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Design optimization of communal solar powered irrigation system

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Communal solar-powered irrigation systems (SPIS) have the potential for sharing the upfront costs hence encouraging farmers to adopt irrigation. Conventional methods of sizing photovoltaic water pumping (PVWP) system for irrigation consider the hydraulic energy requirement by the pump and PV generator capacity separately from the available water source capacity. As a result, the potential of the technology is not optimized, leading to over or under-sizing of the system. Consequently, there is a negative impact on acquisition cost and system performance. The study aimed to determine the optimal PVWP system configuration for communal irrigation. A comparative techno-economic and environmental performance assessment was conducted on different pumping system configurations and a multi-criteria decision analysis approach was used to select the optimal configuration. The findings show a PVWP system with storage tank as the optimal configuration for the communal irrigation. Although the initial capital cost for standalone PVWP system configurations is almost two times that of the conventional diesel pumping systems (CPS), its operation and maintenance (O&M) and lifecycle cost are respectively three times and about four times lower than the CPS cost. Furthermore, the PVWP system for communal irrigation is feasible for irrigation projects that exceed 3 years due to their high acquisition costs. Therefore, promotion of solar-powered irrigation should also focus on the communal approach as a way of improving technology adoption and upscaling.

Key words: Communal irrigation system, photovoltaic water pumping system, solar powered irrigation system, design optimization.

INTRODUCTION

Population growth and food insecurity necessitate an increase in farming all over the world (Hughes et al., 2018). However, Wanyama et al. (2017) indicate that the agricultural sector in sub-Saharan Africa is predominantly subsistence and comprises of smallholder farmers who largely depend on rain-fed agriculture. Consequently, the negative impacts of climate change that are associated with irregular precipitation, extreme rainfall events, long

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periods of drought and extreme temperatures have greatly affected the farm-level production and productivity for most crops (Todde et al., 2019). Hence irrigation is critical in aiding farmers against climate change and plays an integral role in transition from subsistence to commercial farming by ensuring year-round production (Nyamayevu and Chinopfukutwa, 2018).

On the other hand, typical irrigation systems in developing countries (like Uganda) consume a great amount of conventional energy through the use of motorized pumps which are characterized by the high fuel prices, repetitive maintenance costs and carbon emissions that result from their utilization (Phule et al., 2016). Accordingly, there is limited adoption and uptake of irrigation technologies since the low cost alternative of grid electricity in many farming communities is often insufficient or completely absent (Marwa, 2020). Therefore, the use of renewable energy for irrigation is one way of making agriculture more sustainable (Zavala et al., 2020). Solar PVWP system is a well-developed technology and requires almost no maintenance throughout the lifetime of the technology (Hughes et al., 2018). Also, the global decrease in prices for solar panels has made solar pumps for irrigation become an economical, technical, and environmentally viable alternative to conventional pumping systems (Nikzad et al., 2019).

However, the high initial capital cost (ICC) requirement for the PVWP system is a major drawback for technology adoption by smallholder farmers with low purchasing power (Kazem et al., 2015). Furthermore, the land tenure system and conflicts in terms of ownership make land acquisition and compensation a complex enterprise for large-scale commercial farmers (Narvarte and Carrasco, 2018; Zegeye et al., 2014). Alternatively, a communal irrigation model where the water source (valley tank/dam) is shared, acquisition and management of the SPIS become much easier; hence, increased adoption and uptake of this technology amongst the smallholder farmers (Barrueto et al., 2018).

Whereas, PVWP systems for irrigation are characterized by low operation and maintenance costs, factors such as inconsistent solar irradiation, expensive tracking systems, reduction in efficiency due to overheating of panel systems, lower output due to energy conversion, and the high initial capital cost are key design issues for technology adoption (Hughes et al., 2018). On the other hand, the water supply and crop water requirements should be matched with the available water source capacity to achieve a successful design of a PVWP system for irrigation (Zavala et al., 2020). Since irrigation is a seasonal activity, the use of solar energy to power agricultural water pumping offers an opportunity to exploit the variations in solar energy as the increased water requirements for irrigation tend to coincide with the seasonal increase of the incoming solar energy (Maheshwari et al., 2017). When properly designed, the PV systems can also result in significant long-term cost savings and provide access to environmentally sound and reliable energy supply compared to conventional pumping systems.

The common approach for optimizing the PVWP system mainly deals with the improvement of the effectiveness of various system components to minimize the total cost. However Zavala et al. (2020) pointed out that this approach suffers from a lack of systematic quality and static quality. As a result, it does not yield optimal results. Therefore, a systematically integrated of all relevant system components and their performance characteristics have to be developed. Therefore, the design of the PVWP system should not only focus on the initial capital cost requirement but also, on the system performance to available water source capacity and variation in solar energy.

The purpose of the current study was therefore to determine the optimal PVWP system configuration for communal irrigation, which satisfies the objective function of technical reliability, economic viability, and an environmentally safe system over the project period. The results from the current study are essential to supplement the knowledge base for extension officers, suppliers, policymakers, and financing institutions necessary to support farmers who are the major end-user group to appreciate the use of SPIS and be able to make informed decisions towards investment in irrigation.

MATERIALS AND METHODS

Defining objective function and constraint

An optimal PVWP system configuration for communal irrigation should meet the desired crop water demand at minimum energy cost during the irrigation period. In this study, a multi-objective optimization approach has been used to find the optimal size of communal PVWP systems for irrigation using the objective function under a prerequisite. The objective function is to design a communal PVWP system that meets the seasonal irrigation water requirement without exceeding the available water source capacity at a minimum annualized initial capital cost ICC_{ann} ($) and annual operation, maintenance, and replacement cost $C_{o,m}$($) of the system.

The PVWP system failure f_{pv} defined as the hourly drawdown $H_d\ (m)$ (induced by the pumping system during the irrigation season) goes below the minimum pumping level $h_p\ (m)$ (measured from the static water level) or the daily water pumped $Q_{d,pump}\ (m^3/day)$ is larger than the sustainable water volume available, $Q_{d,yield}\ (m^3/day)$.

The hourly decline of the water level and the daily water pumped ($Q_{d,pump}$), which is limited by the water source capacity (Q_{Res}) and dynamically depending on the PVWP system capacity have been summarised in Equation 1and 2 as indicated by Campana et al. (2015):

$$\boldsymbol{\sum f_{pv} = 0; (f_{pv} = \{0,1\}, f_{pv} = 1\ if\ H_d > h_p\ or\ Q_{d,pump} > Q_{d,yield})} \tag{1}$$

$$\boldsymbol{Q_{Avai} = Q_{Res} - Q_{d.seasonal} - Q_{lost}\text{: } Q_{Res} > Q_{d.sea}} \text{ and } \boldsymbol{Q_{Avai} \neq 0} \tag{2}$$

Where $\mathrm{Q_{d.sea}}$ is the seasonal water demand, $\mathrm{Q_{lost}}$ is the seasonal water loss due to evaporation and perforation, and $\mathrm{Q_{Avai}}$ is the available water source capacity.

Description of the design parameters for PVWP system

Irrigation water requirement

The amount of water required for irrigation depends on the farm size, crop type, irrigation method, and the prevailing climatic condition. The crop water requirement is calculated using the methodology proposed by FAO (Mehta and Pandey, 2016). According to this methodology, the real crop evapotranspiration (ET_c), or water consumption for any given period can be calculated according to the following equation

$$\boldsymbol{ET_c = K_c \times ET_o \times K_r} \quad (3)$$

Where ET_o is the reference evapotranspiration (mm), K_c is the crop coefficient and K_r is a reduction coefficient for sparse crops with limited canopy cover (both coefficients are dimensionless).

The net irrigation requirements, N (mm) are equal to the ET_c (mm) minus the effective precipitation that is, rainfall that infiltrates, which is effectively stored in the soil and consequently used by the crop (P_e in mm). This gives the amount of irrigation water needed, Q_d.

$$\boldsymbol{Irrigation\ water\ demand(Q_d) = ET_{r(i)} - P_{e(i)}} \quad (4)$$

Where P_e Can be determined using the following expression:

$\mathrm{P_e} = 0.8 \times \mathrm{P} - 25$ If P> 75 mm/month

$\mathrm{P_e} = 0.6 \times \mathrm{P} - 10$ If P< 75 mm/moth

P is the mean annual rainfall or precipitation (mm/month)

The total system head (H)

The total system head at any time of PVWP system operation is the sum of the static head, the drawdown distance, and the head due to the friction losses in the pipe (Halboot et al., 2016) and can be represented according to Equation 5.

$$\boldsymbol{H_{total} = H_s + H_{dd} + H_D + H_d + H_{Elev.}} \quad (5)$$

Where, H_s is the static head and is equal to the difference between the surface of the water and the discharge point, $H_{Elev.}$ Elevation difference, H_{dd} is the drawdown water level, and H_D and H_d are the equivalent heads due to friction losses in the pipeline and fitting components. The pipeline friction losses (H_D) can be calculated according to the Darcy-Weisbach formula (Moran, 2016).

$$\boldsymbol{H_D = \delta \frac{Lv^2}{2gd}} \quad (6)$$

Where L is the length of the pipeline, d is the internal diameter of the pipeline, δ is the pipeline friction coefficient depending on Reynold's number (0.2461) for moderate turbulent flow according to Halboot et al. (2016), and $\boldsymbol{v}$ is the average speed of the water (m/sec), which is related to the water flow rate and the cross-sectional area of the pipeline indicated as follows:

$$\boldsymbol{v = \frac{4Q_{d(i)}}{\pi d^2}} \quad (7)$$

Similarly, friction losses (H_d) due to fitting components, such as the valve, junctions, pipe entry, and elbow, can be calculated:

$$\boldsymbol{H_d = \beta \frac{v^2}{2g}} \quad (8)$$

Where β, is a coefficient related to the type of fitting component. By considering all equivalent head friction losses, the total equivalent head losses in pipeline and fittings become:

$$\boldsymbol{H_{friction} = \left(\delta \frac{L}{d} + \beta\right) \frac{v^2}{2g}} \quad (9)$$

Pump and motor capacity

The size of the water pump and the hydraulic power of the centrifugal pump according to the following equation (Al-waeli et al., 2017a):

$$\boldsymbol{P_{pump} = \frac{\rho g(H + \Delta H)Q}{\eta_b \cdot \eta_e}} \quad (10)$$

Where ρ is the density of water ($1000\,Kg/m^3$), Q is the required flow rate(m^3/hr) determined from daily crop water requirement Q_d, g is the gravity ($9.81 m/s^2$), $H\ and\ \Delta H$ are total pumping head and hydraulic losses in m, η_b and η_e are pump and electric motor efficiencies, respectively.

In addition, the hydraulic energy E_h (kWh/d) required per day to supply a volume Q_d of water (m^3) at head H_t (m) is given by Chandel et al. (2015b) and Chilundo et al. (2018).

$$\boldsymbol{E_h = \eta_s \cdot P_{pv} = \rho g h Q_d \eta_s} \quad (11)$$

Where η_s is the subsystem efficiency, and E_{pv} is the PV energy.

PV generator capacity for the pumping system

To maximize the output of the solar panels, the orientation and tilt angle of the panel surface should be decided according to the site-specific location (Nikzad et al., 2019). Based on the mounting options for solar panels, that is, the fixed tilt angle and the solar tracker with varying orientation, the fixed installation of solar panels on a rigid structure is the cheapest, most reliable, and most common method (Ahmed, 2019). The installation is typically oriented north or south to have a relatively good distribution of the output for the day. The capacity of the PV generator can be determined according to the following procedure (Sopian et al., 2017).

$$\boldsymbol{PV_{array} = \frac{Peak\ power\ of\ the\ pump}{Overall\ efficiency\ factor}} \quad (12)$$

The total DC (I_{dc}) needed can be calculated by diving the peak power by the DC voltage of the PV module.

$$\boldsymbol{I_{dc} = \frac{Peak\ Power\ of\ the\ pump}{PV\ system\ DC\ voltage}} \quad (13)$$

Modules are connected in series and parallel according to the need to meet the desired voltage and current. The number of modules in series equals the DC voltage of the system divided by the rated voltage of each module.

$$\boldsymbol{N_{series} = \frac{System\ DC\ voltage}{Module\ rated\ Voltage}} \quad (14)$$

The number of modules in parallel equals the total DC (I_{dc}) of the system divided by the rated current of one module.

$$\boldsymbol{N_{parallel}} = \frac{\boldsymbol{I_{dc}}}{\boldsymbol{Rated\ current\ of\ one\ module}} = \frac{\boldsymbol{PV_{array}}}{\boldsymbol{N_{series}*PV\ module\ capacity}} \quad (15)$$

The total number of modules N equals the product of modules in series (N_{series}) and modules in parallel ($N_{parallel}$).

Sizing battery backup system

Batteries have the potential to increase the PVWP system reliability by storing energy and using it when the solar intensity is not available (Al-waeli et al., 2017b). However, batteries increase the acquisition and maintenance cost of the solar PV system for irrigation since batteries require to be replaced after a given period of time (Chilundo et al., 2018). The battery type recommended for use in a solar PV system is a deep cycle battery since they have a high depth of discharge (DOD). The battery capacity should be large enough to cater to the number of autonomy days (days without solar energy for charging). The required capacity of the battery bank for PVWP system can be determined using the following procedure (Sopian et al., 2017):

$$E_{rough} = Energy\ storage\ required * No.of\ autonomy\ day$$

For safety, E_{rough} should be multiplied by the maximum allowable depth of discharge (DOD):

$$\boldsymbol{E_{safe}} = \frac{\boldsymbol{E_{rough}}}{\boldsymbol{Max.depth\ of\ discharge\ (DOD)}} \quad (16)$$

The capacity of the battery bank in ampere-hours can be obtained by dividing the safe energy storage required by the DC voltage of one of the batteries selected.

$$\boldsymbol{Battery\ bank} = \frac{\boldsymbol{E_{safe}}}{\boldsymbol{Battery\ DC\ voltage}} \quad (17)$$

The total number of batteries required is obtained by dividing the capacity of the battery bank in ampere-hours (Ah) by the battery capacity in ampere-hours:

$$\boldsymbol{N_{battery}} = \frac{\boldsymbol{Battery\ bank}}{\boldsymbol{Capacity\ of\ one\ battery}} \quad (18)$$

The number of batteries in series ($N_{b.series}$) and batteries in parallel ($N_{b.parallel}$) obtained as follows:

$$\boldsymbol{N_{b.series}} = \frac{\boldsymbol{System\ DC\ voltage}}{\boldsymbol{Battery\ voltage}} \quad (19)$$

$$\boldsymbol{N_{b.parallel}} = \frac{\boldsymbol{Total\ number\ of\ batteries}}{\boldsymbol{number\ of\ batteries\ in\ series}} \quad (17)$$

Voltage regulator for PVWP system

A good voltage regulator must be able to withstand the maximum current produced by the PV array as well as the maximum load current (Sopian et al., 2017). The sizing of the voltage regulator can be obtained by multiplying the short circuit current (I_{sc}) of the modules connected in parallel (N_p) by a factor of safety (F_{safety}). The result gives the rated current of the voltage regulator.

$$\boldsymbol{I_{regulator}} = \boldsymbol{N_p} * \boldsymbol{I_{sc}} * \boldsymbol{F_{safety}} \quad (21)$$

The F_{safety} is used to ensure that the regulator handles the maximum current produced by the PV array that could exceed the tabulated value and to handle a load current more than that planned and to allow the system to expand slightly. In the current study F_{safety} and I_{sc} have been assumed as 25% and 8.03A, respectively.

Inverter capacity for the PVWP system

Inverters are used in PVWP systems when an AC pump is required. According to El-houari et al. (2021), the input rating of the inverter should never be lower than the total watt of appliances. The inverter must have the same nominal voltage as that of the battery or PV array. For stand-alone systems, the inverter must be large enough to handle the total amount of Watts that will be used at one time. The inverter size should be at least 25% bigger than the total Watts of appliances (Sopian et al., 2017).

Intermediate storage tank capacity

Irrigation is seldom done on a daily basis, depending on crop type, soil type, and climatic conditions. The size of the storage tank to be filled daily is directly related to the pump capacity and the average daily solar irradiation (kWh/m^2day). Therefore, the capacity of the intermediate storage tank should be able to satisfy the daily irrigation water requirement (Q_d) but not exceeding the maximum daily pump capacity ($Q_{d,pump}$) at peak power. Hence, the required volume of storage tank $Q_{st}(m^3/day)$ is given by the equation below (Chandel et al., 2015b).

$$\boldsymbol{Q_{st}} = \boldsymbol{P_{pv}}.\ \boldsymbol{I_t}.\boldsymbol{\mathcal{J}_{mp}}\ .\boldsymbol{\mathcal{F}}/\boldsymbol{\rho g H_t} \quad (22)$$

Where $\boldsymbol{I_t}$ is the average daily solar irradiation (kWh/m^2day) incident on the plane of array, $\boldsymbol{\mathcal{F}}$ is the array mismatch factor, and $\boldsymbol{\mathcal{J}_{mp}}$ is the daily subsystem efficiency.

Water source design for communal SPIS

Communal irrigation system requires high volume of water to satisfy the daily irrigation water demand. Unlike groundwater sources (boreholes), which are usually limited by the yielding capacity of the well (Nsubuga et al., 2014), valley tanks/dams have the potential to withstand a high daily abstraction rate for communal irrigation. Therefore, this study proposed the design modification on valley tanks/ dams to favour the use of submersible pumps for the communal irrigation system.

The valley tank/dam should be constructed with an infiltration gallery through which water is siphoned into an extraction pot similar to a shallow well whose depth should be at least 2 m deeper than the depth of the valley tank to allow maximum extraction of water from the reservoir. Depth of extraction pot ($d_{ext.pot}$) is given by:

$$\boldsymbol{d_{ext.pot}} = \boldsymbol{d_{tank}} + \boldsymbol{x} \quad (23)$$

Where $x \geq 2m$ in order to cater for the pump length, $d_{ext.pot}$ Is the depth of the extraction pot and d_{tank} is the depth of the valley tank/ dam.

An optimization approach for communal PVWP system

Multi-criteria decision analysis approach for selecting optimal PVWP system

The multi-criteria decision analysis (MCDA), was used to evaluate design criteria with conflicting objectives based on the prerequisite performance indicators for communal pumping system. The general

Table 1. Multiple criteria decision analysis approach for determining the optimal pumping configuration.

Criteria	Weighted index	Objective	Indicator	Weight	Pumping configurations
					Scores (1,2,3,4,5)
Technical	0.4	System reliability	Pump use efficiency	0.5	
			Energy use efficiency	0.5	
Economic	0.4	Minimum cost of energy over the irrigation period	Initial capital cost (ICC)	0.1	
			Cost of energy (CoE)	0.25	
			Water discharge cost	0.25	
			Life cycle cost (LCC)	0.4	
Environment	0.2	Safe environment	Carbon emission	1	

Source: The MCDA table has been customized based on the procedure described by Alvaro et al., (2020)

preference score is the weighted average of all criteria and indicators (Alvaro et al., 2020). The design criteria for the current study were technical, economic and environmental with a weighted index of 0.4, 0.4 and 0.2 respectively. The preference scores of each system configuration can then be multiplied by the weighted index of each criterion to obtain the overall system performance as shown in Table 1.

The performance rank of each system configuration is used as a basis for selecting the optimal pumping system configuration for communal irrigation.

Technical optimization approach

This criterion focuses on performance reliability. The optimal pumping system configuration should be able to satisfy the crop water requirement throughout the irrigation season without exceeding the available water source capacity. Since water is a scarce resource and represents a limiting factor for agriculture; reduction of water losses is one of the major design considerations for communal irrigation system. The prerequisite is to minimize system failure during the entire irrigation season. The approach is evaluated according to the pump use efficiency and energy use efficiency (Rafael and Reca, 2020).

The pump use efficiency is used to measure the pump utilization rate (PUR) in the course of satisfying the irrigation water requirement (Gavino, 2018). The maximum PUR recommended is 0.85 or 85%.

$$\boldsymbol{Pump\ utilization\ rate} = \frac{\boldsymbol{Seasonal\ water\ pumped}}{\boldsymbol{Maximum\ possible\ seasonal\ pump\ capacity}} \tag{24}$$

Whereas, the energy use efficiency (EUE), is the fraction of the maximum energy potentially generated by the PV system that is effectively used. The higher the value of EUE, the more efficient use of solar energy generated (Rafael and Reca, 2020).

$$\boldsymbol{EUE} = \frac{\boldsymbol{Energy\ effectively\ used\ to\ pump\ water\ (E_p)}}{\boldsymbol{Total\ energy\ potentially\ produced\ by\ the\ PV\ system\ (E_{pv})}} \tag{25}$$

Economic optimization approach

The economic performance assessment of different communal pumping configuration is done to select a pumping system with minimum energy cost along its life cycle period. The initial capital cost (ICC), annual operation, maintenance and replacement cost, present value cost (PVC), annual equivalent cost (AEC), and life cycle cost (LCC) are numerically compared over the irrigation project period (Zegeye et al., 2014; Nikzad et al., 2019).

Present value cost (PVC)

The PVC of the pumping system can be estimated using the equation by Yousef (2016).

$$\boldsymbol{PVC} = \boldsymbol{ICC} + \sum_{\boldsymbol{n=1}}^{\boldsymbol{n}} \frac{\boldsymbol{ICC_{ann}}}{\boldsymbol{(1+r)^n}} \tag{26}$$

Where ICC is the initial investment cost of the pumping system including the engineering design, civil works, transportation, and installation fees. n is the project period, r is the discount rate and ICC_{ann} is the annualized initial capital cost based on the following equation (Campana et al., 2015).

$$\boldsymbol{ICC_{ann}} = \boldsymbol{ICC}\left[\frac{\boldsymbol{r(1+i)^n}}{\boldsymbol{(1+r)^n-1}}\right] \tag{1}$$

Similarly, the Present worth factor (PWF) can be estimated:

$$\boldsymbol{PWF} = \frac{\boldsymbol{r(1+r)^n}}{\boldsymbol{(1+r)^n-1}} \tag{2}$$

Accordingly, cost of energy (CoE) can be obtained using following equation 29 as described by Mustafa and Hamad, (2016).

$$\boldsymbol{Energy_{cost}} = \frac{\boldsymbol{PVC}}{\boldsymbol{kWh*PWF}} \tag{29}$$

Where kWh is the annual energy, calculated using the following equation:

$$\boldsymbol{kWh} = \boldsymbol{P} * \boldsymbol{n_o} * \boldsymbol{365} \tag{30}$$

Where, n_o is the daily hour of operation.

Annual equivalent cost (AEC)

AEC is useful in analysing the life cycle cost (LCC) of the communal pumping system configurations in comparison with an alternative source of power with different lifespans.

$$\boldsymbol{AEC} = \boldsymbol{PVC}\left[\frac{\boldsymbol{r(1+r)^n}}{\boldsymbol{(1+r)^n-1}}\right] \tag{31}$$

The specific water discharge cost ($US\$/m^3$) can be determined

Table 1. Case study details for the design of communal SPIS.

Particular	**Site-specific parameter**	
Location	Luwero District, Kakukulu parish, Kikakala Village	
GPS coordinates	$0^0 48' \, 03.8'' N$, $32^0 35^I 11.6^{II} E$, 1104M	
GPS coordinates for valley tank	$0^0 47' \, 51.56'' N$, $32^0 35' 07.8'' E$, 1092m	
Dimensions of the valley tank	65*85*4 m or 22,100m^3 holding capacity	
Elevation difference	12m at 600m from the water source	
Mode of recharge	Runoff due to rainfall with limited underground recharge	
Number of farmers and acreage	10 farmers each 5 acres (50 acres in total assessed for irrigation)	
Acreage by crop type	Tomatoes: 14 acre, onions: 12 acre, hot-pepper:14 acre, coffee: 10 acres	
Irrigation pressure requirement	Drip irrigation system	0.5 bars
	Sprinklers irrigation system	(3-5) bars
Static water level	1.0 m	

Source: Primary data collected from the case study location (〖0.8011〗 ^0 N, 〖32.5866〗 ^0 E) for design analysis of optimal communal water pumping system configuration

Table 2. Climatic data for the case study.

Parameter	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Mean daily temperature (°C)	22.4	22.4	22.0	21.2	20.8	20.6	20.1	20.2	20.7	21.2	21.5	21.6
Rainfall (mm/month)	58.2	68.0	127.8	185.0	134.3	71.3	55.3	87.1	100.3	119.0	142.4	94.5

Source: Source: Data derived from http://www.worldclimate.com/cgi-bin/data.pl?ref=N00E032+2100+63680W and https://en.climate-data.org/africa/uganda/central-region/luweero-1051951/

using AEC and taken as a basis for comparing economic performance of different communal pumping configurations.

Environmental optimization approach

This approach aims to minimize carbon emissions by the pumping system configuration during its utilization. According to Nikzad et al. *(2019)*, carbon emissions from PVWP system configurations are negligible. Whereas, emissions by conventional diesel pumping system can thus be estimated according to the approach by Hossain et al. (2015).

$$\boldsymbol{Carborn\ emission =} \\ \boldsymbol{emission\ factor\ X\ Annual\ fuel\ consumption} \tag{32}$$

Validation of the optimization approach

Approach

The optimization procedure was tested on a selected case study based on four PVWP system configurations and a standalone diesel pumping system. A comparative assessment of technical, economic and environmental performance indicators was conducted on the pumping system configurations. A multiple-criteria decision analysis described previously was used to obtain the optimal PVWP system configuration for communal irrigation.

The selected case study was representative of the farming community of multiple smallholder farmers within a vicinity of fewer than 700 m from the communally owned and managed water source, a valley tank/dam as the water source, and high-value crops: Horticulture crops (tomatoes, hot pepper and onions), and coffee (Robusta coffee) (Table 2).

Description of the case study

The mean daily temperature (°C) and the rainfall (mm/month) in Table 3 for the case study location was used. From the average hourly profiles of the total photovoltaic power output *[kWh]* with optimal tilted angle for equator oriented surface, the average annual solar energy potential for the case study area is $5.58\ kWh/m^2/day$ (Global Solar Atlas, 2021).

Assumptions for the economic evaluation of the communal PVWP system

The cost of the PV support structure is assumed as 40% of the total cost of the PV module, the installation cost is 23% of the total system cost and the operating and maintenance cost for the PVWP system is considered as 2% of the initial capital cost (Padmanathan et al*.,* 2017). For the diesel pumping system, the annual operating and maintenance cost is considered as 8% of the initial capital cost of the system, fuel cost is assumed as 1.1 US$/L and installation cost of the diesel pumping system has been taken as 10% of the system cost Table 4.

RESULTS AND DISCUSSION

The capacity of communal water pumping system for irrigation

Irrigation water demand for communal pumping system

The irrigation water requirement for the case study was

Table 4. Initial capital costs for system components.

System component	Units	Unit cost ($)	Life cycle time (years)
Solar PV module each 250 W, 24DCV	US$/W	0.7	25
Submersible pump and motor set	US$/kW	350	15
Inverter/ motor controller	US$/kW	300	15
Voltage regulator	US$/A	3.3	15
Battery capacity 200Ah; 12DCV and DOD 80%	US$/Ah	1.3	8
Diesel generator	US$/kVA	500	13
Intermediate water storage tank	$US\$/m^3$	70	25

Source: Author

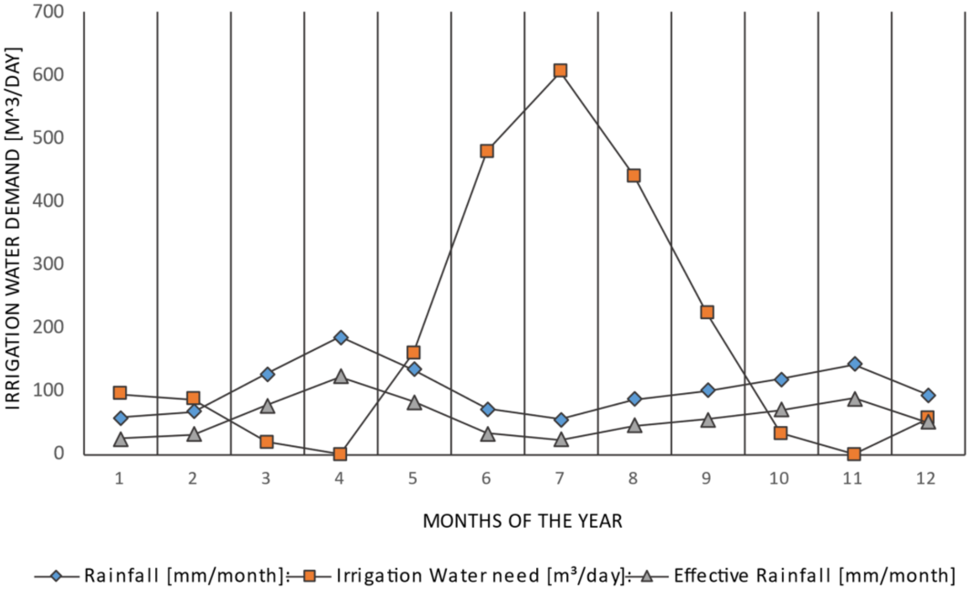

Figure 1. Relationship between the total irrigation water demand and effective rainfall.
Source: Author

obtained as a deficit of the irrigation water demand and effective rainfall as shown in Figures 1 and 2.

From Figure 1, the peak demand is shown in July with a total daily water demand of $606\ m^3/day$ and the lowest effective rainfall of 23.18 mm/month. Similarly, the highest effective rainfall is shown in April and November with total rainfall of 123 mm/month and 88.92 mm/month respectively. Therefore, from March to May and mid-September to Early-December, crops may not demand water for irrigation since the effective rainfall for the location exceeds the crop water demand. Therefore, communal irrigation is required from mid-May to early-September and mid- December to early-February.

Furthermore, Figure 2 reviewed that different crops demand different amounts of water within the same period as indicated by Mehta and Pandey (2016). Therefore, when planting is done with consideration of crop water demand for different growth stages and prevailing rainfall trend, deficit water required for irrigation can be minimized. Similarly, when irrigation scheduling is considered, the average annual daily crop water requirement of 183 $\mathrm{m}^3/\mathrm{day}$ can potentially satisfy the communal irrigation water as shown in Figure 5. Hence, increase in pump utilization rate from 30 to 40% and water saving of up to 35% which is critical in areas with water scarcity. The results from this approach are similar with those obtained by Reddy and Nayak (2018).

Water source design for communal irrigation system

The communal valley-tank was developed as shown in Figure 3a to d with the multi-grade stone filters placed around the perforated culverts in the extraction pot through which a pump-holding pipe (sleeve to guide water flow through the bottom) installed (Figure 3c, d,

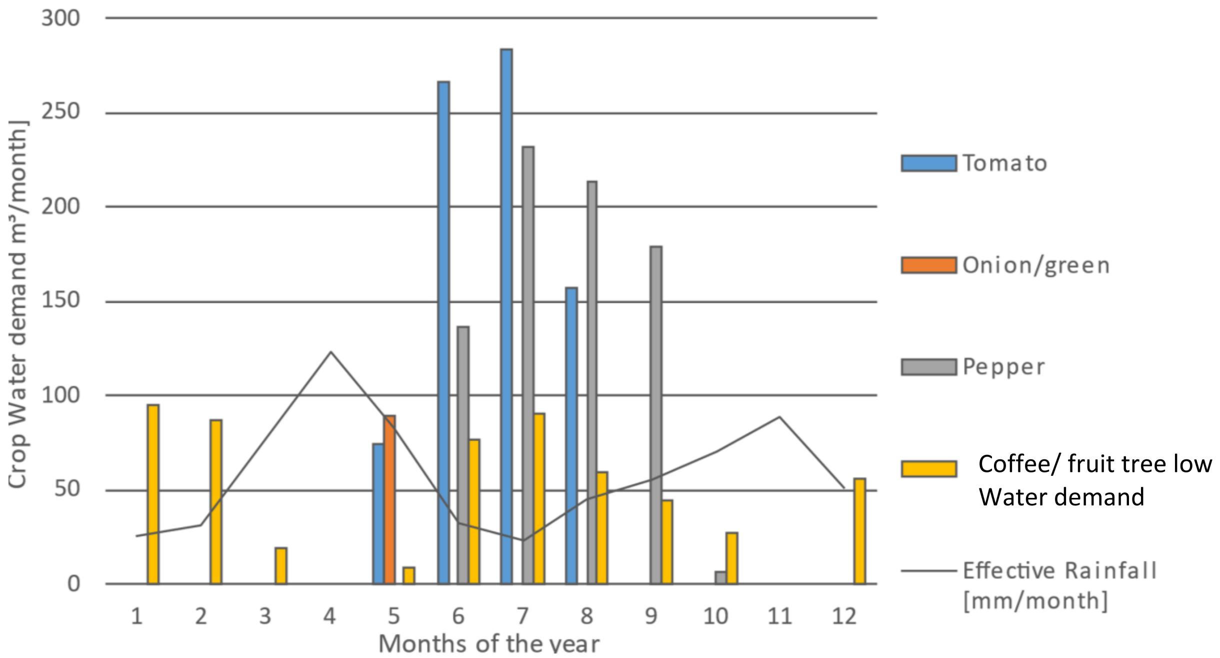

Figure 2. Crop water demand and effective rainfall in months of the year.
Source: Author

Figure 3. Modified water abstraction pot for sustainable use of submersible pump.
Source: Author

and e). The stone filters prevent silt from entering the pumping zone hence, improving its performance.

When a pump is installed in the middle of the communal water source/tank as shown in Figure 4a and b for previous methods, the pump capacity is limited by the installation depth and it stops when water level drops

Figure 4. Previously installed submersible solar pump in the valley tank.
Source: Submersible pump installation in a reservoir for Mawokota Farmers` Association (Mpigi district)

Table 5. Pump testing results for communal valley tank.

Particular	Specific quantity/ units
Valley tank capacity/ dimensions	85 m × 65 m × 4 m (22,100 m^3)
Volume of water in the tank	85 m × 65 m × 3 m (16,575m^3)
Maximum water that can be extracted from the tank (85%)	14,088.75 m^3
Depth of the extraction pot	6 m
Effective water pumping depth for submersible pump	2.5 m
Pump capacity used for testing	6.5 HP, 40 m^3/h flow rate, 30 m head
Pump testing period	8 h
Drawdown/ level drop after pumping	20 mm

Source: Author

to the pump depth (Figure 4b), hence system failure (Barrueto et al., 2018). The additional depth of the extraction pot in Figure 3, improves the effective pumping depth of the submersible pump for communal solar powered irrigation.

Furthermore, the pump testing in Figure 3c and d whose results are shown in Table 5 indicates that, $320\,m^3$of water was extracted in 8 h of pump testing which exceeds the peak irrigation water demand ($183\ m^3/day$) for the case study and a level drop of only $20\,mm$ was observed. Considering the effective pumping depth of $2.5\,m$ and extraction of $320\,m^3/day$, the valley tank capacity can provide irrigation water for $125\,days$ without additional recharge. Therefore, a well-sized rainwater harvesting reservoir/tank is able to satisfy the seasonal water demand for communal irrigation since, the pump abstraction rate is a small fraction of the reservoir capacity. Hence, pumping system failure due to drawdown exceeding the pumping rate can be minimized. Thereby addressing the design constraint indicated by Jana et al. (2017) and Ghoneim (2018).

Hydraulic power requirement for communal pumping system configuration

The capacity of the submersible pumping system for irrigation mainly depends on the required pumping head and flow rate. However, it was observed that the high irrigation pressure demand of $3.0\ to\ 5.0bar$ for direct pumping system can significantly increase the head loss compared with that of storage tank system whose pressure demand is low ($\leq 0.5bar$) particularly for drip irrigation. Therefore, the overall hydraulic energy for communal pumping system depends on the daily irrigation-water demand, downstream irrigation pressure requirement, and head losses in pipes and fittings necessary to deliver water from the source to the required point. The observation is similar with the conclusion made by Chilundo et al. (2018) and Meunier and Migan-dubois (2020).

Similarly, from Figure 5, a pumping system sized using the average annual daily sunshine hours ($5.5\,h$ for the current study) has the potential to satisfy the communal

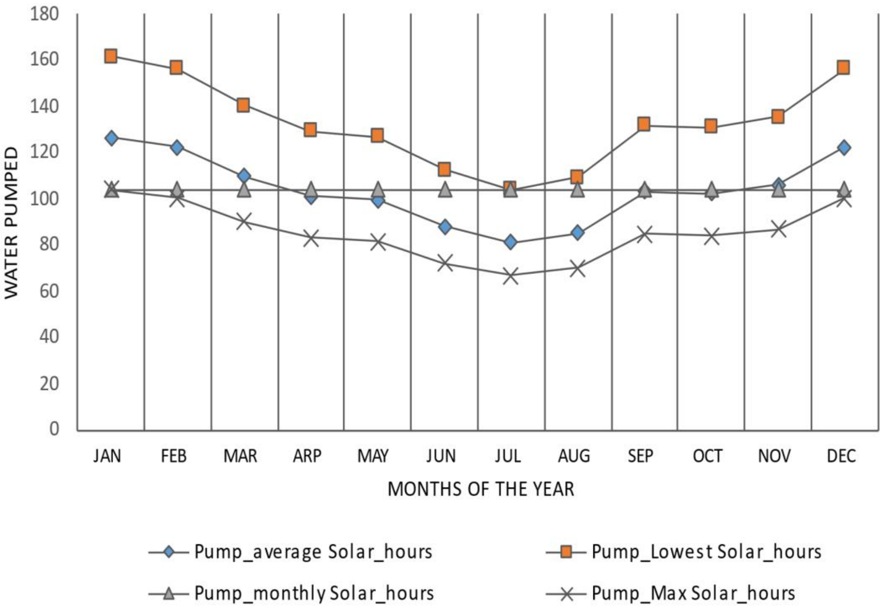

Figure 5. Effect of solar energy variation on pumping performance of the pump.
Source: Author

Table 6. The hydraulic energy requirement for different configurations of the pump.

Pumping system configuration	Head (m)	Flow rate (m^3/h)
PVWP- Direct pumping to sprinklers	85.5	34.04
PVWP- intermediate storage water tank	47.0	20.8
Hybrid PVWP- diesel generator	85.5	22.02
PVWP- battery backup system	85.5	22.02
Standalone diesel pumping system	85.5	31.2

Source: Author

irrigation water demand across the irrigation season. A pump selected at a fixed flow rate of $20.8\,m^3/h$ can deliver $114.4\,m^3/day$ at the average annual daily solar irradiance. During the peak season, the sunshine hours increase to a maximum (about 8.5 h/day for the case study) thereby increasing the possible water pumped per day ($176.8\,m^3/day$) which coincides with the peak water demand for communal irrigation. The deficit water required for irrigation during peak months can be compensated through irrigation scheduling. The findings are in agreement with those achieved by Rafael and Reca (2020**)**. The hydraulic energy requirement for different pumping configurations shown in Table 6 were used to obtain the technical parameter for the complete pumping system as indicated in Table 7.

Economic optimization of communal PVWP system for irrigation

The economic performance analysis for the PVWP systems based on key indicators was compared with the conventional diesel pumping system as shown in Table 8.

The results in the Table 8 indicates that the diesel pumping system has lower initial capital cost requirement, but high operation, maintenance and replacement costs compared with PVWP system configurations. However, the annualized capital cost for the PVWP systems over the entire irrigation project period of 25 years is lower than that of diesel generator powered pumps as shown in Figures 6 and 7. The lower annual operation and maintenance cost and the long lifecycle of the PV components as opposed to that of diesel pumping system, which results from the lower replacement cost for PV components and high replacement cost for diesel generator system. Hence low lifecycle cost (LCC) for solar PV and high lifecycle cost for diesel system which is similar to the conclusion made by Al-waeli et al. (2017b) and Nikzad et al. (2019)**.**

Further reference on Figure 6 shows that, the annual expenses for all PVWP system configurations are higher than those of conventional diesel pumping system at the

Table 7. Technical parameters of different water pumping system configurations for communal irrigation.

System design parameter	PVWP- direct system	PVWP- storage tank system	PVWP- standby generator	PVWP- battery system	Diesel water pumping system
Minimum pump head (*m*)	89	47	89	89	89
Minimum pump flow rate ($\boldsymbol{m^3/h}$)	34.0	20.8	22	22	31.2
Pump-motor capacity (*kWp*)	17.05	7.65	10.225	9.4	13.3
Solar PV generator capacity (*kWh*)	23.52	10.55	14.11	16.21	
Number of panels (24DCV, 250 W)	94	42	56	65	
No. of PV modules in series	2	2	2	2	
No. of PV modules in parallel	47	21	28	32	
Rated power of the inverter (*kW*)	30.58	13.72	18.34	12.22	
Regulator input current (A)	142.6	64	85.5	196.6	111.2
Min. wire to power controller $\boldsymbol{mm^2}$	6	4	4	6	4
Min. wire size to the load ($\boldsymbol{mm^2}$)	16	6	10	10	6
Diesel generator capacity (*kVA)*			16.6		23.42
Battery bank capacity for 8h, (Ah)				7833	
No. of batteries (12DCV,200Ah)				39	
No. of batteries in series				2	
No. of batteries in parallel				20	
Storage water tank capacity ($\boldsymbol{m^3}$)		100			

Source: Author

Table 8. Comparative economic performance for PVWP and Diesel water pumping system.

PVWP system configuration	Economic indicators (US$)			
	ICC	$\boldsymbol{US\$/m^3}$	LCC	COE
PVWP- direct pumping to sprinklers	47,105.93	0.21	94,559	0.23
PVWP- intermediate storage water tank	36,355.73	0.15	65,866	0.21
Hybrid PVWP- diesel generator	37,271.62	0.22	205,391	0.30
PVWP- battery backup system	43,586.28	0.21	137,087	0.27
Standalone diesel pumping system	27,885.00	0.24	354,095	0.51

Source: Author

beginning of the project due to their high initial investment cost.

However, after the First 2 to 4 years of operation, the PVWP system costs decreases due to their low operation and maintenance (O&M) costs unlike the high O&M costs for the diesel generator pumping system which are caused by the high fuel prices and frequent breakdowns.

Similarly, based on the specific water discharge cost analysis in Table 8, the annualized unit cost of water pumped for all pumping options over the project lifetime is lowest under a system with storage tank $0.15\,US\$/m^3$ and highest with a standalone diesel generator pumping system$(0.28\,US\$/m^3)$. Furthermore, the PVWP system configuration with the least cost of energy (COE) $0.22\,US\$/Kw$ is that with a storage tank and highest for the standalone diesel pumping system as 0.47 US$/Kw. These results are close those obtained by Marwa (2020).

Further comparative analysis of life cycle cost (LCC) under Figure 7, the LCC of the standalone diesel generator pumping system is the lowest in the first year of operation compared with the PVWP system configurations due to difference in the system acquisition costs. However, during the 2 to 3rd year of operation, the LCC for diesel pumping system increases drastically and exceeds those of solar PV systems (breakeven point). Implying that for irrigation projects that exceeds 3 years of operation (breakeven point), the PVWP system is more feasible for investment. Therefore, for any irrigation project less than 3 years, diesel solutions may make more economic sense due to their lower initial capital cost (ICC). The 3 years breakeven point obtained in this study is close to the 4 years that were achieved by Nikzad et al. (2019).

Accordingly, among the assessed pumping system configurations, the PVWP system with a storage tank has the lowest life cycle cost (LCC) at the end of the project period (20 years). Therefore, the initial capital cost (ICC) for PVWP system is 1.69 times that of diesel generator

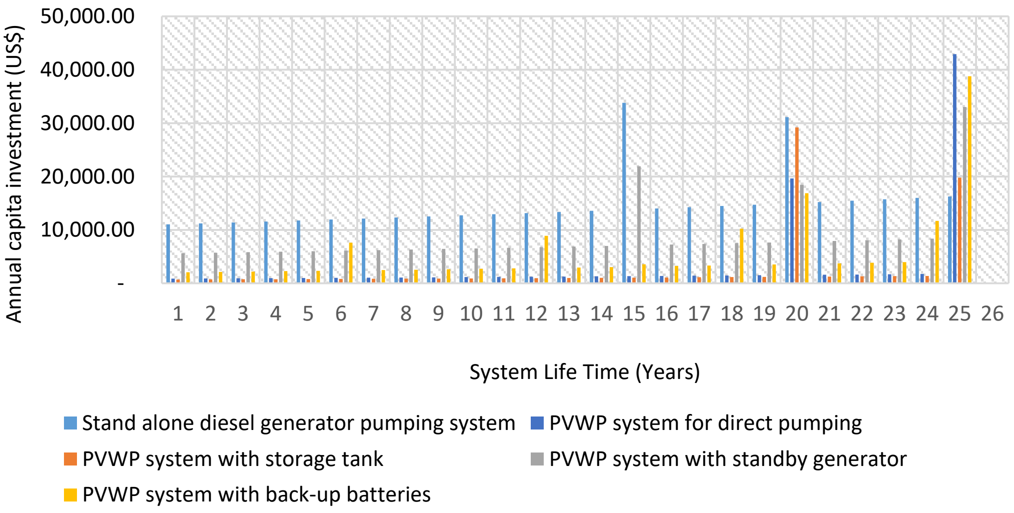

Figure 6. Comparison of annualized capital and operational expenses for PVWP system configuration and a standalone diesel generator pumping system along the project lifecycle period.
Source: Author

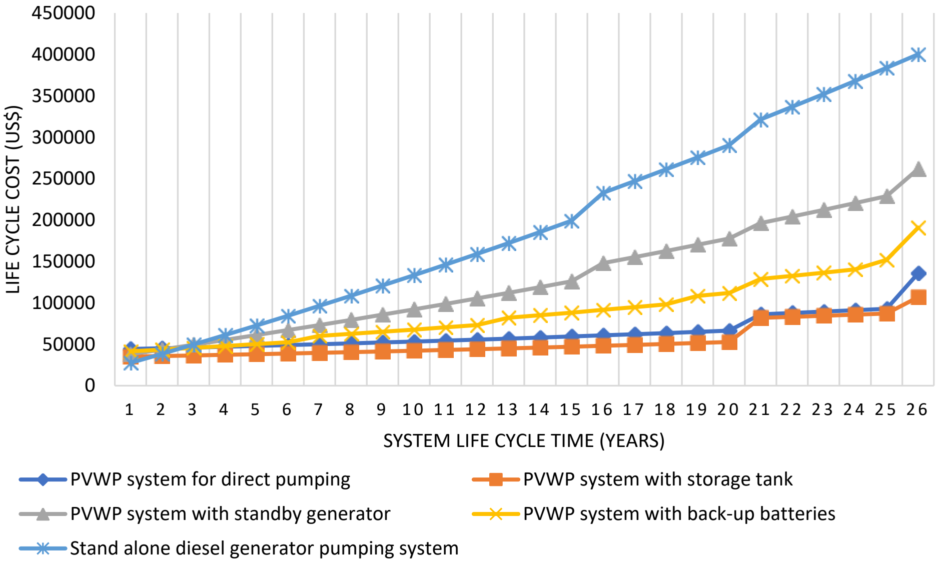

Figure 7. The LCC analysis for different pumping system configurations.
Source: Author

pumping system and the LCC for DWPS at the end of the project period is 3.85 times that of PVWPS as indicated in the study by Marwa (2020).

Environmental assessment for communal pumping system

The carbon emissions from conventional diesel powered system configurations for the hybrid PVWP with a standby generator and the standalone diesel water pumping system have been summarized in Table 9.

The use of PVWP system for communal irrigation has potential to save environment from carbon emissions of about 24.48 ton/year when a standalone diesel pumping system is used and 11.48 ton/year when a hybrid PVWP system with a standby generator is used.

Multi-criteria decision analysis for selecting optimal pumping system configuration

The technical, economic and environmental performance criterion for different communal water pumping system

Table 9. Carbon emission from the pumping system.

System configuration	Carbon emission (ton/year)
Hybrid PVWP system with a standby generator	11.48
Standalone diesel water pumping system	24.48

Source: Author

Table 10. Multiple criteria decision analysis results for selecting optimal pumping system configuration.

Criteria	Weighted index	Objective	Indicator	Weight	Pumping configurations				
					Scores (1,2,3,4,5)				
Technical	0.4	System reliability	Pump use efficiency	0.5	5	5	5	5	5
			Energy use efficiency	0.5	4	5	1	3	1
Economic	0.4	Minimum cost of energy over the irrigation period	Initial capital cost (ICC)	0.1	1	4	3	2	5
			Cost of energy (CoE)	0.25	4	5	2	3	1
			Water discharge cost	0.25	2	5	2	2	1
			Life cycle cost (LCC)	0.4	4	5	2	3	1
Environment	0.2	Safe environment	Carbon emission	1	5	5	2	3	1
			Technical	0.4	3.5	4.5	3	3.5	2
			Economic	0.4	3	4.8	2.2	2.6	1.8
			Environmental	0.2	5	5	2	3	1
Overall score					3.6	4.72	2.48	3.04	1.72
Rank					2	1	4	3	5

Source: Author

configurations were evaluated according to key indicators and subjected to a multi- dimension decision analysis approach. The overall performance score of different pumping configurations is summarized in Table 10 where ranking results indicates that a PVWP system with a storage tank as the optimal configuration for communal irrigation. Whereas, the diesel-powered pumping systems shown the worst performance. The results from this comparative study is similar with those by Jana et al. (2017).

Conclusion

The optimal PVWP system configuration for communal irrigation has been determined as a function of the average daily solar irradiance, crop water requirement and the available water source capacity. The pump testing results for communal water source indicated that, the required pump flow rate for communal irrigation is a small function of the reservoir holding capacity and hence able to satisfy the seasonal irrigation water demand. The techno-economic and environmental assessments of different pumping system configurations were compared using a multi-criteria decision analysis approach. A standalone PVWP system with storage tank has been found as the optimal pumping configuration for communal irrigation. The sensitivity analysis revealed that when capacity of the water storage tank increases, energy cost rises, and therefore, the optimal storage tank capacity for PVWP system should not exceed the average annual daily irrigation water requirement. The initial capital cost for optimal PVWP system is 1.69 times that of conventional diesel water pumping system (DWPS) and the LCC for DWPS at the end of the project is 5.4 times that of PVWP system. Therefore, PVWP systems for communal irrigation are economically feasible for irrigation projects that exceed 3 years due to their high acquisition cost when compared with the diesel water pumping options. The use of PVWP system configuration for communal irrigation has greater potential for minimizing carbon emission of approximately 26.64 tons/year when a diesel pumping system is used.

Recommendations

To operationalize the methodology for selecting the optimal PVWP system configuration for communal irrigation, the development of a decision support tool is required. Furthermore, the impact of deficit irrigation on crop production and productivity is required for optimal sizing of the PVWP system for communal irrigation.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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