# Effects of total system head and solar radiation on the techno-economics of PV groundwater pumping irrigation system for sustainable agricultural production

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# Effects of total system head and solar radiation on the techno-economics of PV groundwater pumping irrigation system for sustainable agricultural production

I.K. Okakwu[1], A.S. Alayande[2,*], D.O. Akinyele[1], O.E. Olabode[3], J.O. Akinyemi[4]

[1] *Department of Electrical and Electronics Engineering, Olabisi Onabanjo University, Ago-Iwoye, Nigeria*
[2] *Department of Electrical and Electronics Engineering, University of Lagos, Akoka-Yaba, Nigeria*
[3] *Department of Electrical, Electronics and Telecommunication Engineering, Bells University of Technology, Nigeria*
[4] *Department of Agricultural Engineering, Olabisi Onabanjo University, Ago-Iwoye, Nigeria*

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ABSTRACT

Several agricultural farms in Nigeria are found in off-grid locations where there is the lack of water supply despite the abundant groundwater resources possessed by the country. Since water is one of the key resources for agricultural production, majority of the farms only resort to the use of fossil fuel-powered generators to pump water for their operations in Nigeria. However, concerns about the frequent increase in fuel cost, the maintenance, and the environmental issues associated with running fossil-fuel generators have driven the need for a clean and sustainable energy source. The photovoltaic (PV)-pumping system is becoming more popular as an alternative energy source of water pumping for irrigation farming. This study presents the effects of total system head and solar radiation on the techno-economic design of PV-pumping system for groundwater irrigation of crop production in Nigeria. It also calculates the quantity of emissions avoided by the PV. The technical design is based on standard methodology to determine the PV capacity that can operate the pump to satisfy the daily water requirements for the crops, while the economic aspect involves the assessment of the life cycle cost and the cost of water per $m^3$. The result reveals that the pump power ranges from 0.158 kW to 0.293 kW and the PV power ranges from 1.90 kW to 3.52 kW for a system head of 10 m and solar irradiation of 5.25 $kWh/m^2/day$, respectively, while the unit cost of water ranges from \$ 0.05/$m^3$ to \$ 0.054/$m^3$, and the life cycle cost ranges from \$ 7004 to \$ 12331. This provides insights into the effects of varying the system head and the solar radiation, demonstrating that the PV-pumping system underperforms at higher system heads, but performs effectively at higher solar radiation. This is due to the decrease in the discharge rate and an increase in power output, respectively. The study will be useful for planning PV-based water pumping system for agricultural purposes.



* Corresponding author.
*E-mail address:* aalayande@unilag.edu.ng (A.S. Alayande).

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**Nomenclature**

| | |
|---|---|
| $A_d$ | Days of autonomy |
| AC | Alternating current |
| $ALCC_{sys}$ | Annualized life cycle cost of the PV-pumping system ($/yr) |
| $B_{battery}$ | Size of battery bank (Ah) |
| $B_{parallel}$ | Number of battery units connected in parallel |
| $B_{series}$ | Number of battery units connected in series |
| $B_v$ | Unit battery voltage (V) |
| $B_{total}$ | Total number of batteries |
| $Crop_p$ | Crop water requirement per day ($m^3$) |
| $C_{water}$ | Unit cost of water ($/$m^3$) |
| $C_i$ | Investment cost ($) |
| $C_r$ | Replacement cost ($) |
| $C_m$ | Operation and maintenance cost ($) |
| $C_{opm}$ | 0.1% of investment cost (S) |
| $C_{icp}$ | Initial cost of replaceable component ($) |
| $DOD$ | Depth of discharge (%) |
| $DG$ | Diesel generator |
| $d$ | Discount rate (%) |
| $E_p$ | Daily energy requirement of pump (kWh/day) |
| GIS | Geographic Information System |
| $g$ | Acceleration due to gravity (m/$s^2$) |
| $G_{in}$ | Average daily global solar irradiation of location (kWh/$m^2$/hr) |
| HOMER | Hybrid Optimization for Electric Renewables |
| $h_{sys}$ | Total system head (m) |
| $I_{sc}$ | Short circuit current of PV module (A) |
| $I_{rating}$ | Solar charge controller rating (A) |
| $I_N$ | Number of controller in parallel |
| $i$ | Inflation rate (%) |
| $K_{loss}$ | Losses due to temperature, dirt and degradation |
| LCC | Life cycle cost ($) |
| LER | Land equivalent ratio |
| $\mathrm{LCC_{pv\text{-}system}}$ | Life cycle cost of the PV pumping system ($) |
| LPSP | Loss of power supply probalility |
| L | Litres |
| $\mathrm{Module_{total}}$ | Total number of PV modules |
| n | Project life (yrs) |
| PV | Photovoltaic |
| $\mathrm{P_{module}}$ | Output power of a single module (kW) |
| $\mathrm{PV\text{-}module_{series}}$ | Number of PV modules configured in series |
| $\mathrm{PV\text{-}module_{parallel}}$ | Number of PV modules configured in parallel |
| $\mathrm{PV_{arrayoutput}}$ | Rating of solar PV array (kW) |
| Q | Discharge rate of pump ($m^3$/hr) |
| $\mathrm{Q_{wd}}$ | Quantity of water produced ($m^3$/day) |
| r | Interest rate (%) |
| t | Duration of pump operation (hr) |
| $\mathrm{V_{sv}}$ | System voltage (V) |
| $\mathrm{V_{sa}}$ | System array voltage (V) |
| $\eta_b$ | Battery efficiency (%) |
| $\eta_{pv}$ | Efficiency of PV module (%) |
| $\rho$ | Density of water (kg/$m^3$) |

## Introduction

Over the past few years, Nigeria has witnessed a tremendous rise in population growth, which resulted in an increase in demand for food [1]. This increase in demand for food has challenged the need for an increase in food production to meet the rise in the population [2]. In Nigeria, temperature and rainfall are the agro-climatic factors that determine crop production, while most farmers are out of jobs during the dry season and local food prices are usually very high during this season as a result of food scarcity [3]. One of the ways to increase food production is to introduce all-around season crop production, which ultimately will require adequate availability of sustained moisture [4]. Irrigation practice has been identified as a major way for sustaining adequate moisture in areas with either erratic or low amount of rainfall patterns [5]. Hence, sustainable food production depends on irrigation farming, which in turn depends on groundwater as the main source of irrigation water. Nigeria is blessed with abundance of groundwater resources and land to embark on irrigation farming in order to ensure all-year-round crop production [6]. Consistent all-year-round crop production will set Nigeria in the pathway for self-sufficient food production, thereby bringing an end to food importation, which invariably will lead to food exportation for foreign exchange earnings for the country.

As far as agriculture is concerned, water is the prime input which is indispensable [7]. Water is supplied either through rainfall or by the irrigation system. Due to unfavorable increasing climate change conditions, water supplies to agricultural crops have become necessary through irrigation [8]. For the irrigation system to be functional, it requires a sustainable water source (groundwater) for pumping to a required head. Also, since excessive or deficit amount of water supply to crop could hinder crop yields, the knowledge of crop water requirements and energy utilization to meet crop water requirement is essential in planning irrigation system, hence, the need for this study.

Previous research studies have identified the use of energy in crop production in Nigeria. An instance of such studies can be found in the work reported in [9] which focused on the design and simulation of a PV-pumping system for irrigation of a hectare of pepper plantation farm in Kaduna, Nigeria. This paper concluded that solar irrigation farming is possible in the study location area. In a related study, some researchers [10] presented an optimal design of a hybrid PV/diesel power system in Kano state, Nigeria for post-harvest cold storage and irrigation farming activities. Their result reveals that integrating renewable energy into farming activity will ultimately lead to food security in Nigeria. Researchers in [11] investigated the techno-economic and environmental benefits of using PV/battery system in replacement of a diesel-generator system to provide energy for a farm livestock facility in Nigeria. The study indicated a huge benefit of utilizing the PV/battery system for replacing diesel generator.

Some other similar studies have been presented on the agricultural aspect. The potential of an off-grid solar photovoltaic and biogas power generation system has been discussed using the Ado-Ekiti slaughterhouse as a case study [12]. The study indicated the potential of the hybrid system through an optimal design and techno-economic analysis based on the Hybrid Optimization Model for Electric Renewables (HOMER) simulation tool. Results reveal an optimal PV/biogas generator/battery/converter system that is able to satisfy a load demand requirement of 164 kWh/day. In another related study, an experimental assessment of a low-pressure desalination system without battery storage was reported for sustainable agriculture in rural locations [13]. The study showed the attractiveness and prospects of solar-driven desalination for irrigation purposes in villages or rural areas. The development of a village-scale, photovoltaic-powered reverse osmosis desalination system has also been discussed for groundwater well in Haiti [14]. This well has been designed and installed to provide water for drinking and agricultural activities in a small local community but with a salinity level of 5,290 ppm; thus, the water is harmful for human consumption and also has an adverse effect on the fertility of the soil. The proposed system is composed of a PV power system, a submersible solar pump, and three reverse osmosis membranes, which are expected to be a low-cost and operational off-grid option for supplying about 4091.5 liters of water to the community per day.

The sustainable solutions for solar PV-based drinking water supply have been presented for rural parts of sub-Saharan Africa, Nigeria in particular [15]. The study considered and assessed technologies for water cleaning and the off-grid power system and their suitability under different conditions. The authors argued that only robust technologies of water treatment powered by solar photovoltaic systems can address the problem of water supply in the rural community at an affordable price. A research study was carried out which focused on the optimization of PV-powered linear-move sprinkler irrigation system [16]. The study first mentioned the essence of a solar-powered linear move sprinkler irrigation system, in terms of its need for precision agricultural and low-energy consumption purposes, and also explained the necessity for optimizing the PV configuration approach. The study used two performance indices – LPSP and the energy excess percentage as the constraints, while the minimum LCC was set as the objective function. The relevance of the proposed method is that it may be used in solar photovoltaic-based energy supply system design and the optimization of linear move sprinkler irrigation for agricultural purposes.

The characterization of a solar-powered poultry egg incubator has been presented using Nigeria as a test case [17]. The authors began by mentioning the lack of commercially-owned hatchery machines, which affects the expansion and make poultry products scarce in the country. However, with the use of a PV-powered system in poultry production, it is possible for farmers to enjoy a sustainable power supply for incubating and hatching poultry eggs and also breeding day-old chicks in the country. The proposed system consists of three basic parts – an energy supply unit, a storage unit, and the egg incubation chamber unit. A solar-powered reverse osmosis plant has been proposed for optimized desalination of seawater for water supply in the coastal area [18]. The potential of agrivoltaic system has also been discussed [19]. The authors simulated this system using the PVSyst tool for the PV generation model, while the SimulateurmulTIdisciplinaire les Cultures Standard (STICS) crop model was employed for the agricultural production to assess the technical potential. The results revealed an increase in economic value with agrivoltaic system compared to the traditional agricultural practice.

The combination of solar PV modules and food crops for optimizing land use has been discussed for new agrivoltaic systems [20]. The idea of this study is that it proposed a combination of PV modules and food crops on the same land space for the purpose of achieving optimal use of the land, which is regarded as the agrivoltaic system. The authors used the LERs to compare the traditional options and the agrivoltaic systems based on the densities of solar photovoltaic modules. The work also showed that the agrivoltaic systems may provide a relatively efficient option for agriculture. The review of community-based solar PV water pumping systems has been discussed for drinking and irrigation purposes [21]. The study also presented the assessment of economic viability, the research gaps, and the barriers to the widespread application of PV water pumping systems. It further discussed the techno-economic aspects such as the performance evaluation, optimal sizing, PV materials, and efficiency enhancement, degradation of PV generating system, and the cost, including the environmental considerations.

A model has been proposed for optimal PV sizing for irrigation water pumping application [22]. The study presented a new hybrid simulation model for sizing solar PV modules for irrigation water pumping application, which is based on dynamic programming and the constraints were based on the simulation model. The proposed model obtained a PV generator size that is smaller compared to when the traditional method of sizing is employed. The feasibility assessment of solar-powered pumping irrigation systems has been discussed [23]. The study is based on an evaluation of dynamic variants of the groundwater table for the irrigation and non-irrigation seasons. It presented the performance analysis in terms of whether or not the groundwater resources can meet the pumping water demand for the growth of pasture. The analysis reveals satisfactory groundwater resources and the water supply for the grassland. Another related research study has been presented that considered solar photovoltaic-based irrigation systems with emphasis on remote rural farms in sub-Saharan Africa [24]. The study also investigated the possibility of solar-powered irrigation systems such as the photovoltaic and solar thermal technologies that may be utilized for agricultural purposes in a rural setting.

The comparison of the environmental and economic impacts of grid-integrated and grid-independent photovoltaic systems with conventional resources for rural irrigation application was carried out in Spain [25]. A solar PV energy supply is utilized solely by the irrigation pumping system in the grid-independent scenario or distributed between the pumping machine and the grid system. Such a system may present most economically- and environmentally viable energy source for pumping in irrigation networks. The suitability mapping framework has been proposed for PV pumps for small-scale farming in sub-Saharan Africa [26]. The authors used multi-criteria evaluation based on the GIS environment with Ethiopia as a test case. The results showed that the groundwater resources are consistent with the available referenced "well depth" data.

The effect of head and PV array configurations on solar water pumping system has been discussed [27]. The authors presented a model to ascertain the effect of the operating head of a water pump, solar radiation, PV array configurations on the performance of a solar water pumping system. Another study has presented a fast and simplified technique based on non-linear translation of operating points for PV modules output and daily pumped water for performance prediction of solar water pumping system at different heads [28]. A novel model is proposed in the study for predicting the quantity of water pumped per day and the pump efficiency for a specified daily PV energy output and any chosen head. The effect of pumping head on solar water pumping system has also been discussed [29]. The authors presented performance analysis of solar water pumping system under varying values of system head.

The hydraulic evaluation of a PV system driving an AC water pump has been presented [30]. The authors considered the system performance under different peak sun hour and also employed performance ratio to ascertain the hydraulic performance of the solar water pumping system through a variable frequency DC-AC converter coupled to the AC surface pump. A comparative evaluation of the economic feasibility of five solar-power irrigation systems has been discussed using the Mediterranean region as a case study [31]. The study is based on calculating the economic metrics of different PV plant capacities in terms of the investment cost, levelized cost of energy and the internal rate of return. A study has also compared the environmental and economic impacts of on- or off-grid PV systems with conventional energy sources for irrigation systems in the rural areas [32].

The aforementioned research studies have provided interesting contributions to the agricultural application aspects in different directions. Some of these include the design of solar PV and biogas generation for the slaughterhouse, agrivoltaic systems application, solar PV-driven desalination system for irrigation water supply, characterization of a PV-powered poultry egg incubator, sustainable solutions for solar PV-based drinking water supply, review of community-based solar PV water pumping systems for drinking and irrigation purposes, the proposed model for optimal PV sizing for irrigation water pumping application, feasibility assessment of solar-powered pumping irrigation system, solar photovoltaic-based irrigation systems for rural farms and the comparison of the environmental and economic impacts of grid-integrated and grid-independent photovoltaic systems for rural irrigation systems application.

These studies show the benefit of utilizing renewable energy resources for agricultural practice and applications. However, most of the studies, especially those presented in [9–26], did not consider the effects of pumping system head and the solar irradiation (i.e. climatic condition) on the techno-economic perspective of the solar PV-powered pumping system for all-year-round food production. The studies presented in [27–32] have made useful contributions in the aspect of sensitivity analysis of solar water pumping based on the head and solar irradiation, and the cost, which form relevant background to this study. This current paper is based on the identified gap using Nigeria as a case study. It introduces an integrated approach in providing a detailed analysis of the impact of water pumping head and the location's solar insolation based on standard mathematical relations in energy design and planning. Considering the effort made so far by the Nigerian Government to diversify the economy from the dependence on oil with a unique focus on agriculture, the aim of this study is to assess the effects of total system head and solar radiation on the techno-economics of utilizing PV-pumping system for groundwater irrigation of crop production in Nigeria. It is expected that the approaches introduced in this study and the

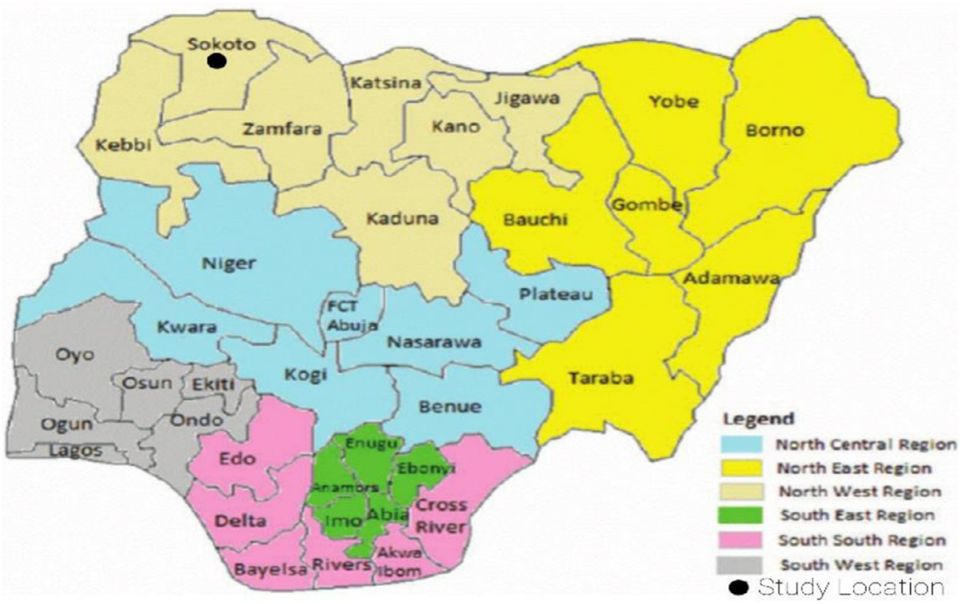


**Fig. 1.** Map of Nigeria showing the area under study [33].

**Table 1**
The Average Monthly Solar Radiation [35].

| Months | Jan. | Feb. | Mar. | Apr. | May | Jun. | Jul. | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AverageSolar (kWh/m$^2$/day) | 5.47 | 6.41 | 6.87 | 7.15 | 7.03 | 6.91 | 6.26 | 5.73 | 6.01 | 6.03 | 5.79 | 5.25 |

results will provide insights into a better understanding of the technical and the economic dimensions of energy planning and performance analyses of irrigation systems in developing countries.

The remaining part of the paper is arranged as follows: Section 2 focuses on the materials and methods; section 3 is based on results and discussion, while the paper is concluded in section 4.

## Materials and methods

### *Study area and solar radiation*

The study was carried out using a farm settlement in Sokoto State, North West region of Nigeria as a case study with geographical coordinates of latitude $12^o$ and $14^oN$ and longitude $5^o$and $7^oE$. Fig. 1 shows the study location in the Nigerian map.

The monthly average daily global solar radiation of the study location as obtained from the Nigeria Meteorological Agency is presented in Table 1.

It is obvious from the data presented in Table 1 that the location's highest and the lowest solar irradiation is 7.15 and 5.25 kWh/m$^2$/day, respectively, for the months of April and December. Apart from the intermittent characteristics of the solar energy resource, the disparity in the values of the solar insolation is also a result of the seasonal variations. However, the values of solar irradiation in Table 1 are relatively higher than the values that could be obtained in the southern part of Nigeria [34]. This implies that the location has good sunshine over the year, which will favor electricity generation from solar PV technology.

### *Crop water requirement*

Crop water requirement is the amount of water required by a crop for normal growth, regardless of the supply source for a period of time under field conditions. The water requirement of crops varies according to growth stages mainly due to changes in crop canopy and weather conditions. They are also governed by crop evapo-transpiration. For this study, six major crops that serve as major sources of food for Nigerians and major income for the study location were selected. Furthermore, climatic indices of the study location were also used in estimating the water requirements of the crops considered for this study. Table 2 presents the crop water requirements of the selected crops considered.

**Table 2**
Crop Water Requirement in Sokoto State, Nigeria [12].

| Selected Crop | Crop Water Requirement (mm) | | | | Crop Water Requirement ($m^3/hac/day$) |
|---|---|---|---|---|---|
| | Initial Stage | Crop Development Stage (Mid-season stage) | Late Season Stage | Total Water Need | |
| Melon | 78.53 | 371.36 | 74.55 | 524.44 | 37.46 |
| Bean (dry) | 61.08 | 153.54 | 33.78 | 248.4 | 29.93 |
| Millet | 61.08 | 133.74 | 78.91 | 273.73 | 22.25 |
| Sorghum | 61.08 | 378.51 | 74.36 | 513.95 | 41.12 |
| Soybean | 61.08 | 395.25 | 57.4 | 513.73 | 35.96 |
| Cucumber | 78.53 | 247.68 | 71.55 | 397.76 | 33.71 |

**Table 3**
Electrical Parameters [42].

| Parameters | Values |
|---|---|
| Power rating per array | 250 W |
| System voltage | 24 V |
| System array voltage | 24 V |
| Short-circuit current | 8.17 A |
| PV module efficiency | 14 % |
| Life time | 20 yrs |

*Estimation of pump rating*

The pump power required to deliver water from the groundwater source to the required head is given by [36]:

$$Pump_p = \frac{\rho \times g \times h_{sys} \times Q}{\eta_p} \tag{1}$$

where the values of $\rho$, g and $\eta_p$ are 1000 kg/m$^3$, 10 m/s$^2$ and 0.65, respectively.

The discharge rate of the pump is given by:

$$Q = \frac{Crop_p}{t}\left(m^3/hr\right) \tag{2}$$

The pump is assumed to be operated for 6 hrs/day in this study.

*Estimation of PV-array rating*

The solar PV array rating required to drive the pump is given by [37]:

$$PV_{arrayout\,put} = \frac{1.25 \;\times E_p}{G_{in} \times K_{loss} \times \eta_{pv}} \tag{3}$$

where the safety factor and the PV efficiency assumed in this paper is 1.25 and 14%, respectively.

The safety factor has been introduced to over-rate the solar PV array by 25 % for the purpose of compensating for the losses due to temperature, incomplete absorption of the radiant energy, dirt, aging, degradation, wiring and inverter, including the effect of seasonal variations [38]. Table 3 shows the electrical parameters of the PV array considered in this study.

The number of PV modules required to be connected in series is given by [14]:

$$PV - module_{series} = \frac{V_{sv}}{V_{sa}} \tag{4}$$

The configuration of the solar PV modules in series is necessary to obtain the system voltage of the design.

The number of PV modules required in parallel is given by [37]:

$$PV - module_{Parallel} = \frac{PV_{arrayout\,put}}{PV - module_{series} \times P_{module}} \tag{5}$$

Therefore, the total number of PV modules required for the design is given by [37]:

$$Module_{total} = PV - module_{series} \times PV - module_{parallel} \tag{6}$$

*Estimation of battery rating*

The battery storage is required to mitigate the intermittency of the solar irradiation. This is because solar energy is not available all the time during the day. This way, the users can pump water at any time. The size of the battery required is given by [39,40]:

$$B_{battery} = \frac{E_p \times A_d}{V_{sv} \times DOD \times \eta_b} \tag{7}$$

The values of 3 days, 80% and 85% are used for $A_d$, $DOD$ and $\eta_b$ in this study.

Suppose that a $12V,\ 200Ah$ battery is selected, then, the number of batteries required to be connected in parallel is given by [39]:

$$B_{parallel} = \frac{B_{battery}}{Unit\ battery\ rated\ capacity} \tag{8}$$

The number of batteries required to be connected in series is given by [39]:

$$B_{series} = \frac{V_{sv}}{B_v} \tag{9}$$

The total number of batteries required is given by [39]:

$$B_{total} = B_{series} \times B_{parallel} \tag{10}$$

*Estimation of solar charge controller rating*

The solar charge controller is needed to help match the PV module voltage and the battery system voltage. The rating of the charge controller is given by [41]:

$$I_{Rating} = 1.25\ \times I_{sc} \times B_{parallel} \tag{11}$$

The value of $I_{sc}$ in this study is 8.74 A. In addition, the total number of charge controllers required in parallel configuration is given by:

$$I_N = \frac{I_{Rating}}{Ampere\ per\ controller} \tag{12}$$

A charge controller rated at $24V,\ 60A$ is selected in this study.

*Economic estimation of PV-pumping system*

The motive behind a PV-powered water system is to achieve a reduced cubic meter cost of water. The economic study involves determining individual components cost that makes up the system such as the investment cost of PV array, controller, battery, installation, civil works, item delivery, cable and borehole, DC pump, etc., the operations and maintenance cost, and the replacement cost of the DC pump and the battery. The life cycle cost of a PV pump system over a life cycle of 20 years can be determined as [42]:

$$LCC_{PV-system} = C_i + C_m + C_r \tag{13}$$

The operation and maintenance cost is assumed to be 0.1 % of the investment cost and is given by [43]:

$$C_m = C_{opm} \times \left[\frac{1+i}{d-i}\right]\left[1 - \left(\frac{1+i}{1+d}\right)^n\right] \tag{14}$$

where the values of 8.4 %, 11 %, 15 % and 20 years are used for the inflation rate, discount rate, interest rate and the project life time, respectively. The replacement cost is given by [43]:

$$C_r = C_{icp}\left[\frac{1+r}{1+d}\right]^n \tag{15}$$

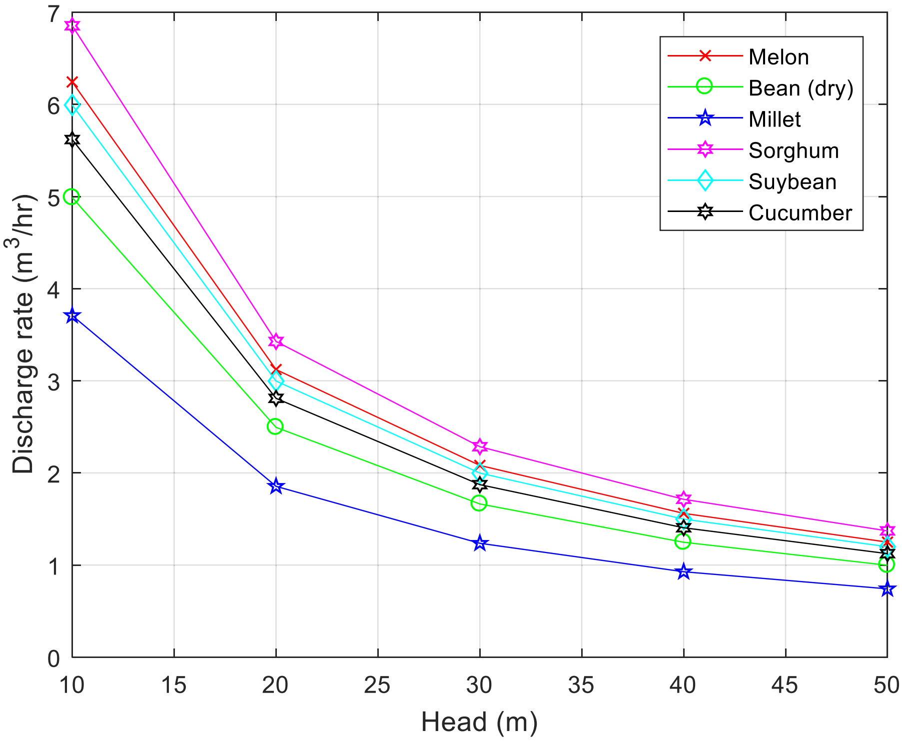


**Fig. 2.** Discharge rate variation with system head.

The pump and the battery are the only components considered for replacement in every 8 years. It is sometimes necessary to evaluate the LCC of a system on an annual basis. The annualized life cycle cost of a PV pumping system can be estimated as [43]:

$$ALCC_{sys} = LCC_{pv-pump}\left[\frac{1-\left(\frac{1+i}{1+d}\right)}{1-\left(\frac{1+i}{1+d}\right)^{n}}\right] \tag{16}$$

The cost of water per $m^3$ is thus evaluated as [43]:

$$C_{water} = \frac{ALCC_{sys}}{Q_{wd} \times 365} \tag{17}$$

After local market survey and literature review, the following are the assumptions made regarding prices of components:

## Results and discussion

The effect of varying system head and techno-economics of PV pumping system is first presented in this section, followed by a discussion on the effects of varying the solar irradiation on the techno-economics of PV pumping system.

### *Effect of total system head on techno-economics of PV-pumping system*

The result of the effect of varying $h_{sys}$on the techno-economic parameters of PV pumping system is shown in Figs. 2 to 5.

Fig. 2 shows the effect of varying $h_{sys}$ on the discharge rate of water. It depicts that the system head is inversely proportional to discharge rate based on Equation 1. The result further demonstrates that for the system heads considered in this study, i.e., 10 to 50 m, Sorghum has the highest discharge rate of 6.85 $m^3$/hr at 10 m, while Millet has the least discharge rate of 0.74 $m^3$/hr at 50 m. This implies that the lower the system head, the higher the discharge rate. However, an increase in the system head will translate to a decrease in the volume of water available for the crop. Fig. 2 also shows a decrease (in an asymptotic manner) in the amount of water available for the different crops studied, which converged on the same value at a head of 50 m head.

Fig. 3 shows the effect of varying $h_{sys}$ on the pump power required. In this case, the pump power is directly proportional to $h_{sys}$ which implies that as the system head increases, the discharge rate decreases, hence, a pump with higher capacity

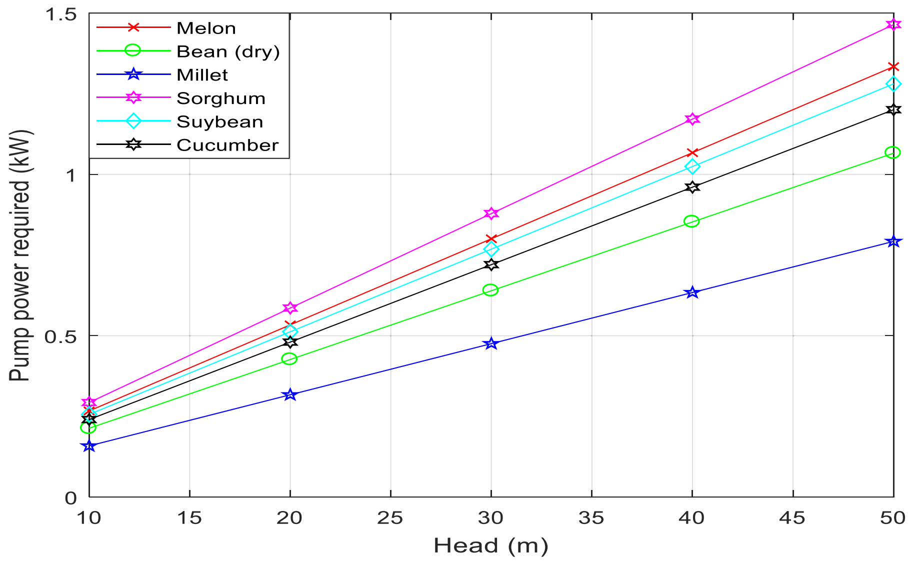


**Fig. 3.** Pump power variation with system head.

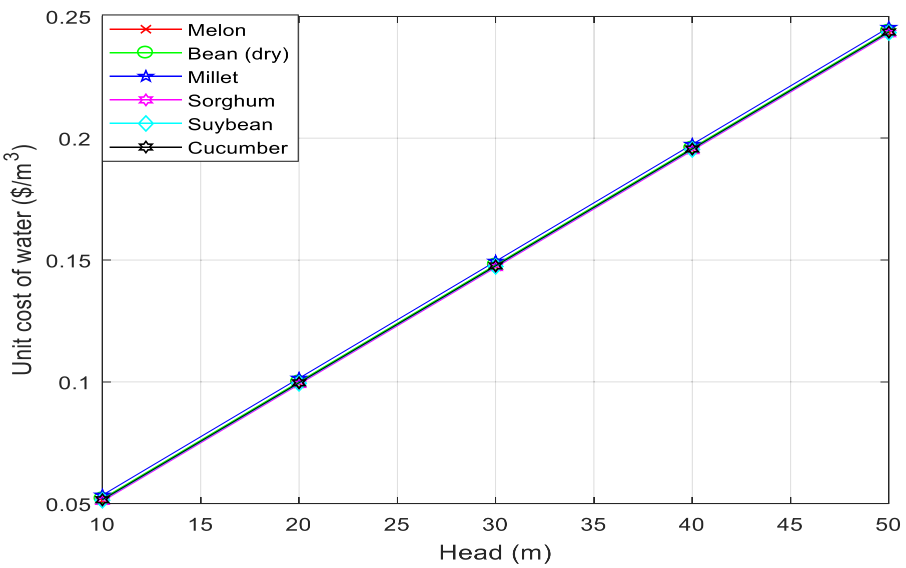


**Fig. 4.** Unit cost of water variation with system head.

will be needed to deliver the required crop water requirement. From the result, the pump power requirement of Sorghum is the highest with 0.29 kW at 10 m, while Millet has the lowest with 0.79 kW at 50 m.

Fig. 4 depicts the effect of varying $h_{sys}$ on the unit cost of water. It is already demonstrated in Fig. 3 that an increase in $h_{sys}$ is associated with a decrease in the discharge rate, which ultimately results in a decrease in the volume of water production. The impact of this is that there is increase in the unit cost of water. Therefore, the unit cost of water is directly proportional to $h_{sys}$. Results reveal that Sorghum has the lowest unit cost of water of \$0.05/m$^3$ at 10 m, while Millet has the highest at \$0.245/m$^3$ at 50 m.

It is obvious that increasing the system head will bring about a reduction in the discharge rate. From the technical point of view, a pump with a higher capacity will be required to deliver the needed discharge rate in order to meet up with the required volume of water per crop. However, from an economic perspective, this will lead to an increase in the investment cost. Therefore, the result clearly demonstrates that $h_{sys}$ is also directly proportional to LCC as presented in Fig. 5.

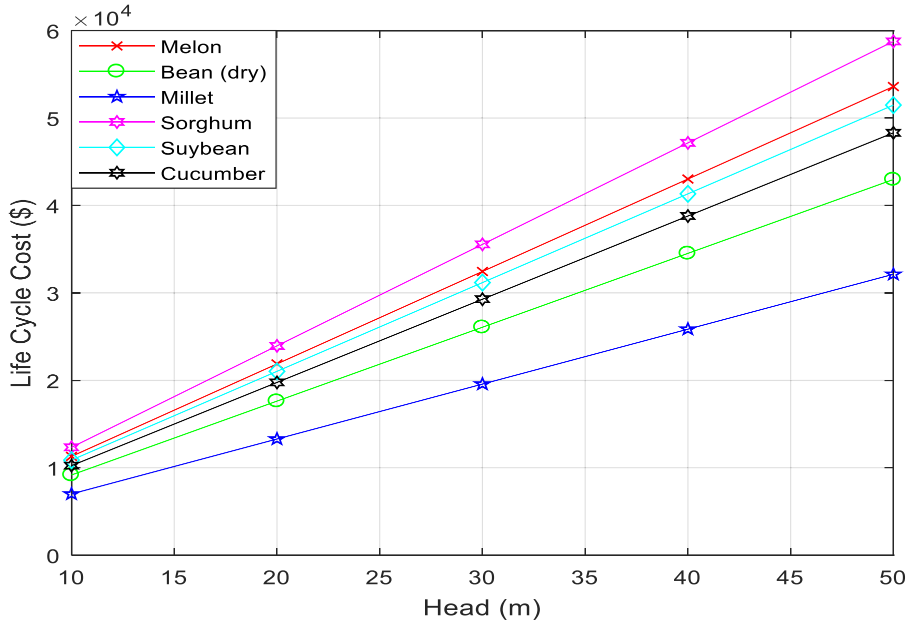


**Fig. 5.** Life cycle cost variation with system head.

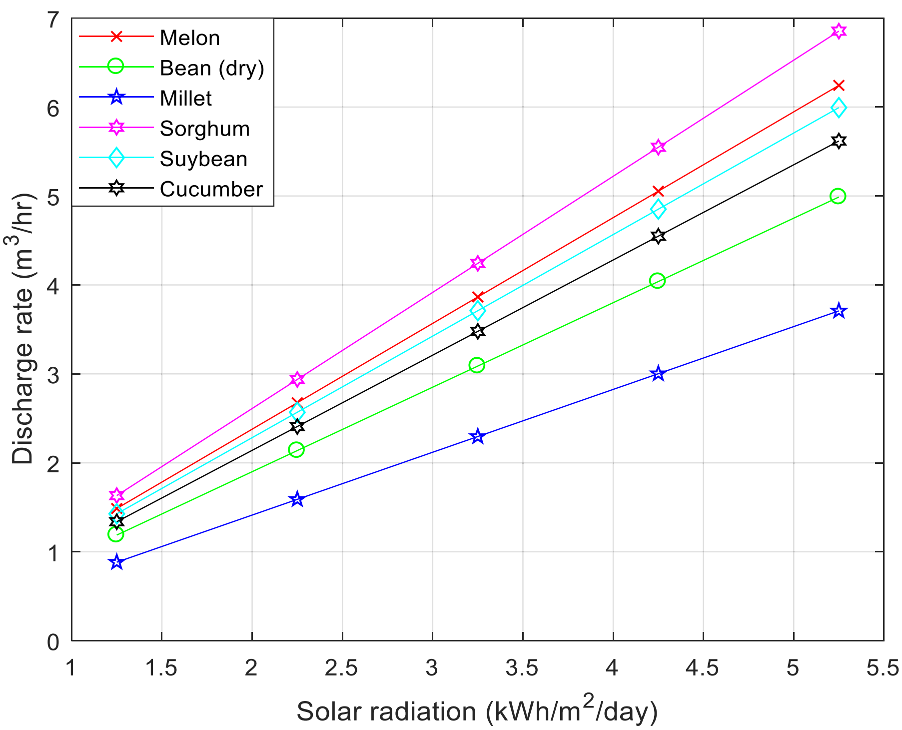


**Fig. 6.** Discharge rate variation with solar radiation.

*Effect of solar radiation on techno-economics of PV-pumping system*

The effect of varying $G_{in}$ on the techno-economic parameters of the PV pumping system is shown in Figs. 6 to 9, respectively. Fig. 6 shows the effect of varying $G_{in}$ on the discharge rate of water. It depicts that solar radiation is directly proportional to the discharge rate. Sorghum has the highest discharge rate of 6.85 $m^3$/hr at 5.25 kWh/$m^2$/day, while Millet has the least discharge rate of 0.88 $m^3$/hr at 1.25 kWh/$m^2$/day. This implies that higher solar irradiation promises a better

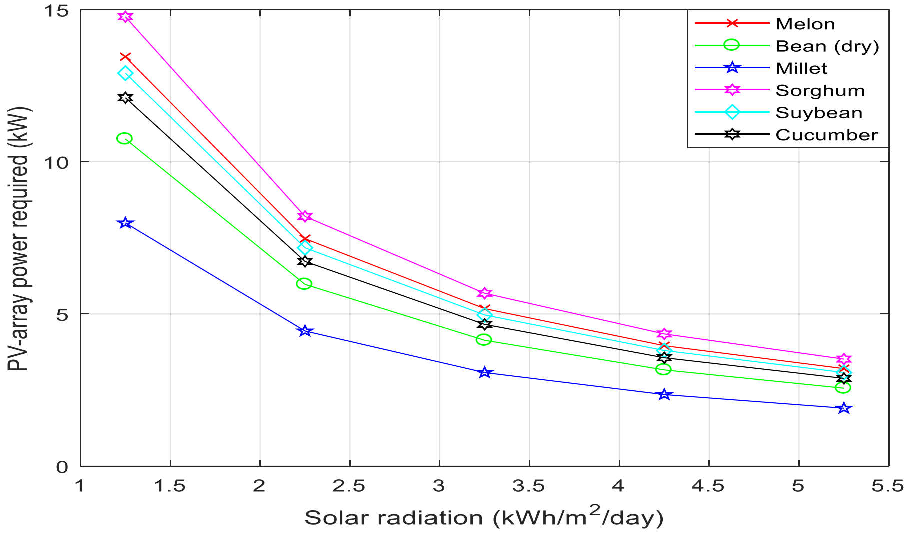


**Fig. 7.** PV-array power required variation with solar radiation.

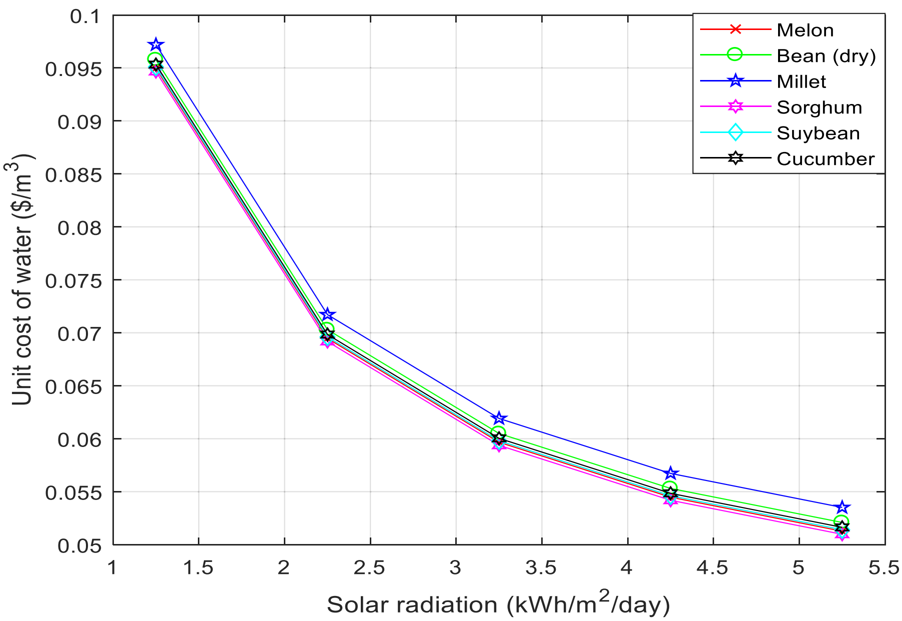


**Fig. 8.** Unit cost of water variation with solar radiation.

performance for the PV/charge controller/battery arrangement compared to when the system operates with relatively low solar irradiation.

Fig. 7 shows the effect of varying $G_{in}$ on the PV array rating required. It demonstrates that the required PV array rating is inversely proportional to solar radiation. This means that as the solar radiation increases, the required PV array rating decreases, translating to a low capacity requirement for delivering the quantity of water for crop production. The results reveal that the PV array rating required for Sorghum is the highest with 14.77 kW at 1.25 kWh/m$^2$/day, while that of Millet is the lowest with the value of 1.90 kW at 5.25 kWh/m$^2$/day. It can be seen that the rated capacity of PV array required for Millet production is over 87 % less than that required for Sorghum production in relation to the variation of $G_{in}$.

Fig. 8 depicts the effect of varying $G_{in}$ on the unit cost of water. As presented in Fig. 6, an increase in $G_{in}$ is associated with an increase in the discharge rate, which ultimately results in increase in the volume of water produced. It is possible for the excess water to be stored for other uses. However, excess water production may be forestalled by reducing the rating of the PV module, which is also expected to reduce cost. Therefore, the unit cost of water is indirectly proportional to the solar radiation. Results show that Sorghum has the lowest unit cost of water of \$0.05/m$^3$ at 5.25 kWh/m$^2$/day, while Millet has the highest at \$0.097/m$^3$ at 1.25 kWh/m$^2$/day.

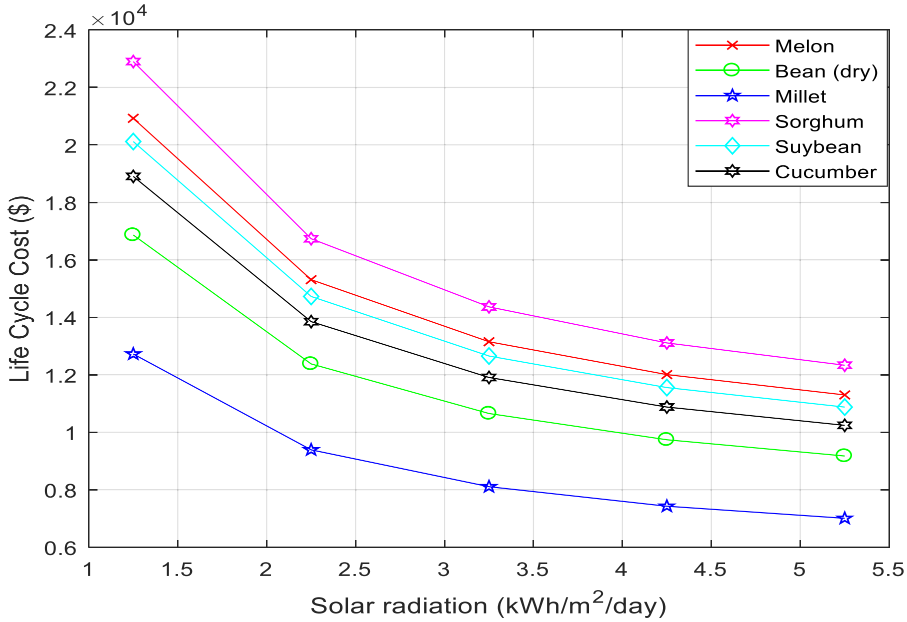


**Fig. 9.** Life cycle cost variation with solar radiation.

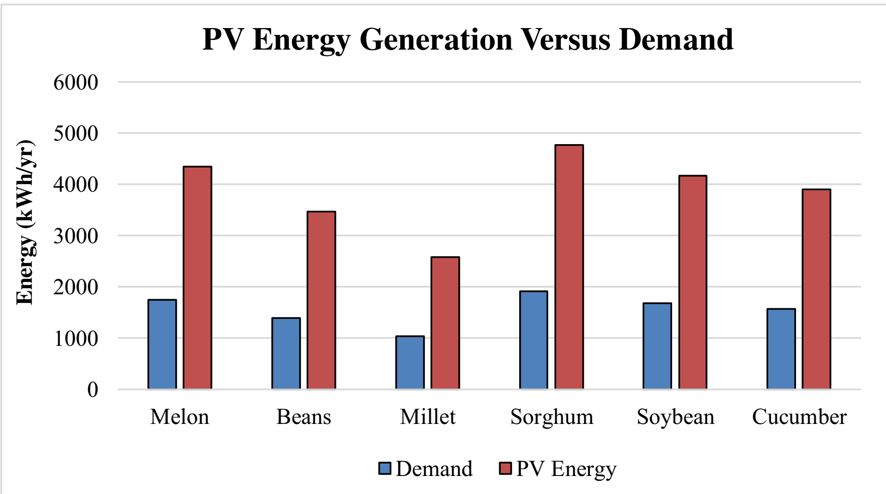


**Fig. 10.** Energy generated by the PV and the load demand of the pump over the year.

Since the result demonstrates that an increase in solar radiation brings about an increase in the discharge rate; and in order to satisfy the water requirement per crop, then the required PV array capacity to deliver the needed discharge rate will be reduced. This translates to a decrease in the investment cost. Therefore, it may be concluded that solar radiation is inversely proportional to LCC as shown in Fig. 9.

It may also be deduced from the results that when the pumping power capacity of the PV system is met, the effect of varying $G_{in}$ becomes insignificant, while $h_{sys}$ becomes a key factor in determining the techno-economic metrics of the PV pumping system. However, if the pumping system head is met, the effect of $G_{in}$ becomes a major factor in determining the performance of the PV pumping system.

Fig. 10 shows the energy generated by the PV array compared to the pump electrical load demand over the year. This result clearly demonstrates that the solar electricity produced is able to satisfy the energy requirement of the pump to provide water for crops processing. For example, Millet and Sorghum presents the lowest and the highest load demand of 1036 kWh/yr and 1919 kWh/yr, and the energy values of 2578 kWh/yr and 4,766 kWh/yr are supplied by the PV array to meet these demands for their processing.

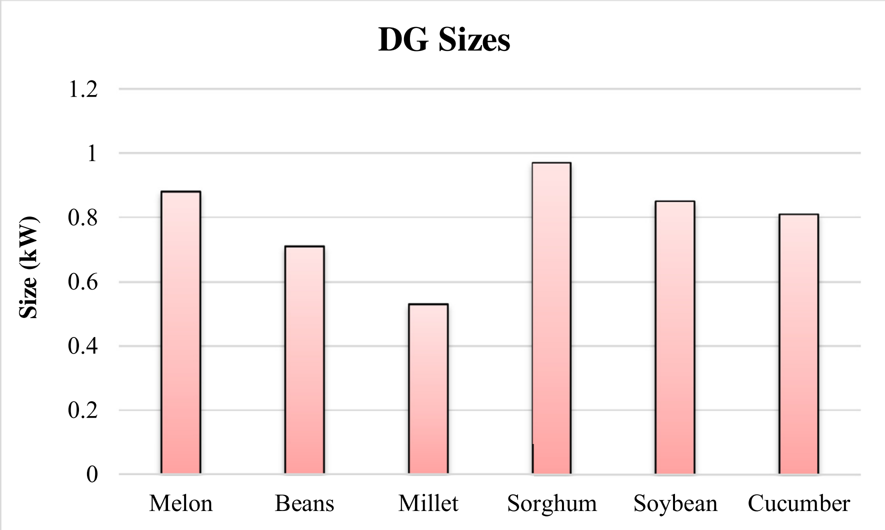


**Fig. 11.** Diesel generator sizes for processing different crops.

**Table 4**
Technical and cost parameters of components [42].

| Description of items | Unit cost ($) |
|---|---|
| PV Module (250W, 24V) | 150 |
| Solar controller (100A, 24V) | 300 |
| Cost per PV installation + civil works + item delivery (10% of PV-array) | 15 |
| Cost of DC Pump (1HP) | 37.5 |
| Cost of cables per PV-Array | 3.75 |
| Cost of storage Tank per cubic meter | 2.5 |
| Cost of bore-hole | 625 |

**Table 5**
Emissions that will be generated by DGs.

| Emission | Melon | Beans | Millet | Sorghum | Soybean | Cucumber |
|---|---|---|---|---|---|---|
| Carbon dioxide (kg/yr) | 1504 | 1213 | 909 | 1648 | 1450 | 1363 |
| Carbon monoxide (kg/yr) | 9.48 | 7.65 | 5.73 | 10.4 | 9.14 | 8.59 |
| Unburned hydrocarbons (kg/yr) | 0.414 | 0.334 | 0.25 | 0.453 | 0.399 | 0.375 |
| Particulate matter (kg/yr) | 0.0574 | 0.0464 | 0.0347 | 0.0629 | 0.0554 | 0.0521 |
| Sulfur dioxide (kg/yr) | 3.68 | 2.97 | 2.23 | 4.03 | 3.55 | 3.34 |
| Nitrogen oxides (kg/yr) | 8.9 | 7.18 | 5.38 | 9.76 | 8.58 | 8.07 |

*Environmental impact analysis*

Fig. 11 shows the different sizes of diesel generator that will be used to pump water for all the crops processing suppose that solar PV system is not utilized in the farm. This represents the prevailing situation in several off-grid agricultural farms in Nigeria. It can be seen that the lowest and the highest diesel generator sizes of 0.53 kW and 0.97 kW, respectively, are associated with Millet and Sorghum crops processing. These DGs also consume the lowest and the highest diesel quantity of 347 L/yr and 629 L/yr. These results are obtained by using HOMER simulation tool based on the parameters defined in the technical aspect of this study, such as the sizes of the pumps for different types of crops, and the hour of operation of the pump per day. Besides, pumps are essentially inductive loads, which implies that they place a relatively high starting requirement. This was also considered in determining the sizes of the DGs (Table 4).

Table 5 presents the emissions produced by the DGs if they are used to drive the electrical demand shown in Fig. 10 instead of utilizing the PV system. This analysis is also based on HOMER simulation. It is obvious again that the lowest and highest emissions are produced by DGs used for processing Millet and Sorghum crops. These emissions, i.e., carbon dioxide, carbon monoxide, unburned hydrocarbons, particulate matter, sulfur dioxide and nitrogen oxides, contribute to global warming, which is why renewable energy resources are embraced around the world to mitigate the effect by minimizing the utilization of the fossil-fuel resources. Therefore, these emissions are assumed to be avoided when a solar PV system is employed to drive the pumping machine. The cumulative effect of this is expected to help mitigate global warming issue in the long-term.

## Conclusion

This study presents the effects of the total system head and the solar radiation on the techno-economic metrics of a solar PV-water pumping system for irrigation of some selected crops in Nigeria. The crop water requirements of some selected crops were obtained from a typical farm settlement in Sokoto State, Nigeria using the climatic data of the study location. The average water requirement of crops ranges from 22.25 $m^3$/hac/day to 41.12 $m^3$/hac/day, with a daily average discharge rate of 3.71 $m^3$/hr to 6.85 $m^3$/hr.

The study adopted a detailed standard sizing process in which the discharge rate of the required crop water is modeled directly as a function of PV pumping output power. The techno-economics of the PV pumping system with varying values of the system head and the solar radiation were also determined. The results revealed that the unit cost per cubic meter of water per day, life cycle cost, pump power rating and the PV system output power ranges from \$0.050 to \$0.054, \$7004 to \$12331, 0.158 kW to 0.293 kW, and 1.90 kW to 3.52 kW, respectively, for a system head of 10 m and solar radiation of 5.2525 kWh/$m^2$/day.

The results also showed the effects of varying the system head and the solar radiation. It was observed that at higher system heads, the PV pumping system under-performed. However, the system performed well at higher solar radiation. This is due to the decrease in discharge rate - a direct impact of an increase in the system head and the higher power as a result of increased solar radiation, respectively. Results further indicate that the PV-pumping system has the potential to avoid emissions, compared to when using the diesel generators to pump water. This study will provide useful insights into understanding the variability of certain important parameters such as the solar irradiation and the system head in the application of a solar-powered water pumping system for irrigation purposes. Adopting this method of supplying crop water requirements will go a long way to guarantee food security in Nigeria and other developing countries with similar climate and economic situations. Such a method is expected to lead to zero hunger in the country in the long-run.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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