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Original article

Design and Simulation of a Solar Photovoltaic Water Pumping System for Agricultural Irrigation Applications in Libya

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Abstract
This paper presents a study of the use of a solar PV water pumping system (SPVWPS) in Tripoli. This system is applied to a medium farm located in the Ayn Zara municipality (Wady Al-Rabey), which has an average water consumption of 41.5m3 /day. This study provides detailed system sizing. The system's sizing has been carried out using PVSyst software. A deep well of 80 m depth needs a 3.4 kW pump, 4 kW MPPT-DC converter, and 4.4 kW PV array. The type of the pumping system was direct coupling. PVSyst simulation results show that this system can provide 96% of the water needed during the year. The results showed that the costs of the solar water pumping system are lower compared to conventional systems, especially the diesel generator pumping system. It was obvious that SPVWPS is very suitable and recommended in sunny spots like Libya.
Keywords. Solar Energy, Water Pumping, Solar Pumping System, Pvsyst Simulation, Renewable Energy.

INTRODUCTION

Modern societies still draw the bulk of their energy from coal, petroleum, and natural gas, yet the intensive exploitation of these fuels carries serious environmental consequences. Burning fossil fuels and biomass releases carbon dioxide (CO_2), one of the principal greenhouse gases driving climate change. This reality has motivated an ongoing effort to identify cleaner alternatives and to develop practical approaches that reduce the environmental burden of energy production [1]. Among the available alternatives, renewable energy technologies stand out as the strongest candidates to replace conventional fuels: their resources renew themselves continuously through natural processes, which makes them inherently sustainable over the long term [2]. In areas where rainfall alone cannot satisfy crop irrigation demands, farmers must rely on pumps to raise groundwater to the surface. These pumps have traditionally been driven either by grid electricity or by diesel generators. This dependence gives agriculture a considerable environmental footprint, since fuel-powered generators emit greenhouse gases that contribute to global warming. Replacing them with solar PV water pumping systems offers a direct way to cut this reliance on fossil-based electricity [3].

In addition to being clean, such systems demand little maintenance, consume no fuel, and exploit a solar resource that is freely available in virtually every part of the world [4]. Libya's energy sector is dominated by hydrocarbons: oil and natural gas supply nearly all of the country's primary energy, and its main conversion activities are oil refining and thermal electricity generation. Solar applications, by contrast, remain marginal. This is striking because Libya ranks among the countries with the greatest untapped renewable-energy potential worldwide, particularly with respect to solar energy [5]. According to the Global Solar Atlas by the World Bank [6], Libya receives, on average, more than 6,000W/m2 global solar radiation each day on a horizontal surface. Depending on geographical location, the global solar radiation varies between a minimum of 5,400W/m2/day in the northern part and a maximum of 7,000W/m2/day in the southern part of Libya. As shown in Figure 1. The primary objectives of this study are to evaluate the potential of solar energy for irrigation applications in Wady Al-Rabey, located south of Ayn Zara. Additionally, the research aims to design a photovoltaic (PV) water pumping system capable of meeting the farm's water demand efficiently. The performance of the proposed system will be analyzed through simulation using PVSyst software to assess its feasibility and effectiveness. Furthermore, the study will compare the costs associated with a photovoltaic solar water pumping system and a diesel generator-based water pumping system to determine the most cost-effective and sustainable solution.

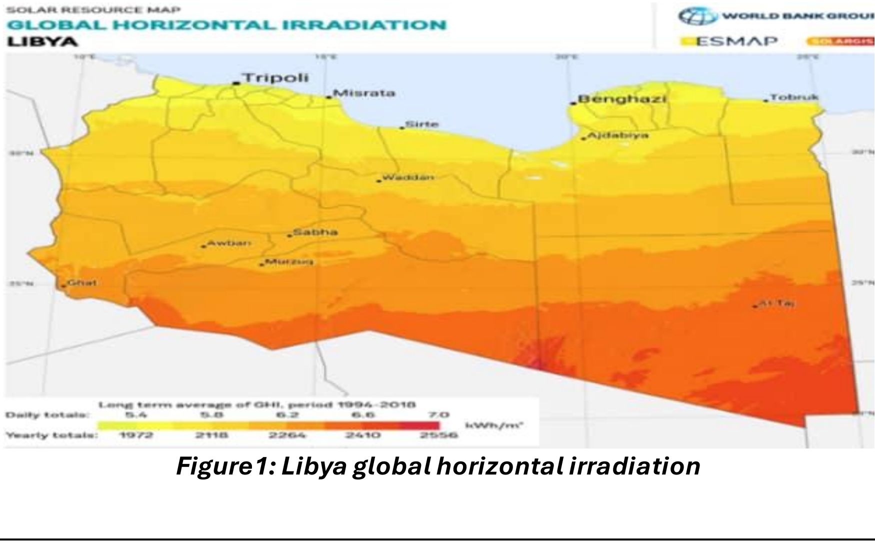

Figure 1: Libya global horizontal irradiation

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Site PV system details

This study was conducted on a typical farm situated at a latitude of 32.7373°N, a longitude of 13.3093°E, and an altitude of 56 meters in the southern region of Ain Zara, specifically in Wady Al-Rabey. The farm primarily consists of 1,100 grape trees, as illustrated in Figure 2. The irrigation system relies on an 80-meter-deep well, which is currently powered by a diesel generator. However, due to frequent electricity outages, alternative energy solutions are being explored. Wady Al-Rabey is located southeast of Tripoli, approximately 30 km from the city center.

Figure 2. Grape Trees, Wady Al-Rabey

The average annual solar radiation at the site is 5.75 kWh/m2, as seen in Fig. 3a. Figure 3b shows the study's annual weather temperature data.

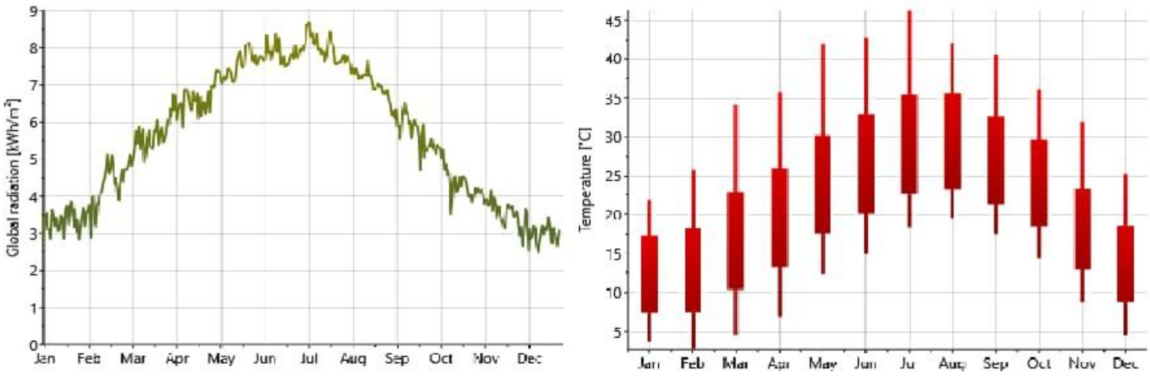

Fig. 3. (a) The study's annual solar radiation data. (b) The study's weather temperature data for the entire year.

System Design and Size

Correct sizing of the solar system is a decisive design step, particularly when the load is a large pump with a high energy demand. An undersized or oversized system penalizes both the project cost and the energy yield. For this reason, the sizing of a solar water pumping system follows a defined sequence of steps that guarantees the components are selected safely and appropriately. In this work, the case study described above is used to apply these steps and to assess how well they perform in practice.

Water source

Whether it is a well or a pond is one of the most crucial factors to be determined due to the pump type. Pump type selection depends on the head and flow rate, as the water source plays a big role in that. In this case study, a well with 80 m depth is the water source, but the pump level was selected to be at a depth of 75 m. Five meters were left for the accumulation of water underground, avoiding pump damage from any sand or stones.

Determination of water need

The water demand is not fixed every day, but there is fluctuation happens on a seasonal basis, as shown in Figure 4. For instance, in summer, plants need more water than in other seasons due to summer fruits, including grapes.

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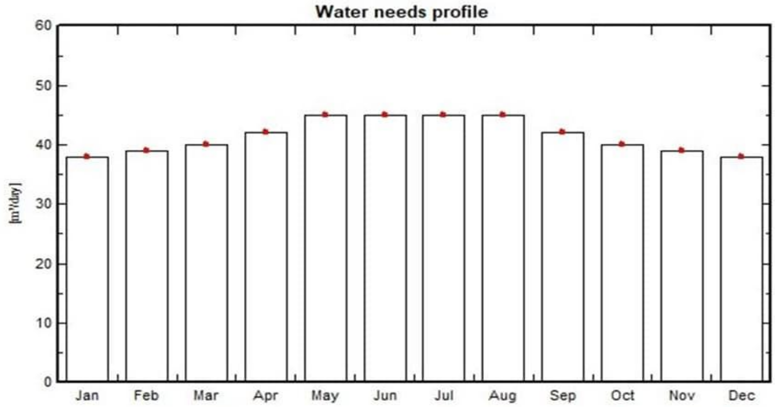

Figure4: Water demand in $m3$/day in a year

The average amount of water required per day by 1100 grape trees is about 41.5 m3/day from a deep well. The worst water-need condition was taken into consideration to determine the water needs.

Calculation of the flow rate

Equation 1 determines the maximum flow rate by taking into account the total water need and the number of peak sun hours (PSH).

$$Q = \frac{water\ need}{PSH} \quad (1)$$

The water need is equivalent to 41.5m3 per day, and the PSH annual average number of peak sun hours equivalent is at least 5 h/day. Therefore, by substituting into Equation 2, the pump flow rate becomes 8.3m3 per hour.

Calculating the total dynamic head (TDH)

To calculate the pump size which is based on estimating the total dynamic head (TDH) for pumping water. It considers pipe length as well as some mechanical friction. Equation 4 determines the total dynamic head. The following parameters are considered for TDH estimation, and they are based on such a case study.

Those parameters are illustrated in Figure 5, as well as the pipe length. The pipe length is 80 m; the pipe's internal diameter is 2".The bore depth is 80 m; however, the pump will be installed at 75 m depth, while the average water level is 60 m.900standard elbows are installed as shown in Figure 5.

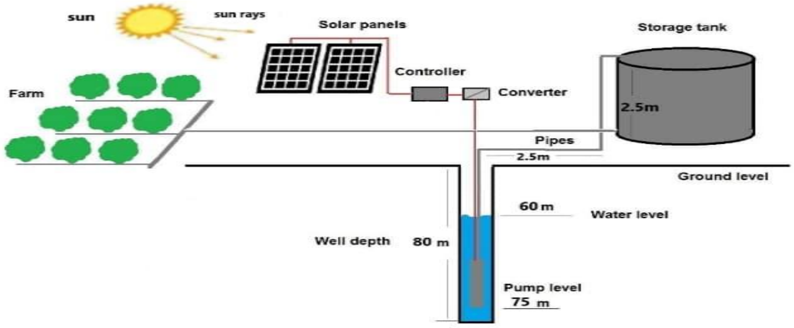

Figure 5. Schematic view of the solar PV water-pumping system

The following Equation 2 is used to calculate the frictional head loss for pipe, using the Hazen-Williams Formula.

$$\text{Friction head loss for pipe} = \frac{(10.67)*(l)*(Q)^{1.852}}{(C)^{1.852}*(D)^{4.8704}} \quad (2)$$

where: - C the roughness coefficient = 140 in polyethene (PE) pipe.

Q the Flow rate ($\frac{m^3}{s}$).

D the internal pipe diameter(m).

L the pipe length (m).

Therefore, by substituting into Equation 2, the friction head loss for the pipe becomes 2.37 m. Elbow friction loss is also present; it is 0.9

TDH=vertical rise + friction loss (3)

TDH = 74 m (vertical) + (0.9 x 3) (elbow friction loss) +2.5 m (vertical) + 2.37 m (friction head loss) = 81.57 m

Thus, the total dynamic head is approximately 81.6 m that will be used in pump size selection. To start sizing such a system, the pump size is an important aspect that needs to be assessed. As the total head and water demand are known for a farm, the pump size calculation is straightforward and can be completed using the following Equations

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Ph=$\rho * g * TDH * Q$ (4)

Ppump =$\frac{\rho*g*TDH*Q}{\eta P}$ = $\frac{\rho*g*TDH*Q}{\eta P}$ (5)

where: - Ph is hydraulic power (KW)
TDH the total head which is 81.6m
ρ the density of water which is $\frac{1000kg}{m^3}$
g the Acceleration of gravity which is $\frac{9.81m}{s^2}$
Q is water flow rate is 0.0023 $\frac{m^3}{s}$
ηP is the pump efficiency, which is obtained from the catalog let us take it as 54%. Results from equations 5,6 show that the calculated pump size is 3.42 kW, which can deliver the required amount of water [10,11].

3.5. Choice of the MPPT-DC Converter

The output current of the converter is determined by taking into account the electrical power and the voltage from the pump motor.

IOUT=$\frac{power\ electrical}{Voltag\ motor}$ (6)

Equation 6 becomes IOUT = $\frac{3420\ W}{240V}$ = 14.25A So, the MPPT converter was chosen based on the output current and efficiency.
V_{moto} = 240 V from the technical datasheet.

Solar PV Array Power Size

The array capacity of the system depends on the power of the pump, MPPT-DC converter efficiency, and the efficiency factor, which is a factor considering all losses in the system due to temperature, solar radiation variation, soiling and dirt, and cable losses. Considering the selected MPPT-DC converter efficiency is 98%. Equation 7 determines the Solar PV power sizing.

Power pv array = 1.25 × pump power (7)

Ppv array= 1.25 × 3.42 = 4.275KW. A safety factor (1.25) was added due to the losses that occur in the system.

- Calculation of the total number of modules. The number of solar PV modules is determined by taking into account the chosen module or PV electrical characteristics; in this stage, we need the peak power.

Table 1: PV module electrical characteristics

Type	JKM 365M-72-V-SI-mono
Maximum power at STC (W)	365 Wp
Maximum Power Voltage (Vmp)	39.7 V
Maximum Power Current (Imp)	9.20 A
Open Circuit Voltage (Voc)	48.2 V
Short Circuit Current (Isc)	9.57 A
Module Efficiency (%)	18.82 %

Based on Table 1 from the technical datasheet. The total number of modules is calculated as follows:

Ntotal mod = $\frac{PPVarray}{PN\ ,STC}$ (8)

With $PPVarray,$ the power calculated in the previous paragraph, which is 4.275 kW, and PN, $STC,$ the nominal power for one module at the STC, we have chosen 365Wp.

Ntotal mod = $\frac{4275}{365}$ = 11.712 ≅ 12 Modules

- Calculation of the number of strings

An essential part of array design is establishing how many modules may be placed in a single series string. Each module added in series raises the string voltage, and the sum of the module voltages defines the operating voltage of the string. The minimum and maximum number of strings, $Ns\ min$ and $Ns\ max$, respectively, are calculated based on the MPPT-DC converter operating voltage range and the voltage of the photovoltaic solar panel (Vmp, Voc), as follows:

Nsmin=$\frac{Min\ MPPT-DC\ operating\ voltage}{Vmp\ (panel)}$ (9)

Nsmax=$\frac{Max\ MPPT-DC\ operating\ voltage}{VOC\ (panel)}$ (10)

From Equations 9 and 10, the number of solar panels in series can be obtained;

Ns min = $\frac{240}{39.7}$ = 6 panels or Ns max = $\frac{375}{48.2}$ =7.78 ≅7 panels

Min MPPT-DC operating voltage > 238v, Max MPPT –DC operating voltage=375v from the technical datasheet.
V_{oc} (panel) = 48.2v, Vmp(panel) =39.7v from the technical datasheet.

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- Number of solar in parallel calculation: since Ns min and N_{total} are now known, the value of the number of parallel strings Np s can be determined by Equation 11

$$NP\ s = \frac{Ntotal}{Ns\ min} \quad (11)$$

By substituting Equation 12, the Number of parallel strings becomes 2.
Table 2 shows the numbers of series panels and parallel panels to achieve the desired power output.

panel connection	connection	Voltage (Volts)	Current (Amps)
	none	39.7	9.2
+ –	series	238.2	9.2
+ – + –	series& parallel	238.2	18.4

Table 2: PV module connections in parallel and series

PV array surface area calculation.
The surface area of the PV array is determined by Equation 12

$$\text{Area}(m^2) = \frac{PPV}{\eta PV * PSI} \quad (12)$$

Where PSI (Peak Sun Insolation) is 1000 $W/m2$ at STC (Standard Test Conditions), and ηPV is the PV efficiency. Therefore, we get Area $(m^2) = \frac{4275\ w}{1000 w/m^2 * 0.1882} = 22.715 m^2 \cong 23 m^2$

Water storage tank sizing

Solar pumping installations normally store water rather than electrical energy, using a tank sized to cover several days of demand. Practical design experience suggests the tank should hold enough water for an autonomy period of roughly three to five days. Thus, the size of the tank is going to be estimated as: Proper tank size = Number of storage days ×The average amount of water = 5 $days$ ×41.67 $m3$ = 208 ≅ 200 m^3. Therefore, if the height of the tank was already known, which is 2.5 meters, the diameter of the tank is shown below in the layout.

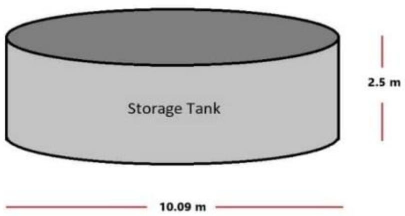

Figure6: 200m^3 Capacity water storage tank

The tank is made from concrete, which is the common type for irrigation in Libya. The tank is a cylindrical shape as shown in Figure 6. The cylinder volume should be the same as estimated in the following expression:

$$V = \pi \times r^2 \times h \quad (13)$$

Where: V: volume in m^3, r: radius in m, h: height in m, $V = \pi \times 5.046^2 \times 2.5 = 200\ m^3$

Results and discussion

PVSyst tool has been used to find the most fitting power requirement for the Wady Al-Rabey area to supply the farm with irrigation water. PVSyst is a dedicated engineering package for modeling and evaluating photovoltaic installations. The designer enters the site location and the load profile, selects the system components, and the program then computes the corresponding system behavior automatically. Its energy-yield estimates incorporate the losses arising from local weather and climatic conditions, which makes it particularly well suited to PV pumping systems that rely on hydraulic (tank) storage. The simulation of the present system produced the results described below [9].
The results will be presented using PVSyst software and discussed by comparing them with the ones already gotten from the hand calculation. As shown in Figure 7, The Geographical coordinates of the site have been set and selected for the software to recognize the site; however, if the data is not very well set or is wrong the user might be working on the wrong site, which can affect the output results as well.

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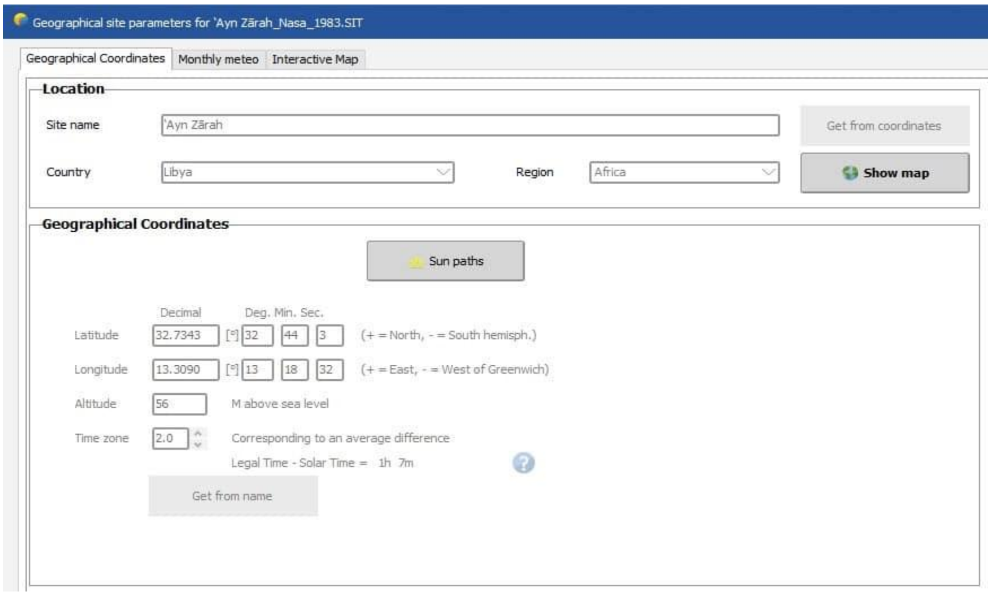

Figure7: Geographical coordinates of Wady Al-Rabey

Figure 8 shows Global horizontal irradiance, horizontal diffuse radiation, and temperature at the location based on the geographical coordinates of Wady Al-Rabey.

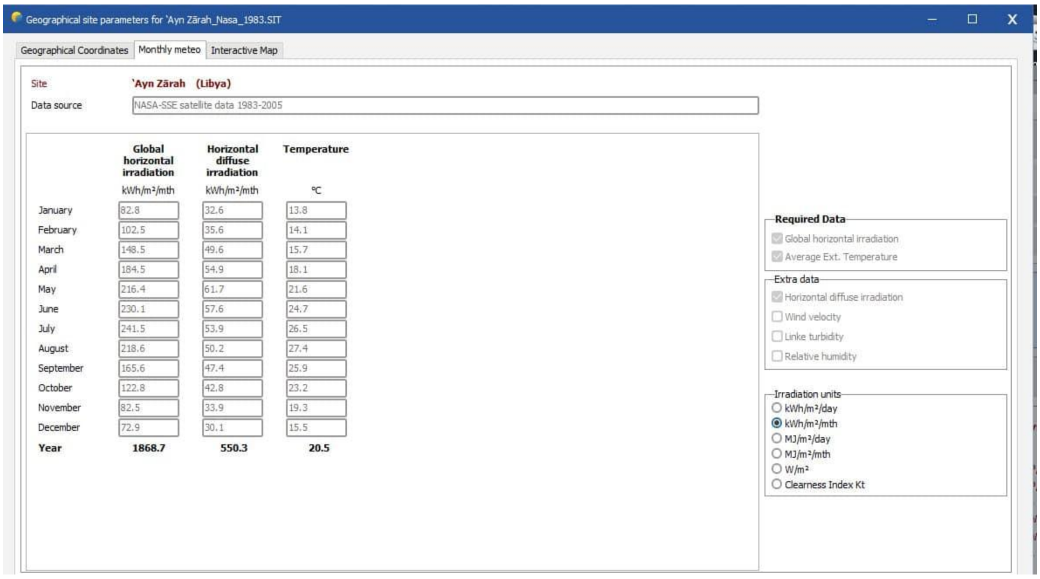

Figure 8: Meteorological data of Wady Al-Rabey

Figure 9 represents the suited orientation for PV modules or the loss rate due to the orientation. This is designed by taking into account the geographical coordinates such as latitude and longitude, and here the tilt angle is set to 30 degrees based on 13.3 degrees for longitude and 32.7 degrees for latitude, and it is found that the loss/opti = 0.0%; the above parameters and values have been set yearly.

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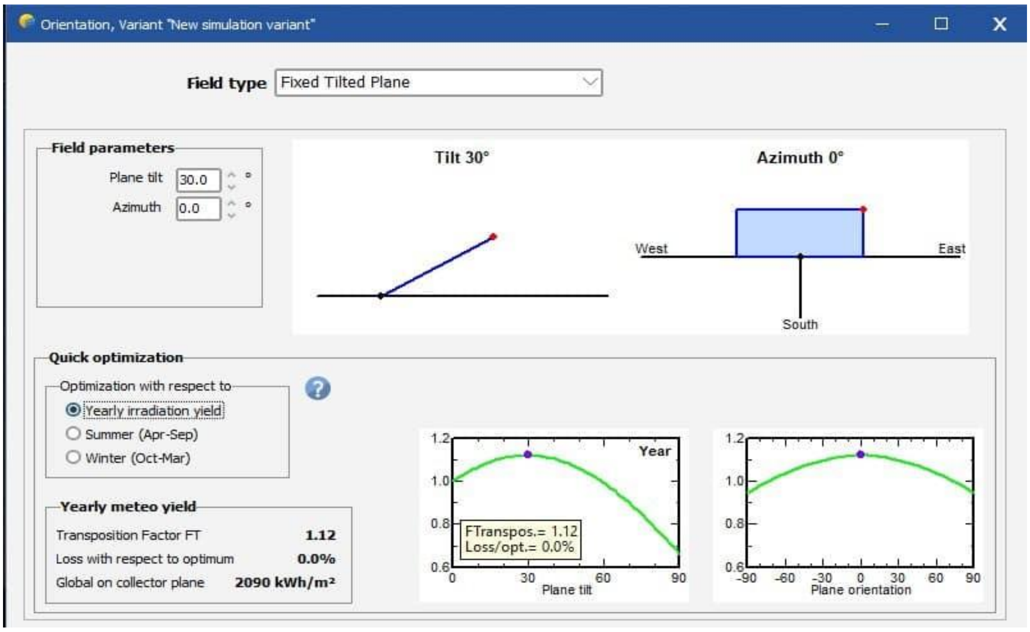

Figure 9. Module orientation and tilt angle

Figure 10 shows the input data for well characteristics, the hydraulic circuit, and the storage tank. Based on the water source, the hand calculations, and the geological data we collected from Wady Al-Rabey, as mentioned previously.

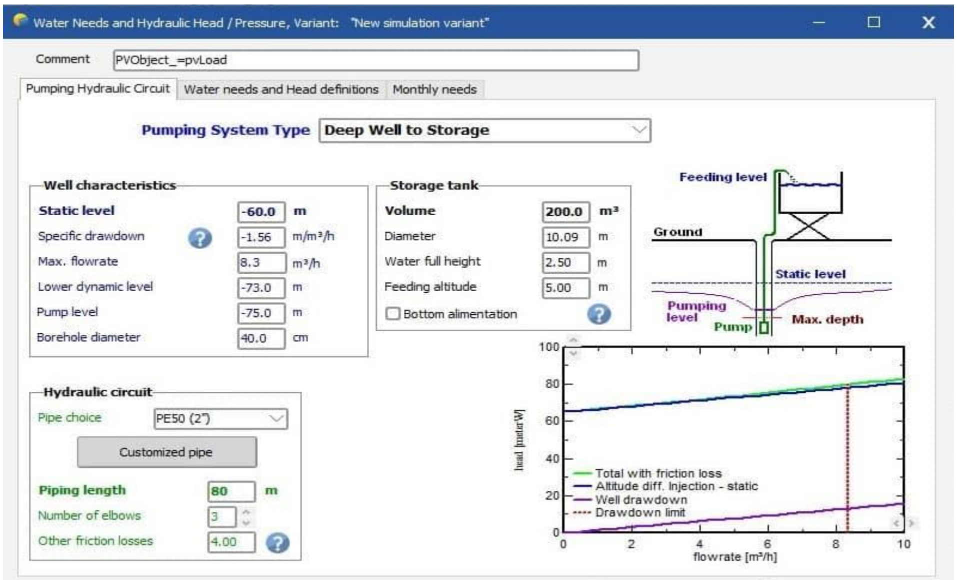

Figure10: The input data for the pumping hydraulic circuit

Based on the water needed and the geological data collected from Wady Al-Rabey, the static level is set at 60 m, and the water need is 41.5 m3/day; by calculating the average yearly water needs to be gotten 15153 m3. As shown in Figure 11 the hydraulic energy is estimated at 7.35 kWh/day, with electrical energy from the PV of 24.83kWh/day.

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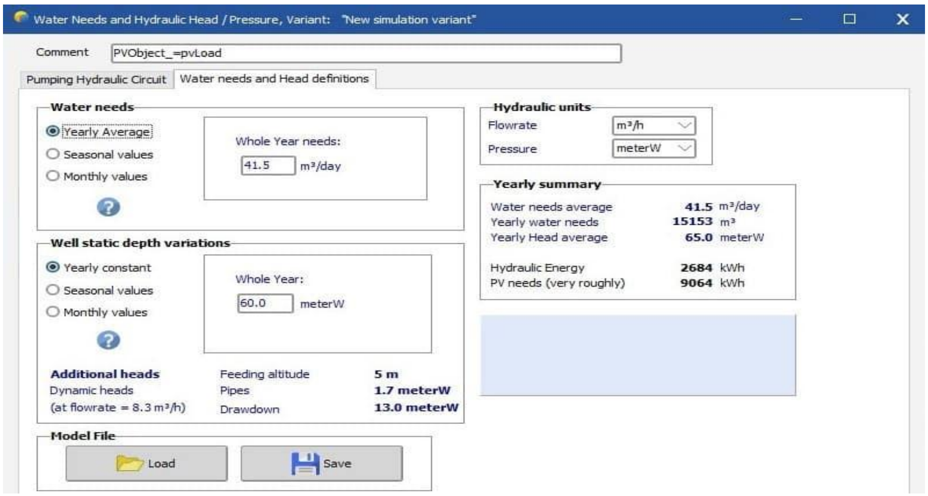

Figure11. Hydraulic input data based on water need

Figure 12 shows the system design by choosing different parameters from pump manufacturers. Therefore, a centrifugal multistage PS4000 C-SJ8-15 pump from the LORENTZ manufacturer was used based on the flow rate and head range. However, the flow rate of the chosen pump was slightly lower than the manually calculated flow rate.

Figure 12. Pump choice

Figure 13 shows the system design by choosing different parameters from PV to the manufacturers. Therefore, the JKM 365M-72-V from Jinkosolar was manufactured,1MPPT DC converter from LORENTZ was used based on the pump motor. Besides, Figure 13 depicts how the PV modules were selected based on their electrical characteristics; therefore, 2 strings were connected in parallel, and each string has 6 modules configured in series. This configuration was made to reach the operating conditions of voltage and current at different temperatures. However, the series modules helped to reach the voltage needed for our system, which is rated at 246V at 20 degrees, at 1000w/m2 irradiance, and 4 kW was obtained at the maximum operating power, and the array nominal power at STC was 4.4kWp.

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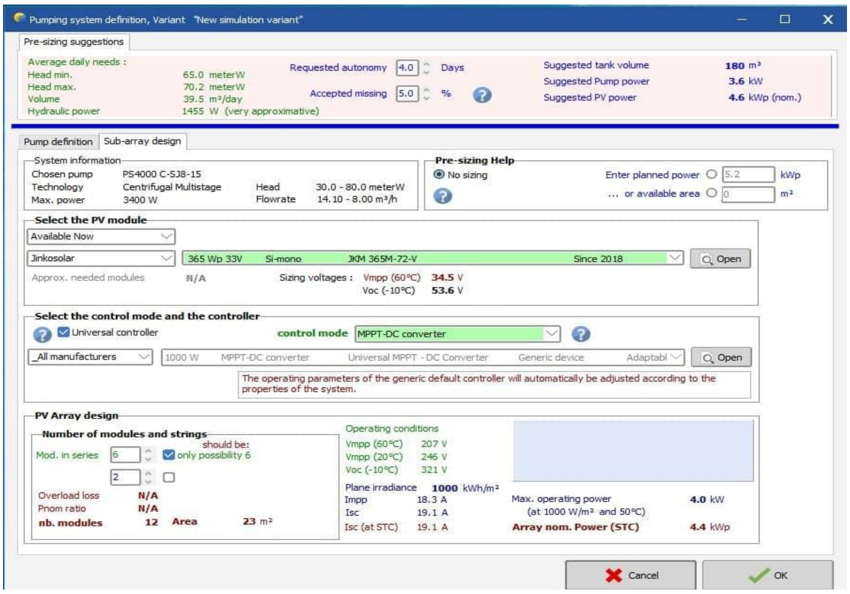

Figure13. PV system design parameters

Main result presentation from PVSyst

The result presented in Figure 14 shows the yearly summary of the whole system, which represents 96% of the water pumped with 6086kWh of energy at the pump, which is 95.8% of the total energy used, and the other 4.2 % can be used for another purpose. The system efficiency is 82.3% with a pump efficiency of 48.2%.

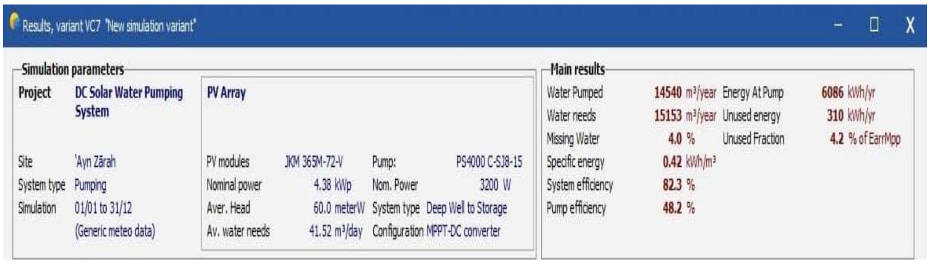

Figure 14. The main results and the simulation Parameters

Table 3 summarizes the overall system. The annual photovoltaic array virtual energy at MPP of the designed photovoltaic system is 7397.5kW-hour and the annual energy available to operate the WPS is 6086.1 kW-hours. The total annual water demand of the site is 15153 m3; the total water pumped volume is 14540 m3; the total volume of the missing water is 528.1 m3.

Table 3: Simulation results of SPVWPS.

Balances and main results

	GlobEff	EArrMPP	E_PmpOp	ETkFull	H_Pump	WPumped	W_Used	W_Miss
	kWh/m²	kWh	kWh	kWh	meterW	m³	m³	m³
January	118.0	464.6	432.0	0.00	71.97	1026	1065	113.1
February	133.0	519.4	478.4	0.00	72.65	1155	1090	1.7
March	169.2	649.9	537.3	32.42	72.83	1304	1240	0.0
April	185.4	703.4	515.9	98.71	73.19	1260	1260	0.0
May	195.1	730.5	576.4	59.68	72.83	1394	1395	0.0
June	196.5	723.3	560.9	47.91	72.53	1346	1350	0.0
July	210.0	762.3	583.9	31.25	72.32	1393	1395	0.0
August	209.4	755.8	579.2	21.57	72.13	1374	1395	0.0
September	180.1	660.2	537.4	10.17	72.45	1287	1260	0.0
October	152.0	569.2	495.0	8.16	71.69	1164	1240	0.0
November	113.9	440.0	403.0	0.00	71.11	933	1027	142.6
December	106.6	419.0	386.6	0.00	71.39	904	907	270.7
Year	1969.0	7397.5	6086.1	309.86	72.27	14540	14625	528.1

System Cost

No project design is complete without an economic assessment. This section therefore estimates the total capital cost of the proposed solar-powered water pumping system. Consideration is made of the PV solar modules, the pump, pump controller, pipes, and wiring. Table 4 shows the assumed value of the cost of each component.

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Table 4. Cost of the SPVWPS components

Components	Unit cost	Total Cost
PV module	$55	$660
Pump including controller	$2470	$2470
Pipes and wiring	$150	$150
Running Cost	5%	$165
Net project cost	-----	$3,455

Considering 12 PV modules of 4.4KW, 1 pump 3.4KW including the MPPT controller, pipes, and wiring listed above, and finally 5% for running cost of the system, Table 5 describes the Net project cost of the SPVWPS. Figure 15 illustrates the repartition of cost in terms of percentages, and we realized that the pump takes more than two-thirds of the cost of the entire system.

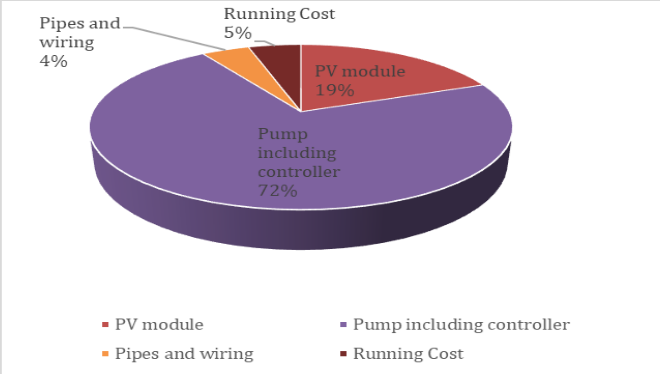

Figure 15. Cost in percentage

The solar PV modules are assumed to work for 20 years, and the Pump and controller for 10 years. This is the amount of money that could be obtained in 20 years of operating and maintenance costs, including pump and controller replacement. The Life Cycle Cost in 20 years is $6,211. In this case, the annual cost of SPVWPS is only $311 for 20 years, including operation and maintenance. The water cost and energy cost are estimated by PVSyst as shown in Table 5.

Table 5: Water cost (PVSyst screenshot)

Total installation cost	**6216 USD**
Operating cost	311 USD/year
Energy used for pumping	6086 kw/year
Excess energy (tank full)	310 kw/year
Water pumping	14540m^3
Cost of pumping water	0.02USD/m^3
Energy cost	0.05USD/m^3

Based on the results of the PVSyst software, in Libya, 1 cubic meter of water costs $0.02 as shown in Tables 5 and 6 while having the probability to pump 14540 cubic meters per year. Moreover, the cost of 1 kW-hour of energy used for pumping is $0.05 as shown in Table 7, with a probability of 6086 kWh per year. The solar PV water pumping system cost is reasonable when it is compared to conventional systems, especially the diesel generator pumping system. diesel generator needs to be replaced every 5-7 years, depending on the quality of maintenance. The cost of the generator is (1650 USD), and the maintenance cost is around 220 Libyan dinars (35 USD), which is conducted twice a year, and fuel cost is around 7 Libyan dinars (1 USD) per week (fuel price is $0.024/L). The water pump is replaced every 8 to 10 years. Table 7 shows the assumed value of the cost of each component in a conventional water pumping system which capable of meeting our daily water needs.

Table 7: Cost of components of a conventional WPS

Components	Unit cost
Generator	$1,650
Pump including control box	$650
Running and maintenance cost	$120/year
Pipes and wiring	$150
Total Cost	$2,570

Assuming the generator has an operational lifespan of 10 years. Running and maintaining the generator for 10 years costs $1,200, excluding the pump, pipes, wiring, and generator. The pump, pipes, wiring, and generator are estimated at $2,450,

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bringing the total cost to $3,650. The Life Cycle Cost in 10 years is $3,650. The Life Cost Cycle in 20 years is $7,150. including operation costs and pump and generator replacement after 10 years. SPVWPS is considered one of the best ways for drawing water out of a well. Moreover, it is cheaper than conventional systems despite the low diesel prices in Libya. A solar pumping system will be the cheapest cost of water pumping in the long run.

Conclusion

The Solar Photovoltaic Water Pumping System (SPVWPS) demonstrated its capability to completely fulfill the water requirements during the summer season, extending from March to October. During this period, the system achieved full utilization of the daily pumped water, indicating 100% usage efficiency. This high performance can be attributed to the abundant solar radiation available throughout these months, which enhances the energy generation capacity of the PV modules, as well as to the increased water demand caused by the hot and dry climatic conditions. The summer months in Libya are characterized by long sunshine durations and elevated ambient temperatures, both of which contribute to optimal system performance and justify the full consumption of the pumped water due to the prevailing water scarcity in this season. Although the current study was confined to a single location, Ayn Zara—considered a region of moderate solar potential—it is important to note that several other areas within Libya, particularly in the southern region, experience significantly higher levels of solar irradiance. This spatial variation in solar energy availability suggests that the overall potential for solar water pumping systems across the country is much greater than what is represented by the case study location. The southern Libyan desert regions, for instance, receive some of the highest global horizontal irradiance (GHI) values in North Africa, making them ideal for large-scale solar energy applications. Furthermore, within solar PV water pumping systems, the integration of water storage tanks serves as a practical and cost-effective energy storage solution. Instead of relying on conventional battery storage—which often increases system cost and maintenance requirements—water tanks enable the storage of pumped water during peak sunlight hours for later use during low or no solar radiation periods. This approach enhances the overall reliability and operational efficiency of the system, ensuring a continuous water supply even under intermittent weather conditions.

Conflict of interest. Nil

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