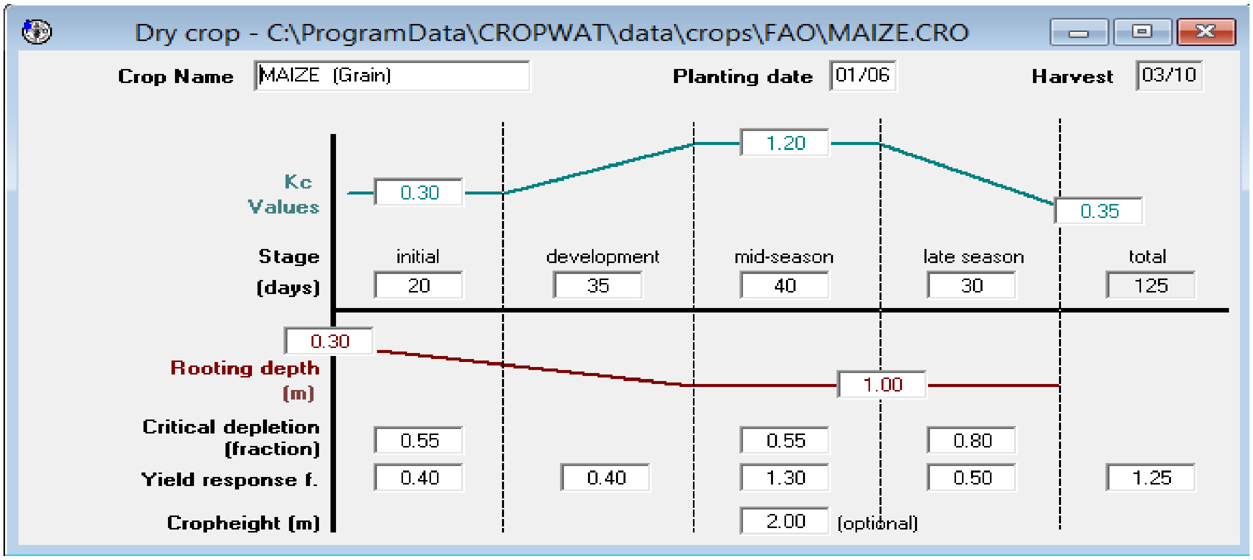


Figure 3: Values of crop coefficient

6.2.4. Soil data

Average soil texture in Gasabo District has high levels of sand [37].

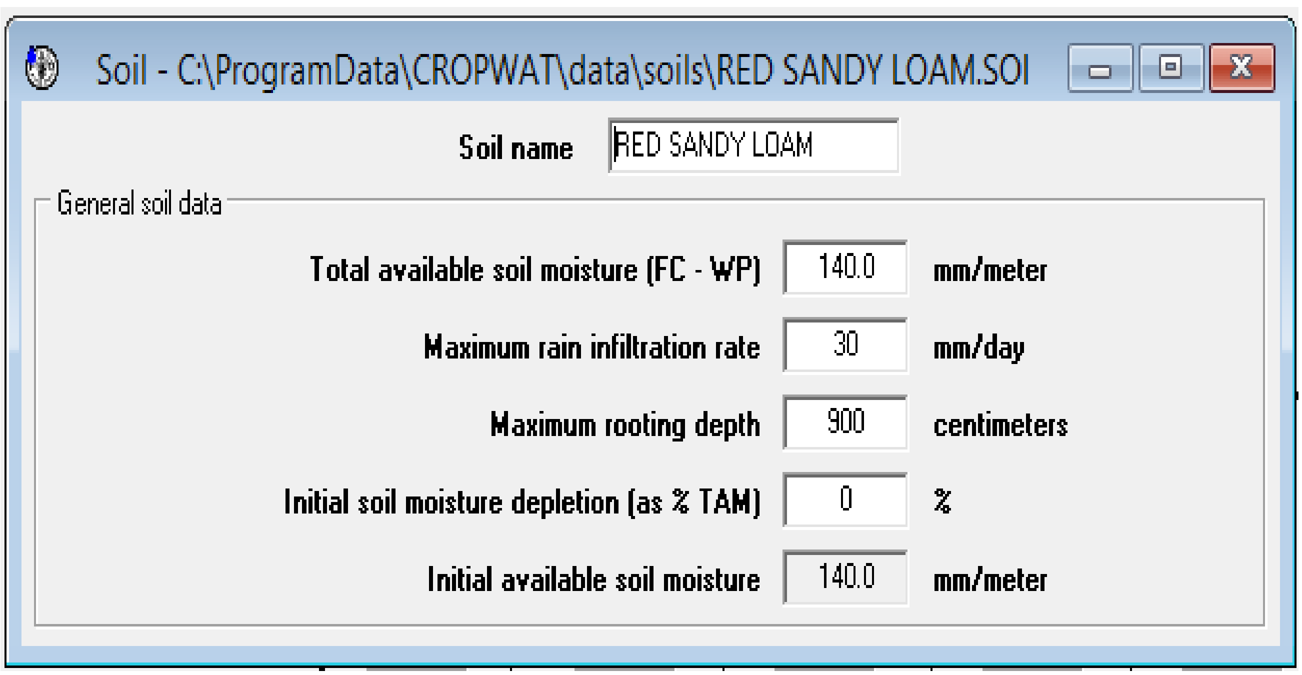


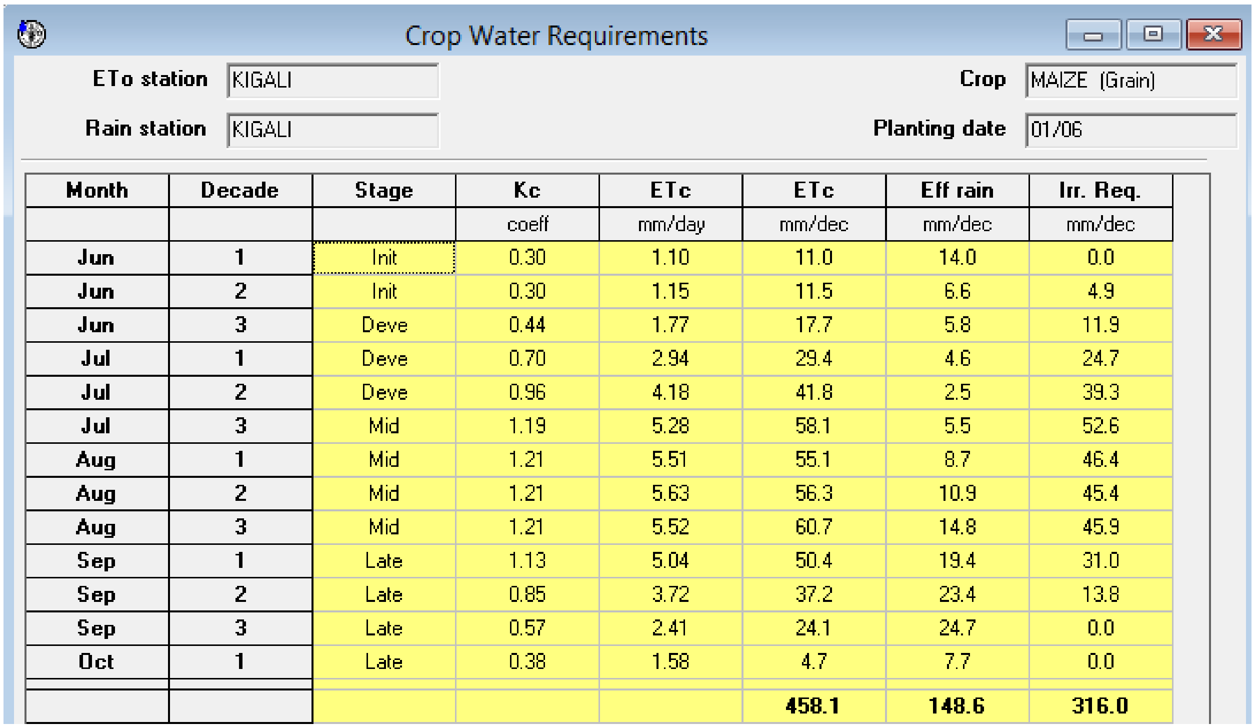
Figure 4: Soil data input

6.2.5. Irrigation requirement assessment

ISSN 2320-9186

The irrigation water requirements are determined by a subtraction of available rainfall from plant water requirements.

$$IRn = \sum_{t=0}^{T} (Kc * ETo - Peff) \tag{5}$$


Crop Water Requirements

ETo station: KIGALI
Rain station: KIGALI
Crop: MAIZE (Grain)
Planting date: 01/06

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.
			coeff	mm/day	mm/dec	mm/dec	mm/dec
Jun	1	Init	0.30	1.10	11.0	14.0	0.0
Jun	2	Init	0.30	1.15	11.5	6.6	4.9
Jun	3	Deve	0.44	1.77	17.7	5.8	11.9
Jul	1	Deve	0.70	2.94	29.4	4.6	24.7
Jul	2	Deve	0.96	4.18	41.8	2.5	39.3
Jul	3	Mid	1.19	5.28	58.1	5.5	52.6
Aug	1	Mid	1.21	5.51	55.1	8.7	46.4
Aug	2	Mid	1.21	5.63	56.3	10.9	45.4
Aug	3	Mid	1.21	5.52	60.7	14.8	45.9
Sep	1	Late	1.13	5.04	50.4	19.4	31.0
Sep	2	Late	0.85	3.72	37.2	23.4	13.8
Sep	3	Late	0.57	2.41	24.1	24.7	0.0
Oct	1	Late	0.38	1.58	4.7	7.7	0.0
					458.1	148.6	316.0

Figure 5: Output of Crop water requirement of maize

When Eff rain is greater than crop water requirement value there is no irrigation required. The volume of water required is obtained by multiplying the area to be irrigated and the irrigation requirement IR [38].

In table1 the water requirement is showed for different stages of the one hectare maize irrigation.

Table 1: volume of water required for maize irrigation

Months	Decade	Stage	IR(mm/dec)	Q(m^3/ha/dec)
June	1	Init	0.0	0
June	2	Init	4.9	49

June	3	Dev	11.9	119
July	1	Dev	24.7	247
July	2	Dev	39.3	393
July	3	Mid	52.6	526
August	1	Mid	46.4	464
August	2	Mid	45.4	454
August	3	Mid	45.9	459
September	1	Late	31.0	310
September	2	Late	13.8	138
September	3	Late	0.0	0.0
October	1	Late	0.0	0.0

6.3. Sizing of the solar water pumping system

The condition of worst-case considers the availability of solar energy and the required water and the design month is chosen by considering the smallest ratio between average every day solar irradiance and water needs [39].

Table2: Solar irradiance and water demand ratio

Month	It (KWh/m^2day)	Wg(m^3/ha day)	Ratio (%)
June	5	11.9	42
July	5.22	52.6	9.9
August	5.28	45.9	11.5

September	5.17	31.0	16.7

The lowest ratio is obtained for the month of July and therefore it is chosen for designing the size of the system. For proper irrigation of 1 hectare of maize crop in kajevuba site, for the month of July everyday requirement of water is 52.6m^3corresponding to the flow rate of 117LPM.

6.4. Estimation of Pump power required and PV generator Size

The daily required hydraulic energy E_H can be obtained by considering the daily water demand and total dynamic head by using equation 9

$$E_H=\rho g Q\ TDH /3600 \qquad (6)$$

Nyarugenge_Kanyinya_Nzove_Rutagara I is the nearest ground water station from Kajevuba marshland; the data from this station shows that the water static level is 4.73m [44]. From above references a total dynamic head of 20m is assumed in our design calculations and the value of daily required hydraulic energy calculated using the equation 9 is obtained as 2.87KWh/day.

6.4.1. Required hydraulic power calculation

The hydraulic energy calculated above can be used to determine the minimum hydraulic power dividing the needed energy by the daily sun hours.
Hydraulic power required Ph=2.87/7.5=382W. The efficiency of motor pump changes between 40 and 60% and the most of motors has efficiency varies from 75% to 85%. The value of overall efficiency η_{mp} varies between 30-50%. [45]

For calculating the net suitable motor, the shaft power of the pump has to be calculated. The shaft power is equal to the pump required power divided by the pump efficiency. By assuming an average pump efficiency of 50%, the required pump shaft power is obtained as 764W or 1.024hp.

6.4.2. Pump system electrical power

The obtained hydraulic energy Eh is used to calculate the electrical power (Pe) needed by by the pump system of η_{mp} efficiency with the help of the relation 10.

$$Pe=Ph/\eta_{mp} \qquad (7)$$

If the pump is AC, the inverter is also involved with its efficiency η_{inv} and(10) can be written as follows [46]:

$$Pe=Ph/(\eta_{mp}\eta_{inv}) \quad (8)$$

Different sizes of pumps and the corresponding head and sizes of pipes are available from manufacturers to select-based on particular needs.

By assuming the motor-pump group overall efficiency of 30%, the electrical power required by pump-motor system is calculated using the equation 10 and obtained as 1.27KW.

6.4.3. Peak PV capacity determination

The sizing of the PV array is to be done by considering the daily hydraulic energy requirement for lifting the required amount of water Eh, solar array mismatch factor, the daily average irradiance on the solar module S_R and the overall efficiency of subsystem as expressed in equation 12. [48]

$$P_{SA}=Eh/\,(S_R FE) \quad (9)$$

The average of mismatch factor F is 0.85 and the everyday efficiency of subsystem E ranges between o.25 and 0.4.

By assuming a daily subsystem efficiency of 0.395, the peak PV capacity required is obtained as 1.637KWp according to equation 12

6.5. Computer-Based System Sizing and Simulation

In this project, a GRUNDFOS sizing tool is used to select the appropriate solar pump and the system and complete system equipment corresponding to the selected solar pump is proposed by the software.

By entering the geographical location of the site, the daily flow rate, estimated static lift above the ground and dynamic water level, month of sizing and solar module type, a series of corresponding best pumps appears and SQF-5A-7 pump is selected. It is a centrifugal pump for low heads and large flow rates. The sizing results of the selected pump include the pump type, solar module type, module connections and PV array power as shown in figure 6.

Sizing results

Pump:	SQF 5A-7, 1 x 95027342
Solar module:	GF 270, 6 x 99299012
Number of solar modules in series:	6, in parallel:1
Solar array power	1.62 kW
Flow (Q)	118.3 l/min
Friction losses	1.239 m
Total head	20.24 m
Cable length (pump)	17 m
Cable size (pump)	0.75 mm²
Cable loss (pump)	3.4 %
Total water production per year	20200 m³/Year
Avg. water production per day	55.3 m³/day
Avg. water production per Watt per day	34.2 l/Wp/day
User-defined day	July
Energy from Solar array	2990 kWh/year

Figure 6: SQF-5A-7 pump sizing results

7. Findings and Discussions

The estimation of reference evapotranspiration for a particular region is very important for knowing the balances between water and received solar energy.

ETo is principally affected by weather factors as solar radiation, humidity, air temperature and wind speed. [53]

The influence of those parameters is positive except that of relative humidity [54]. The average of daily reference evapotranspiration for the study site was found to be 3.88mm. The highest value is 4.65mm obtained in the month of August whose maximum temperature is high with the value of 27.6^{o}C; the lowest is 3.37mm for the month of May whose maximum temperature is the lowest with the value of 25.5^{0}C.

The highest maximum temperature is obtained in the month of September having the value of 27.7^{0}c (approximately equal to that of August), but the solar radiation and wind speed are highest in the August. The number of sun hours in August is greater than that of September with respective values of 6.9 and 6.0. The humidity in September is greater when compared with that of August and their respective values are 69 and 61%. The solar radiation and maximum temperature in May are the lowest with the respective values of 16.5MJ/m^2/day and 25.5ºC. The lowest level of rainfall is obtained in month of July with the value of 12.5mm. This month has a high solar radiation and the highest number of sun hours of 7.5.

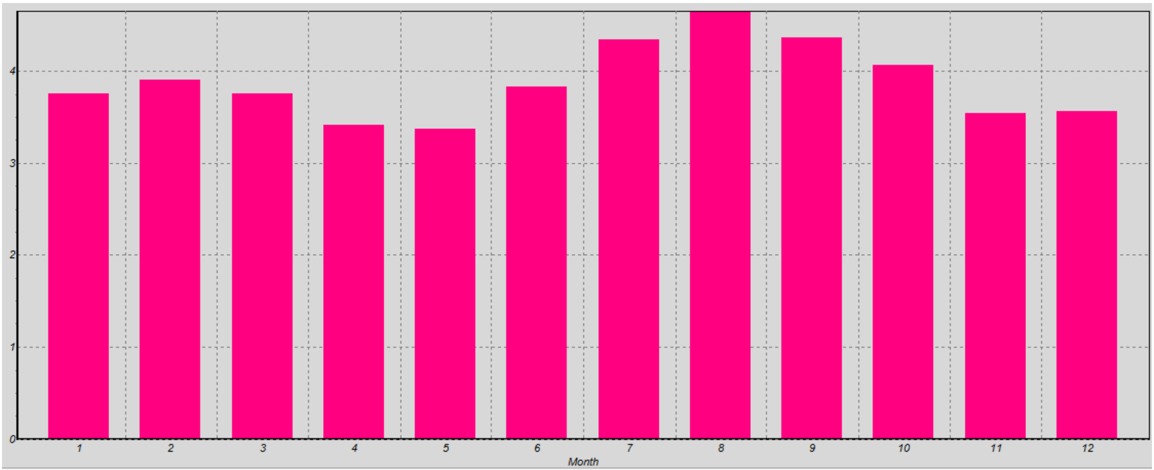


Figure 7: Average daily ETo

Recorded site irrigation water requirement for maize is highest in the month of July with the value of 52.6mm/dec as shown in Figure 4.2. This month has the lowest rainfall level of 12.8mm and the high CWR of 58.1 mm/dec and has finally been taken as the design month in this project.

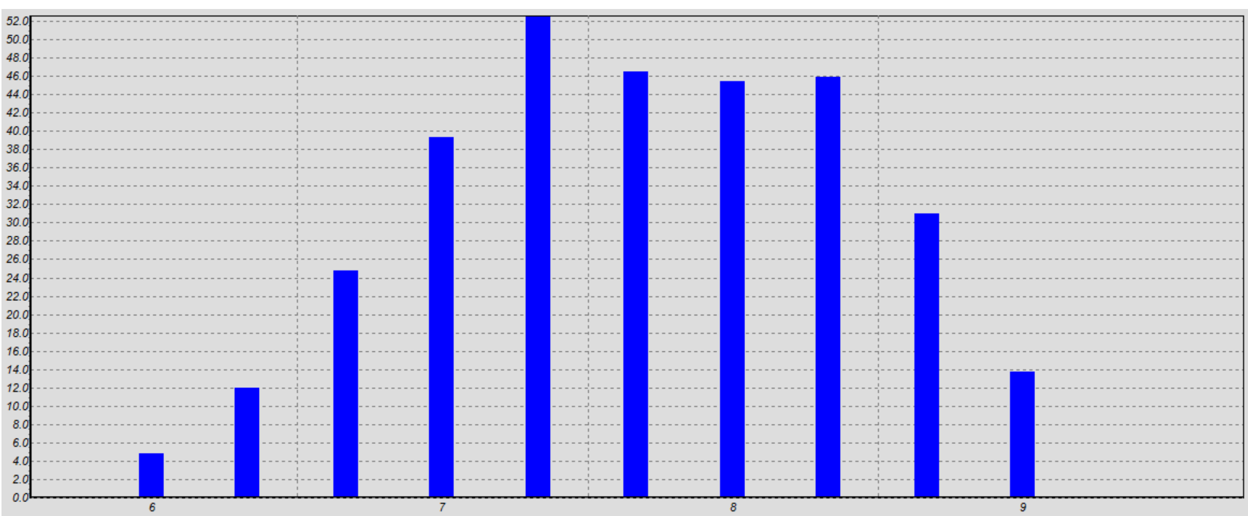


Figure 8: Irrigation Requirements Graph

Table3 shows the irrigation scheme by net daily and monthly irrigation requirements.

CWR changes considerably with the development of the crop through different stages of growth because of effect of change in received rainfall water.

The total irrigation requirement in the months of August is highest with the value of 137.8mm.

Table3: Irrigation scheme

Net scheme irr.req.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
in mm/day	0	0	0	0	0	0.6	3.8	4.4	1.5	0	0	0
in mm/month	0	0	0	0	0	16.8	116.6	137.8	44.8	0	0	0

In the starting and closing stages, the requirement of irrigation is low and it becomes higher in mid stages.

8. Conclusion and recommendations

8.1. Conclusion

Nowadays, agriculture contributes significantly to economic development in many countries. Irrigation is a timely manner to help in improvement of the productivity of agriculture.

This research was focused on design of small scale SIS to be implemented in Kajevuba marshland of Gasabo District in Kigali city for irrigation of one hectare maize crop.

By using CLIMWAT and CROPWAT software, the daily amount of water needed was found to be 52.6m^3.

GRUNDFOS sizing tool was used to choose the appropriate pump system and the corresponding solar modules. The peak solar array capacity necessary to drive a pump system of 1.4 kW was obtained as 1.62 kWp.

Six modules were connected in parallel, each one having 31.6V, 8.76A and 270W as technical specifications.

ISSN 2320-9186

The irrigation of the crop is necessary whenever the crop water requirements is greater than the effective rainfall and the amount of irrigation water needed is dependent on both ET_0 which is influenced by climatic conditions and the type of the grown crop. The higher amount of water requirements is obtained in the month having higher reference evapotranspiration.

The type and size of both solar irrigation pump system and the corresponding solar array depend on the size of the plot to irrigate, type of crops, plantation and harvesting dates, soil and climatic condition of the site of interest.

The findings of this study can be used to improve the efficiency of use of water by a better pump sizing and management of irrigation water extraction which will help not only in practicing a modern, productive, cost effective and clean agriculture but also in quick diffusion of SISs in the all provinces of Rwanda.

8.2. Recommendations

Future researchers should also study carefully the sustainability all country aquifers, water quality and groundwater depth across the country and the corresponding soil textures.

The government of Rwanda should encourage farmers and corresponding partners to implement PVWPS by fixing the amount of subsidies for both on and off grid SISs.

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