

(RESEARCH ARTICLE)



DESIGN OF A PHOTOVOLTAIC PUMPING IRRIGATION SYSTEM IN THE COMMUNE OF KOMSILGA, BURKINA FASO

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ABSTRACT

The objective of this study is to design an optimal photovoltaic (PV) pumping irrigation system for agricultural production. The selected site is located in the municipality of Komsilga, Burkina Faso. The field to be irrigated covers an area of 51,116.3 m². Based on a reference evapotranspiration of 6.5 mm/day, representing the worst-case scenario, a total daily water requirement of 318 m³ was established. Three boreholes were drilled to meet this daily water demand. A water tower with a capacity of 106 m³ was constructed for each borehole. A preliminary study estimated the borehole depth at 60 m with a diameter of 50 cm. A total dynamic head (TDH) of 165 m was determined through simulation using PVsyst software. For practical and techno-economic reasons, we opted for a "run-of-sun" photovoltaic pumping system. To optimize pumping, we used crop coefficients corresponding to the mid-season growth stage and selected the potential evapotranspiration rate for March, 6.5 L/m²/day, as the design basis. Three three-phase electric pumps, each with a power rating of 16 kW and a nominal voltage of 400 V, were sized and selected for this application. They will operate from 9:00 AM to 3:00 PM, with peak pumping occurring at 12:00 PM. Subsequently, the photovoltaic solar array was sized. To meet the requirements, a PV array consisting of 162 monocrystalline silicon modules, capable of delivering a peak power of 81 kWp, was selected based on sizing calculations. To power the AC electric pumps, three 40 kVA inverters were sized and chosen.

Keywords: Irrigation; Optimal; Evapotranspiration; Pumping; Photovoltaic

1 INTRODUCTION

To meet the challenge of development, countries must seek to harness the potential of the resources at their disposal. Agriculture is considered a key sector for the survival of humanity. Its development enables countries such as Burkina Faso to achieve food self-sufficiency. Agriculture is at the heart of the economies of developing countries such as Burkina Faso, especially since it accounts for a large portion of their gross domestic product (GDP). However, this sector faces a number of challenges, such as water scarcity in certain regions, caused by the adverse effects of climate change on rainfall patterns and exacerbated by poor water management. These problems lead to a decline in agricultural yields and, consequently, a constant threat of famine. Furthermore, population growth entails an exponential increase in the demand for agri-food products, hence the need to increase production accordingly [1]. Irrigation using solar-powered pumps helps address insufficient rainfall and its inconsistent spatial and temporal distribution, which is often unsuitable for certain crop varieties. Among the many ingenious solutions proposed in the agricultural sector are solar-powered irrigation systems. There are three main types of irrigation: surface irrigation, sprinkler irrigation, and micro-irrigation or drip irrigation. In this study, we address the issue of water supply through the research and design of a solar-powered irrigation system for a farm in the municipality of Komsilga, Burkina Faso. Komsilga is a rural commune located 25 km south of Ouagadougou, at geographic coordinates 12.1809 degrees' north latitude and -1.6308 degrees' west longitude. The area has a tropical Sudano-Sahelian climate with rainfall that varies irregularly from year to year. It is characterized by two alternating seasons: a long dry season, from November to May, influenced by the dry, hot Harmattan air current; and a short rainy season, from June to October, influenced by the humid monsoon winds. Precipitation is significant, averaging 933.5 mm, and the average annual temperature is 28.1°C. The territory of the municipality of Komsilga consists of three soil classes:

2 MATERIALS AND METHODS

2.1 Irrigation Techniques

Irrigation involves the artificial supply of fresh water to land for agricultural purposes; it is therefore a form of artificial precipitation, often automated using sprinkler or drip irrigation systems, but it can also be done manually. For irrigation to be effective, a certain amount of water is required. In most cases, it is combined with the application of chemical inputs (including fertilizers). Its implementation also requires very specific techniques, which depend on the soil, the crops being grown, the area, and the amount of water to be supplied.

There are three main irrigation techniques: surface irrigation (or gravity irrigation), sprinkler irrigation, and drip irrigation. A smart irrigation system is a system designed to deliver water precisely to plants on a farm or in a garden. It uses weather data and/or soil moisture data to determine the irrigation needs of cultivated land. The design of smart irrigation systems thus eliminates the need for direct farmer involvement by automatically performing the farmer's tasks. Furthermore, with advances in information technology and the emergence of the Internet of Things (IoT), it is possible to control and monitor a smart irrigation system remotely via a web or mobile app that provides system data. This data includes, among other things, temperature, soil moisture, relative humidity, soil pH, and the water level in the reservoir [4], [5], [6].

There are several irrigation methods and techniques. The most common today include surface irrigation (or gravity irrigation), sprinkler irrigation, and drip irrigation (or micro-irrigation). Gravity irrigation was the only viable method until the mid-20th century. In the vast majority of cases, water is transported through open-channel systems. The total irrigated area worldwide is approximately 250 million hectares, and of this total, 80 to 90 percent is irrigated by gravity. It is therefore a technique that remains very widespread, particularly in developing countries. As a result, the cost of constructing a gravity-fed system is 3 to 4 times lower than that of a pressurized system, and energy consumption is minimal or nonexistent. On the other hand, the efficiency of these systems is low, usually less than 30 percent, whereas pressurized systems easily achieve 75 to 95 percent efficiency. Furthermore, they require a large workforce. The low efficiency of gravity-fed irrigation is due, among other things, to significant losses from runoff and the extremely rudimentary or nonexistent regulation of these numerous irrigation systems [5]. This method of irrigation imposes numerous constraints that must be taken into account in the regulation of the canals [6], [7], [8].

The second irrigation technique, sprinkler irrigation, is generally recommended in the following cases:

- Shallow soils that cannot be properly leveled for surface irrigation while maintaining sufficient depth;
- Soils that are too permeable, which do not allow for uniform water distribution when using surface runoff irrigation;
- Land with irregular slopes and rugged microtopography, which does not allow for the installation of a gravity-fed, open-surface irrigation system.

However, it should be avoided in regions with very frequent winds and also when irrigating with saltwater on plants with salt-sensitive foliage. Winds exceeding 4 or 5 m/s significantly reduce the uniformity of watering. A pressurized irrigation system generally consists of equipment that provides the necessary operating pressure, flow measurement and control devices, and a main line that carries water to the secondary and tertiary lines. Other components may be used, including a filter or a filter bank and a device for adding fertilizers. The third technique, micro-irrigation, delivers water in small doses, thereby limiting soil wetting to the plant's root zone.

It is, therefore, a water-efficient system that uses only what the plant needs. This technique also helps reduce weed growth in plantations [6]. It offers up to 95% efficiency with water savings ranging from 30% to over 50%.

- The following factors must be considered when designing any pressurized irrigation system:
- The size and shape of the area to be irrigated and the soil type;
- Available or potential water sources and their characteristics;
- Climatic conditions in the region, accessibility to the plot, and the crop to be irrigated.

In most cases, automation using controllers linked to sensors, volumetric and/or hydraulic valves, and solenoid valves is required to ensure more efficient and effective use.

The irrigation technique used in this study is drip irrigation, also known as micro-irrigation, while it offers the greatest water savings (from 30% to over 50%) and the highest yield (up to 95%).

2.2 Photovoltaic Pumping

There are two types of systems: one that stores energy in batteries, and another that operates during daylight hours and requires water to be stored in a reservoir. Water pumped during the day is stored for later use at night [7]. The battery-storage pumping system eliminates the need to rely on the sun's availability and resolves synchronization issues between the photovoltaic generator and the motor pump. The major drawback of this technology is that it involves several components that negatively impact the system's reliability and overall cost. Batteries are fragile and are often the first components that need to be replaced. They often require constant maintenance and rigorous monitoring of their charge and discharge cycles. The controllers used to regulate battery charging and discharging age quickly and can prove unreliable. Batteries also introduce a certain degree of efficiency loss, amounting to approximately 20% to 30% of energy production.

Solar-powered pumping uses a reservoir to store water until it is needed. It allows for a photovoltaic system that is simpler, more reliable, and less expensive than a battery-based system. Storage occurs hydraulically in an above-ground reservoir, with water being pumped when there is sufficient sunlight. It is then distributed by gravity as needed [8]. The performance of a solar pumping system depends on the characteristics of the site and the equipment [9].

Photovoltaic pumping systems typically consist of:

- Photovoltaic solar modules that convert solar radiation into electrical energy, electrically interconnected to form a direct current (DC) power generation unit;
- A power control and management unit, consisting of a charge controller, batteries, and converters (inverters), capable of providing voltages with adjustable amplitudes and frequencies based on the available power from the solar generator;
- A set of submersible electric pumps, consisting of an asynchronous motor and a centrifugal pump;
- Electrical wiring, through which power flows from the generator to the motor, and a safety control system.

The associated command and control electronics in the case of an electric pump with a DC motor could include a chopper that extracts the maximum available power from the PV generator at any given moment and transfers it to the load that is, to the motor. This is a matching stage between the PV generator and the load that acts as an interface between the two components ensuring through a control mechanism governed by its duty cycle, the transfer of the maximum power supplied by the generator so that it is as close as possible to the maximum available power [10], [11], [12]. However, in our case, we will use AC electric pumps. This requires a DC/AC converter. This DC/AC converter, also known as an inverter, converts the direct current produced by the PV modules into alternating current, similar to that of the grid. The choice of an inverter depends on the electrical characteristics of the pump to be powered (power and voltage) [13].

We will use MPPT inverters. These help optimize the efficiency of the power generation system [14], [15].

The energy required to operate a pump depends on many factors [16]:

- The properties of the fluid: density, viscosity, compressibility;

- The characteristics of the system: length, diameter, roughness, singularities;
- The characteristics of the flow: velocity, flow rate, suction head, pressure.

There is a wide variety of pumps, which can be classified into two main groups:

Positive-displacement pumps transfer the kinetic energy of the motor through a reciprocating motion, enabling the fluid to overcome gravity through successive changes in volume that alternately occur at the suction port and the discharge port. They always consist of a moving part within a hollow chamber that displaces the liquid by varying the volume contained within the chamber. The main advantage of positive-displacement pumps is their ability to convey a fluid under very high pressures. However, they are only suitable for low flow rates, which severely limits their use for crop irrigation. Centrifugal pumps are designed for a relatively fixed total head. The flow rate of this pump varies depending on the motor's rotational speed. Its torque increases very rapidly with this speed, and the discharge head is proportional to the square of the motor's speed. The motor's rotational speed must therefore be very high to ensure a good flow rate. Power consumption varies in proportion to the cube of the speed. Centrifugal pumps are typically used for high flow rates and medium or shallow depths (10 to 100 meters). The choice of one type of pump over another depends on the fluid flow conditions [14]. For all these reasons the electric pumps selected for filling the three castles are therefore centrifugal pumps. Depending on the physical location of the pump, we distinguish between surface pumps and submersible pumps. A pump requires mechanical energy as input. In most cases, this mechanical energy is supplied by an electric motor (electric pump), which can be either direct current (DC) or alternating current (AC); in other cases, it is supplied by an internal combustion engine, such as a diesel or gasoline motor pump [17]. In DC motors, the current in the rotor is commutated using brushes, made of carbon or graphite, or through electronic commutation. Brush-type motors are the most common, but their brushes must be replaced periodically. This is particularly problematic in the case of submersible pumps, where the pump must be removed from the well to replace the brushes. Furthermore, the motor's insulation must not be compromised to prevent it from becoming vulnerable to water infiltration [17]. The DC motors used for solar pumping applications are series motors. They can generate sufficient starting torque to overcome a pump's starting resistance and respond well to varying current. The connection is either direct or optimized via a power-adaptive chopper controlled by its duty cycle. This type of setup requires relatively simple electronics but suffers from the drawback of DC motors, which require regular maintenance. For low- and medium-power applications, up to a few kilowatts, the standard single-phase grid is sufficient. For high-power applications, AC motors are generally powered by a polyphase power source. The most commonly used system in such cases is the three-phase system provided by electric utilities. These alternating-current motors come in two types: synchronous motors and asynchronous motors. The term "asynchronous" stems from the fact that the speed of these machines is not necessarily proportional to the frequency of the currents flowing through them; that is, the rotor slips relative to the speed of the stator's rotating field [18].

2.3 Storage

Energy storage in this solar PV system with photovoltaic pumping can be achieved in two ways: electrical energy storage or water storage. The latter method is often chosen because it is more practical to store water in reservoirs than to store electrical energy in heavy, expensive, and fragile batteries. Furthermore, a battery-based storage system incurs additional costs, involves battery maintenance issues, and requires replacement after 3 to 7 years for lead-acid batteries and after 10 to 15 years for lithium batteries of use. In addition, energy efficiency is higher when no batteries are used. For these reasons, we have opted for water storage. The reservoir is easy to construct, and its storage capacity can range from one to several days. This tank does not require complex maintenance and is easily repaired in the event of damage during use. The use of a three-phase asynchronous motor which is more robust, less expensive, and requires minimal maintenance. That is becoming a more economical and practical solution, even at the cost of a more complex electronic control circuit for photovoltaic pumping systems. For example, grid-connected electric pumps have long used this type of motor. It is used specifically for submersible pumping in boreholes and open wells. The development of efficient inverters has enabled the use of this type of motor in solar pumping applications.

2.4 Sizing the photovoltaic pumping system

This will be based on data collected on-site and an assessment of the crops' water requirements. This will be followed by the sizing and selection of the components for the photovoltaic pumping system.

The field to be irrigated has a total area of 51,116.3 m², divided into six (06) sections. Since the soil and climate are suitable for certain crops, the selection of specific crop types made it possible to design the irrigation system and its various components. A preliminary study conducted on-site by the company SMRS-Forages.SAL revealed that water was already present at a depth of just 50 m. For the design of the solar pumping system, we opted for the "sun-tracking" pumping technique. The energy produced by the photovoltaic generator is used directly to power the electric pump, which stores water in tanks during the pumping process for later use in irrigation. This type of system is preferable given the cost of batteries and the fact that they represent the weak link in a photovoltaic system due to their maintenance requirements and limited lifespan. Water requirements for irrigation depend on the type of crop,

meteorological variables such as temperature, humidity, wind speed, soil evapotranspiration, the season of the year, the irrigation method, and also the crop coefficient (K_c), which represents how a crop's water requirements change depending on its growth stage.

Reference evapotranspiration (ET_0) represents the amount of water lost through soil evaporation and plant transpiration. It is often estimated using the Penman-Monteith method, as standardized by the FAO. This method uses meteorological data and location-specific data. The average hourly evapotranspiration is given by Equation (1) [19]:

$$ET_0 = \frac{0.408 \cdot \Delta \cdot (R_n - G) \cdot d + \gamma \cdot \frac{37}{t + 273} \cdot v (e_w - e)}{\Delta + \gamma \left(1 + \frac{r_s}{208} v \right)} \quad (1)$$

ET_0 is the reference evapotranspiration in mm/h; R_n , the net solar radiation in $W \cdot m^{-2}$; G , the soil heat flux in $W \cdot m^{-2}$; d , the time step in kiloseconds ($d = 3.6 \times 10^{-3}$ ks); t , the hourly average air temperature in $^{\circ}C$; Δ , the slope of the saturated vapor pressure curve in $kPa \cdot ^{\circ}C^{-1}$; γ , the psychrometric constant in $kPa \cdot ^{\circ}C^{-1}$; e , the vapor pressure at temperature t in kPa; e_w , the saturated vapor pressure in kPa; v , the average wind speed at a height of 2 m in $m \cdot s^{-1}$.

In practice, the pumping system must be sized to meet the crop's peak water consumption, represented by the values circled in red in Table 1 [20].

Table 1: Crop coefficient values (K_c) for various crops based on their stage of development [20].

CROPS	INITIAL PHASE	GROWTH PHASE	MID-SEASON PHASE	LATE-SEASON PHASE
Green beans	0.35	0.70	1.10	0.90
Cabbage	0.45	0.75	1.05	0.90
Cucumbers	0.45	0.70	0.90	0.75
Tomatoes	0.20	0.6	0.90	0.70
Corn	0.40	0.80	1.00	0.90
Millet	0.35	0.70	1.00	0.65
Onions	0.5	0.75	1.05	1.00
Peanuts	0.45	0.75	1.05	0.70
Potatoes	0.45	0.75	1.05	0.85
Eggplant	0.50	0.60	0.90	0.60
Bell peppers	0.50	0.60	0.70	0.60
Sorghum	0.35	0.75	1.10	0.65
Wheat	0.30	0.80	1.10	1.00
Beans	0.35	0.70	1.10	0.30
Lettuce	0.40	0.60	0.7	0.70

To calculate the maximum daily water requirement of a crop, Equation (2) is used:

$$CWR_{\max} = A \times K_c \times PET \quad (2)$$

Where: $CWR_{\max}$ is the Maximum Daily Volumetric Crop Water Requirement in l/m^2 or $m^3/1,000 m^2$; A , the cultivated area in m^2 ; K_c , the crop coefficient; PET or ET_0 , the potential or reference evapotranspiration, or climatic water demand, in l/m^2 .

To determine the average evapotranspiration, we will use Table 2.

Table 2: Average PET from 1991 to 2007-Ouagadougou Airport-Meteorological Station

Month	Average PET in l/m ² .d
January	5.8
February	6.3
March	6.5
April	6.3
May	6.3
June	5.8
July	4.9
August	4.4
September	4.8
October	5.5
November	5.6
December	5.8

To design the irrigation system, we will size the pumping capacity to meet the crops' peak water demand, using the Kc values corresponding to the mid-season phase and the potential evapotranspiration (PET) for the month of March as a reference.

Since the site is divided into several sections, we have decided to grow two to three types of crops in each section. Tables 3 to 8 show the water requirements for the different types of crops in the six sections of our site.

Table 3: Calculation of water requirements for crops in Section 01

Section (01) : 12,960 m ²				
Crops	Cultivated Area (m ²)	Kc	PET (L/m ²)	Water Requirement (L)
Eggplants	4,320	0.9	6.5	25,272
Peppers	4,320	0.7	6.5	19,656
Cucumbers	4,320	0.9	6.5	25,272
Total: 70,200 L				

In this section on crops, it appears that eggplants and cucumbers have the same water requirements, which are higher than those of bell peppers, whose crop coefficient is lower than that of the first two.

Table 4: Calculation of water requirements for crops in section 02

Section (02) : 11,843 m ²				
Crops	Cultivated Area (m ²)	Kc	PET (L/m ²)	Water Requirement (L)
Corn	3,947	1.00	6.5	25,655.5
Wheat	3,947	1.10	6.5	28,221.05
Beans	3,949	1.10	6.5	28,235.35
Total : 82,111.9 L				

In Section 2, beans and wheat have the same water requirements. Corn, which is also grown there, requires less water than the first two crops.

Table 5: Calculation of water requirements for crops in section 03

Section (03) : 4758 m²				
Crops	Cultivated Area (m ²)	Kc	PET (L/m ²)	Water Requirement (L)
Millet	2,379	1.00	6.5	15,463.5
Sorghum	2,379	1.10	6.5	17,009.85
Total : 32,473.35 L				

In Section 3, sorghum is more water-loving than millet.

Table 6: Calculation of water requirements for crops in Section 04

Section (04) : 10,547 m²				
Crops	Cultivated Area (m ²)	Kc	PET (L/m ²)	Water Requirement (L)
Salad	5,273.5	0.7	6.5	23,994.425
Cabbage	5,273.5	1.05	6.5	35,991.6375
Total : 59,986.0625 L				

In Section 04, we see that cabbage requires more water than lettuce.

Table 7: Calculation of Water Requirements for Crops in Section 05

Crops				
Crops	Cultivated Area (m ²)	Kc	PET (L/m ²)	Water Requirement (L)
Tomatoes	3,459	0.9	6.5	20,235.15
Onions	3,459	1.05	6.5	23,607.675
Peanuts	3,460	1.05	6.5	23,614.5
Total : 67,457.325 l				

In Section 5, onions and peanuts have the same water requirements as the cabbage grown in Section 4 and the potatoes grown in Section 6, however, due to the differences in cultivated areas, the quantities of water used differ.

Onions and peanuts require more water than tomatoes.

Table 8: Calculation of Water requirements for crops in Section 06

Section (06) : 679.30 m²				
Crops	Cultivated Area (m ²)	Kc	PET(L/m ²)	Water Requirement (L)
Potato	339	1,05	6,5	2534,025
Green beans	340,30	1,10	6,5	2433,145
Total : 4967,17 l				

In Section 6, green beans require more water than potatoes and are just as water-loving as sorghum (Section 3), beans, and wheat (Section 2). This analysis is based on crop coefficients rather than cultivated areas.

Figure 1 shows the daily water requirements of the various crop varieties in the different sections under cultivation.

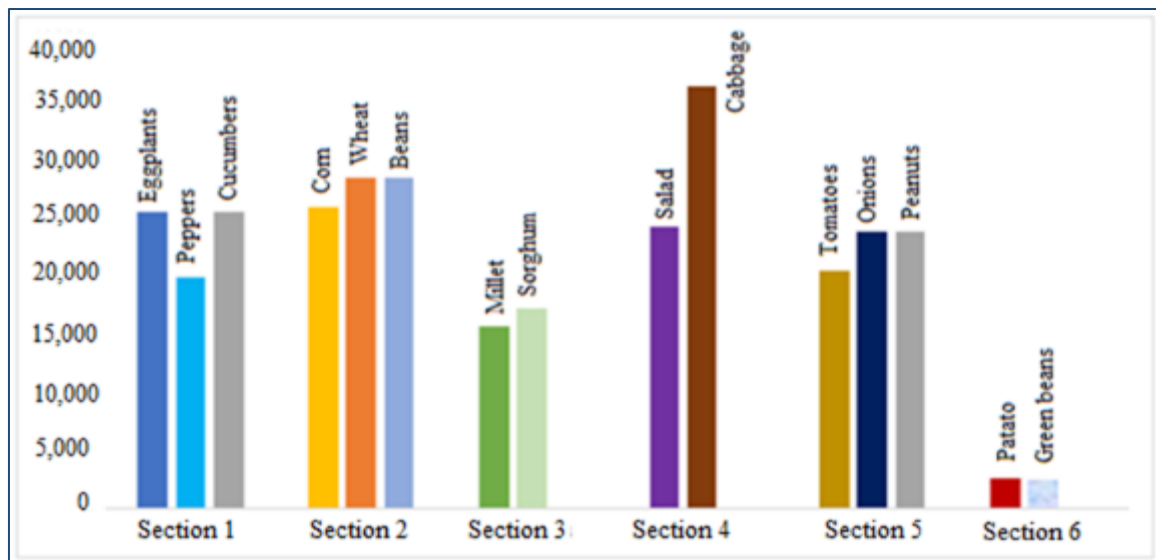


Figure 1: Water requirements for different crops in the sections (L/day)

When we add up the daily water requirements for each crop, we arrive at a total of 317,195.8075 liters of water per day, equivalent to approximately 317.20 m³/day. In this study, we will therefore consider a maximum water requirement of 318 m³ of water per day. In solar pumping systems, the flow rate or daily water requirement is expressed in m³ per day (m³/day). To ensure a longer service life for the electric pump, we estimate that the solar pump selected for this application will operate from 9:00 a.m. to 3:00 p.m., with peak pumping at 12:00 p.m., resulting in 6 hours of operation per day. Since the flow rate Q is the ratio of the volume of water V (in m³) to the operating time t (in h), we then obtain:

$$Q = 318/6 = 53 \text{ m}^3/\text{h}$$

To achieve this flow rate and meet the daily water demand, three (03) wells, each with its own storage tank, are planned for the site. Each well will supply 106 cubic meters of water per day, and the electric pump will have a flow rate Q_{ep} calculated as follows:

$$Q_{ep} = 106/6 = 17.66 \text{ m}^3/\text{h}$$

Electric pumps with a flow rate of 18 m³/h are therefore required for this application.

The total dynamic head (TDH) of a pump is the difference in pressure, expressed in meters of water column, between the suction and discharge ports.

When sizing a hydraulic system, it is essential to take pressure losses into account. There are two types :

- Constant pressure losses, also known as linear losses, which are losses due to friction against the walls of the pipes. They are calculated using Darcy-Weisbach equations (3) and (4):

$$h_r = \lambda \frac{L}{D} \cdot \frac{v^2}{2g} \quad (3)$$

$$\Delta p_r = \rho g h_r = \lambda \frac{L}{D} \cdot \rho \cdot \frac{v^2}{2} \quad (4)$$

Δp_r is the pressure drop, expressed in Pa ; h_r , the height of the fluid in question, in m ; λ , the coefficient of steady pressure losses; L and D are the length and inner diameter of the pipe, respectively, in m; v , the average fluid flow velocity in m/s; g , the acceleration due to gravity in m/s²; ρ , the density of the fluid in kg/m³.

- There are also local or singular pressure losses caused by changes in direction or variations in the internal diameter of the pipes. These can be determined using Equations (5) and (6) :

$$h_L = K \cdot \frac{v^2}{2g} \quad (5)$$

$$\Delta p_L = K \cdot \rho \cdot \frac{v^2}{2} \quad (6)$$

h_L and Δp_L in meters and pascals, respectively; K is the singular pressure drop coefficient.

The total pressure drop, h_t or $\Delta J/\Delta P_t$, is given by Equation (7):

$$h_t = h_r + h_L \quad \text{or} \quad \Delta p_t = \Delta p_r + \Delta p_L \quad (7)$$

The total dynamic head is calculated using Equation (8):

$$TDH = H_g + \Delta J \quad (8)$$

Where TDH is the total dynamic head in meters of water column (mWC); H_g , the geometric head in meters of water column (mWC); ΔJ , the pressure losses (linear and singular) in meters of water column (mWC).

The diameter of the pipes must be calculated so that these pressure losses do not exceed 10% of the total geometric head [21], [22].

Figure 2 Illustrates the components of the geometric head

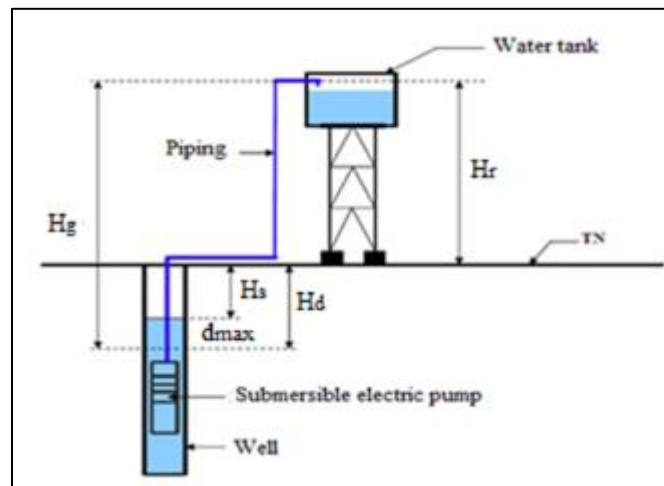


Figure 2: Pumping System with Water Storage

$H_g = \text{Dynamic Water Level (H}_d\text{)} + \text{Discharge Head (H}_r\text{)}$

The difference between the dynamic water level and the static water level is called drawdown. $d_{\max}$ is the maximum acceptable drawdown before the pump shuts down.

To determine the total dynamic head, we used PVsyst, a design and simulation software program for solar photovoltaic systems. Using this software, we determined the dynamic level (H_d), which represents the depth to which the pump must be submerged to achieve the desired water flow rate. We then decided to place the water towers 10 m above ground level, which represents the discharge head (H_r). To meet the daily water demand, we have planned a water tower (Figure 3) with a capacity of 106 m³ of water for each well. We plan for the tower to have a vertical cylindrical shape with a diameter of 5.2 m and a useful height of 5 m.



Figure 3: Water Tower

The simulation shown in Figure 4 indicates that, for a daily water demand of 106 cubic meters, a well with a minimum depth of 145 meters is required to achieve a pumping rate of 18 cubic meters per hour. The minimum depth to which the pump must be submerged is 140 meters, which corresponds to the dynamic level (H_d). We then obtain:

- $H_g = 140 \text{ m} + 10 \text{ m}$; that is, $H_g = 150 \text{ m}$;
- $\text{TDH} = 150 \text{ m} + 10\% \times 150 \text{ m}$; that is, $\text{TDH} = 165 \text{ m}$.

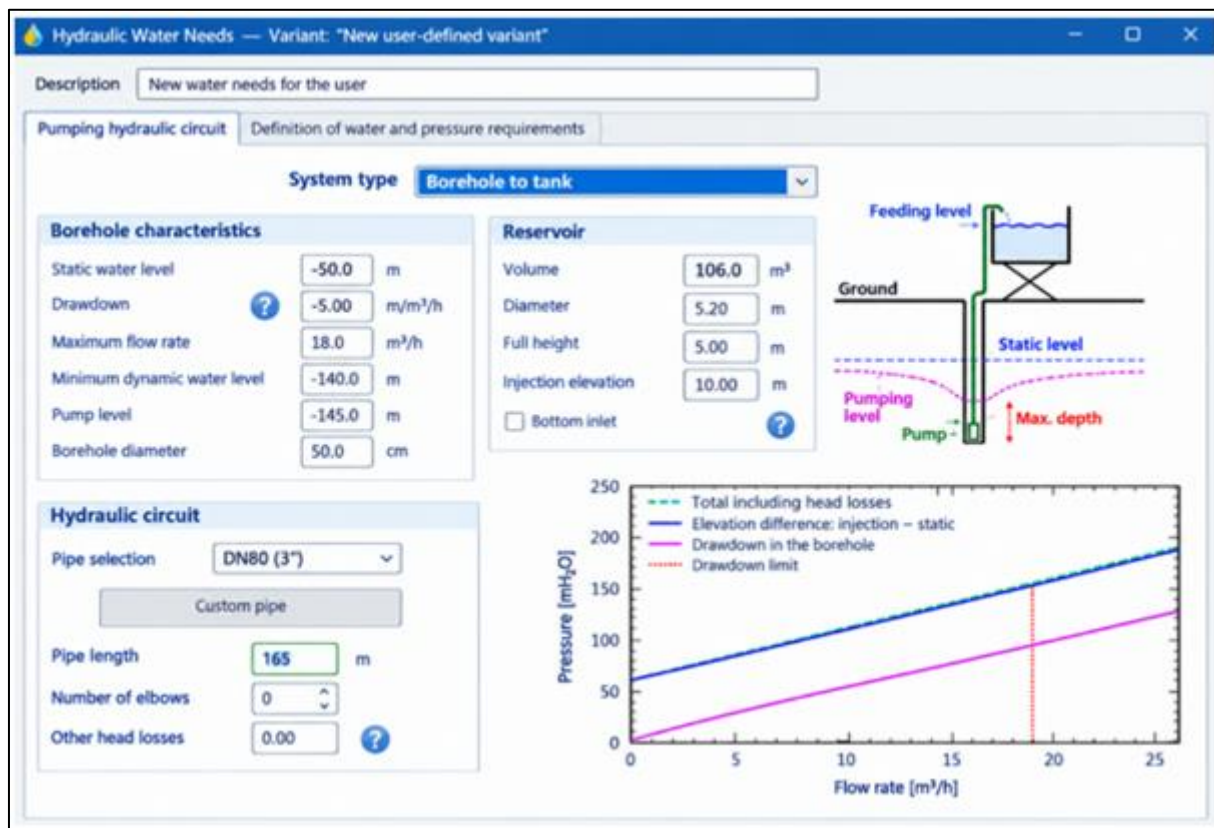


Figure 4: Simulation page with PVsyst

When operating a solar pumping system, the goal is to raise a certain amount of water to a certain height every day. This requires a certain amount of mechanical energy. To calculate the electrical energy required to power motor pump E_{e1} , the pump's efficiency must be taken into account. This efficiency varies depending on the type of pump. However, in cases where the efficiency is unknown, the reference values in Table 9 will be used [23]:

Table 9: Reference efficiency values for motor pumps

PUMP TYPE	Positive Displacement	Centrifugal (< 2 HP)	Centrifugal (>2 HP)
Reference Efficiency	0.6	0.4	0.6

The calculations will be performed for a solar-powered pumping system with a centrifugal pump equipped with an alternating-current motor having an efficiency of $\eta_m = 0.85$ and a centrifugal pump with an efficiency of $\eta_p = 0.6$ under optimal operating conditions. The daily electrical energy E_{e1} in watt-hours per day (Wh/day) required for the pump to operate properly is calculated using Equation (9) [24] [25]:

$$E_{e1} = \frac{\gamma \cdot V \cdot TDH}{\eta_m \cdot \eta_p} \quad (9)$$

With $\gamma = \frac{\rho \cdot g}{3600} = 2.725 \times 10^{-3}$ which is the hydraulic constant of water.

Equation (9) can be rewritten as follows:

$$E_{e1} = \frac{\rho \cdot g \cdot V \cdot TDH}{3600 \cdot \eta_m \cdot \eta_p} \quad (10)$$

The calculation allow us to obtain: $E_{e1} = \frac{106 \cdot 165 \cdot 2.725}{0.6 \cdot 0.85} = 93,451.47 \text{ Wh} / d$

To calculate the power of the electric pumps to be selected, we proceed as follows:

- **Step 1:** Calculate hydraulic power: $P_h \text{ (kW)} = 2.725 \times 10^{-3} \times Q \times TDH$; that is, $P_h = 8 \text{ kW}$;
- **Step 2:** Calculate mechanical power: $P_m = P_h / \eta_p$; that is, $P_m = 13.33 \text{ kW}$.
- **Step 3:** Calculate the motor's electrical power: $P_e = P_m / \eta_m$; that is, $P_e = 15.68 \text{ kW}$.

We will therefore need to install a pump with an electrical power greater than or equal to 15.68 kW for each well.

The specifications for each of the three electric pumps are listed in the Table 10.

Table 10: Characteristics of the selected electric pumps

Centrifugal electric pump Maximum flow rate: 18 m ³ /hour Maximum discharge head: 170 m Power/Voltage: 16 kW/400 V	
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2.5 Sizing and Selection of Photovoltaic Modules

There are many types of PV modules (monocrystalline silicon, polycrystalline silicon, cadmium telluride (CdTe), amorphous silicon (a-Si), thin-film, etc.). All have their advantages and disadvantages and vary in cost and efficiency. Monocrystalline silicon (Mono-Si) modules with an efficiency between 18% and 24% and polycrystalline (Poly-Si) modules with an efficiency between 14% and 18% (currently) are recommended. These two types of modules are very similar and can be installed interchangeably. Polycrystalline modules are slightly less expensive than monocrystalline ones, but they have a lower efficiency. To achieve the same power output, a larger area of polycrystalline modules must therefore be installed, which offsets their lower price. The two solutions are thus nearly equivalent in terms of

performance and price. As a result, availability from suppliers is generally a more important factor in the selection process than efficiency. [26].

The town of Komsilga is located at latitude 12.1809 North and longitude -1.6308 West. Since we are in the Northern Hemisphere, the modules will be oriented due south. The tilt angle i varies depending on the latitude of the site in question; however, in practice, the values given in Table 11 can be used.

Table 11: Tilt angle of the photovoltaic panel as a function of latitude

Latitude L	Inclination i
$L < 10^\circ$	$i = 10^\circ$
$10^\circ < L < 30^\circ$	$i = L$
$30^\circ < L < 40^\circ$	$i = L + 10^\circ$
$L > 40^\circ$	$i = L + 15^\circ$

Depending on the latitude, the tilt angle of the modules is 12° . However, for practical reasons, a tilt angle of 15° is used in Burkina Faso. The solar radiation data were obtained using the PVGIS software and are presented in Table 12.

Table 12: Solar irradiation data

Month	Global Horizontal Irradiation (kWh/m ² /day)	Global Irradiation at Optimal Angle (kWh/m ² /day)	Global Irradiation at a 15° Angle (kWh/m ² /day)	Temperature (°)
January	6.12	7.11	6.89	26.7
February	7.00	7.72	7.58	28
March	6.87	7.08	7.07	32.3
April	6.77	6.57	6.66	33.5
May	6.58	6.09	6.23	32.7
June	6.09	5.53	5.70	30.4
July	6.09	5.57	5.74	26.9
August	4.98	4.77	4.85	25.3
September	5.63	5.64	5.67	25.8
October	6.30	6.76	6.68	27
November	6.17	7.06	6.86	26.8
December	5.93	7.03	6.78	26.3

To calculate the power output of the PV modules to be installed, we need to know their average efficiency coefficient based on the type of mounting system. This coefficient accounts for various losses generally caused by temperature fluctuations, dust that accumulates on the PV modules, and voltage drops in the cables [26].

Table: 13 Reference efficiency of PV modules by mounting system type

SELECTING THE EFFICIENCY COEFFICIENT Based on the Type of Mounting System for PV Modules and Operating	Permanent Installation of PV Modules	Horizontal-axis sun tracking (adjustment of the tilt angle according to the season)	Sun tracking with an inclined or vertical axis (adjustment of the inclination based on	Automatic sun tracking on 2 axes
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Conditions			the time of day)	
Reference efficiency in dusty environments or when panels are not cleaned properly	0.5	0.6	0.7	0.8
Reference efficiency in a clean environment or with regular cleaning of the PV modules	0.6	0.7	0.8	0.9

The peak power is ultimately given by Equation (11):

$$P_p = \frac{P_e}{\eta} \quad (11)$$

Where η , the module efficiency is a function of the substrate.

For each electric pump, we obtain: $P_p = \frac{16,000}{0.6} = 27kWp$

The characteristics of the selected photovoltaic modules are giving by table 14.

Table 14: Characteristics of the selected PV modules

Monocrystalline PV modules
Nominal power: 500 Watt-peak.
Maximum power voltage (V_{max}): 37.68 V.
Open-circuit voltage (V_{oc}): 45.46 V
Maximum power current (I_{mpp}): 13.14 A
Short-circuit current (I_{cc}): 13.99 A
Module efficiency: 20.85%

To achieve this power output, we need to install 54 PV modules of 500 Wp per electric pump. This results in a total of 162 PV modules for all the electric pumps.

Today, there is a wide variety of photovoltaic inverters available from various manufacturers. For a system without storage, the number of modules to be connected in series can be determined by considering the inverter's nominal voltage and maximum input voltage, or the MPPT input voltage range. Each of the three inverters to be selected has 4 MPPT controllers, each capable of handling 2 strings. This will result in 8 strings per inverter.

The number of modules that must be connected in series is the ratio of the inverter's nominal voltage or the voltage selected within the MPPT input voltage range to the nominal voltage of a single module. We will consider a voltage of 260 V within the 200–1,000 V range of the MPPT input of the selected inverter.

The number of modules in series is therefore $N_s = V_e/V_m$; this gives $N_s = 260/37.68 = 7$ PV modules to form a string.

To determine the number of parallel branches, we divide the total number of PV modules to be installed by the number of modules in series per string. This confirms that we need 8 parallel branches, or strings, per inverter.

2.6 Sizing and Selection of Inverters

Inverters are required to convert the direct current obtained from the PV array into alternating current. The total power of the inverters is calculated using Equation (12) [26]:

$$P_{AC} \geq \frac{P}{K} \quad (12)$$

P_{AC} : Nominal power of an inverter in W;

P: Peak power of all loads connected to the inverter in W;

K: Inverter load factor.

It is recommended not to load the inverters beyond 80% of their rated power to ensure their longevity.

$$P_{AC} \geq \frac{27,000}{0.8} \text{ or } P_{AC} \geq 33,750W$$

We will consider three inverters, whose specifications are listed in Table 15.

Table 15: Selected PV inverter Type

40 kVA Three-Phase Inverter - 4 MPPT
Nominal AC Output Power: 40 kVA
4 MPPT - 2 Strings per MPPT
Maximum DC Input Power: 52 kW
MPPT Voltage Range: 200 V–1,000 V
Maximum efficiency of over 98.8%.
4-MPPT design with precise MPPT algorithm
IP65 rating for outdoor installations
Integrated RS485/Wi-Fi/GPRS interface, with support for remote updates
Wi-Fi monitoring available; app available for iPhone

2.7 Cable Sizing and Selection

The cross sectional area of the DC-side cables that is, the cables used to connect the inverters to the strings can be determined using Equation (13):

$$\Delta V = b \cdot \frac{\rho \cdot L}{A} \cdot I \quad (13)$$

With, ΔV is the voltage drop in volts (V); b, the coefficient taken as 1 for three-phase systems and 2 for single-phase and DC systems; ρ , the resistivity of the conductor material under normal operating conditions, ($0.023 \Omega \cdot \text{mm}^2/\text{m}$ for copper and $0.037 \Omega \cdot \text{mm}^2/\text{m}$ for aluminum); L, the simple length of the conduit in m; A, the cross-sectional area of the conductors in mm^2 ; I, the rated operating current in A.

Using Equation (13), we obtain the cross-sectional area A:

$$A = b \cdot \frac{\rho \cdot L}{\Delta V} \cdot I \quad (14)$$

Assuming that the DC cabinet is located 100 m from the PV array, with a current of 16 A in the DC cables and a permissible voltage drop of 3%, we arrive at a cross-sectional area of 10 mm^2 .

On the AC side, the three-phase electric pump has a mechanical power of 13.33 kW and an electrical power of 16 kW at a voltage of 400 V with a power factor of 0.8. Its current is therefore 28.87 A. Assuming the boreholes are located 10 m from the AC panels and with a dynamic head of 140 m, we obtain a total cable length of approximately 150 m.

Formula of Equation (14) yields a cross-sectional area of 9 mm².

The DC cables will therefore be type H1Z2Z2-K with a cross-sectional area of 10 mm², and the AC-side cables will be harmonized type H07RN-F with a cross-sectional area of 9 mm², in accordance with IEC 60364.

2.8 Protection System

Installations that include an inverter or a generator present increased risks to electrical safety and are more prone to failures (faults) and must comply with the standards and regulations applicable to alternating current. We will therefore use :

- DC and AC surge arresters to protect the system against overvoltage;
- A DC main circuit breaker (between the PV generator and the inverter);
- DC-side circuit breakers (for overcurrent protection per string on the PV module side);
- AC circuit breakers (for the AC circuit between the inverters and the motor pumps);
- Grounding connections.

We will also size and install a transformer between the inverters and the motor pumps to provide galvanic isolation and ensure greater stability of this power supply system.

To make the pumping system more efficient and optimize the expected results, smart management is essential [27], [28].

3 RESULTS AND DISCUSSION

To irrigate an area of 51,116.3 m², divided into six (06) plots intended for the production of different crop varieties, the daily water requirements were estimated at 318 m³. To ensure greater efficiency of this initiative and optimize water conservation, a precious resource in our climate zone, a drip irrigation system was selected. This system offers an efficiency of between 90 and 95 percent, with water savings of up to 50 %. Regarding crop varieties, the study showed that some are very water-intensive (such as cabbage and beans, among others). Conversely, others, such as potatoes and green beans, require only a small amount of water.

Three boreholes, each with a capacity of 106 m³ of water, are to be drilled. Consequently, water storage was deemed necessary. Three cylindrical reservoirs, each with a diameter of 5.2 m and an effective height of 5 m, must be constructed. A single reservoir of the same shape, with a diameter of 9 m and the same height, is equivalent to these three.

A simulation performed using Pvsyst software determined a total dynamic head (TDH) of 165 m, a value required for sizing the piping.

A PV generator consisting of 162 monocrystalline 500 Wp modules has been sized to power three 16 kW electric pumps. It will supply the electric pumps with 81 kWp of power. To power them with a three-phase 400 V, 50 Hz voltage, three inverters, each capable of delivering 40 kW of power, have been selected.

Other components, such as a transformer to provide galvanic isolation between the AC loads and the DC grid with its inverters, surge arresters to protect against atmospheric overvoltages (lightning strikes), circuit breakers to protect against overcurrent on both the DC and AC sides, and connection cables, among others, must be provided.

4 CONCLUSION

This study involved the design of an irrigation system equipped with a photovoltaic pumping system. First, it provided an opportunity to review the various irrigation methods and select the most appropriate one for the Komsilga site. This method is micro-irrigation, or drip irrigation. Based on the reference evapotranspiration rate of 6.5 mm/day corresponding to the worst-case scenario, namely the month of March provided by the Ouagadougou Airport Meteorological Station, the water requirements for the various crop varieties were calculated. By summing these various quantities, a total water requirement of 318 m³ per day was determined, which establishes the required well capacity. For water storage, the farm developer has the choice between constructing three reservoirs with a diameter

of 5.2 m and a height of 5 m, or a single reservoir with a diameter of 9 m and the same height. The sizing analysis determined that a field of 162 monocrystalline silicon PV modules is required to form the PV array, which can deliver a power output of 81 kWp. Three inverters, each with a capacity of 40 kW, are needed to power the electric pumps with a three-phase AC voltage of 400 V, 50 Hz.

This work is of paramount importance to any agricultural developer seeking to control productivity parameters, especially during the dry season or in arid regions that have groundwater reserves.

To be effective, this irrigation system requires a smart control system. Various tools, hardware, and software resources can be used to design the smart management system. This will be the focus of the next part of our study, in which we will discuss the fundamentals of smart farming.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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