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Optimization of Standalone Photovoltaic Drip Irrigation System: A Simulation Study

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Abstract: This paper presents the optimal design of a photovoltaic (PV) drip irrigation system. Designing a PV system is based on calculated motor power, solar irradiance level and other meteorological parameters at a certain geographical location. Therefore, a simulation study of the designed PV system were performed by a PVGIS simulation tool. The PVGIS simulation tool analyzes the potential of power generation with optimal PV modules tilt angle and orientation on a monthly and annual basis, and an analysis of the overall shading situation (horizon) as well as the internal shading between the PV module rows. The selection of water pump and motor depends upon the depth of water table and desired discharge and head to operate the irrigation system. Furthermore, a locally developed Solar-Drip Simulation Tool (SoSiT) was used for load and supply optimization. Based on ambient temperature, solar irradiation and water requirements, SoSiT calculates net generation by a PV system and resultant water output of the irrigation system. The particular drip irrigation site has two zones; the maximum water requirement for zone 1 (row crop) is 50,918.40 Liters/day and for zone 2 (orchards) is 56,908.80 L/day. From PVGIS simulation results, the maximum daily energy production of the designed PV system was 6.48 kWh and monthly energy production was 201 kWh in the month of May. SoSiT results showed that the PV system fulfilled the required crop requirement by only using 28% of the potential water supply, and 72% of the potential water supply from a solar-powered pump was not used. This value is high, and it is recommended to grow more or different crops to utilize the fuel-free electricity from the PV system. The unit cost of PV-powered drip irrigation is USD 0.1013/kWh, which is 4.74% and 66.26% lower than the cost of subsidized electricity and diesel, respectively.

Keywords: photovoltaic system; variable frequency drive; drip irrigation systems; water pumping system; PVGIS; SoSiT; performance analysis; energy saving

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1. Introduction

The growing global energy demand is motivating government authorities and policymakers to develop renewable energy technologies such as solar, biomass, wind and geothermal [1]. Currently, traditional energy sources, especially fossil fuels, are the major cause of climate change and have severe environmental implications [2]. The high dependence on fossil fuels will not only lead to environmental pollution such as greenhouse gas emissions, but also global warming [3]. Many studies have shown that these fossil fuels will be exhausted in the near future [4]. Therefore, many countries (both developed and developing) are planning to transition to renewable energy technologies in order to meet the electricity demand of the growing population and improve utility grid operation [5–9]. Among all renewable energy technologies, the solar PV technology is the most widely used for a number of reasons [10]. The output power of a PV system is generally influenced by operating conditions, including environmental conditions and the occurrence of faults [11]. With an efficient control system, the PV system generates the maximum achievable amount of energy [12].

Today, all areas of society such as agriculture, drinking water, sanitation and industry require clean, safe and consistent water supplies. As a result, the world's water systems face a supply imbalance and hazardous problems [13]. According to a study conducted by UNESCO [14], about 0.7 billion people in 43 countries are affected by water scarcity. In addition, the report predicts that by 2025, two-thirds of the global population may live in a water-polluted environment and 1.80 billion people will live in areas with complete water scarcity. As part of sustainable growth, Pakistan's economy relies on smart agriculture, which accounts for 25% of the GDP [15]. As a result, the agriculture sector consumes the most freshwater resources [16].

Policymakers and researchers are paying close attention to PV energy systems (renewable energy source) as an alternative to conventional grid energy for irrigation water pumping in rural areas [17]. The PV energy generation systems have shown exceptional economic and environmental performance as compared to irrigation systems driven by diesel engines [18] in rural and urban areas, with payback periods of 3–5 years [19]. In the past few years, the use of PV energy in various sectors has increased, and irrigation is one of its most suitable sectors [20–22]. Many agricultural farmers or growers are interested in this technology because it helps to increase their revenues by lowering their electricity or fuel costs [23–25]. Furthermore, in off season when irrigation water is not required, energy generated by a PV system is used at high capacity to run the other activities in the farm [26–28].

Currently, the use of PV energy generation to operate water pumps is an emerging technology that faces many obstacles or challenges. PV technology has the potential to be used on a wider scale, and it also offers an environmentally friendly alternative to electricity of fossil fuels (diesel, etc.) driven by traditional water pumps [29,30]. In addition, due to the continuous depletion of fossil fuel reserves and increasing energy costs, the importance of PV energy to operate water-pump power has increased, and that is the main area of concern for developing nations [31,32]. A photovoltaic water-pumping system (PVWPS) provides irrigation and domestic water in remote rural areas, and its reliability and performance and acceptance have made tremendous progress. The installation of PVWPS has many benefits for water-pumping sites that do not have a national grid connection and are rich in solar energy resources. In addition, PVWPS can also survive in extreme weather conditions such as snowfall [33,34]. The use of a PV energy generation system to run the pumping system in the irrigation sector is the most suitable and best option, as there is a natural relationship between solar energy availability and water demand [35]. Currently, Pakistan has more than 0.6 million tube wells in the agriculture sector. A significant amount of the energy is required to run these pumps. Water is extracted from the ground using a variety of pumps, including pumps powered by grid electricity or diesel fuel [36,37].

To meet the expected requirement of irrigation water, it is critical to choose the right PV pumping system equipment. The design of PV systems for a drip irrigation system should be based on crop water demand, average efficiency of system and subsystem, water pump characteristics, and solar irradiation [38,39]. Bengnum et al. [40] used the developed empirical model to analyze the impact of the pumping head on the performance of PV-operated irrigation systems. For the proper size of a PV system for positive displacement pump (PDP) and centrifugal pump (CP), two mathematical models were proposed by Hamidat and Benyoucef [41] that relate PV energy to the discharge of a water pump against a total dynamic head (TDH).

Globally, PV-operated drip irrigation systems are frequently used sunlight is available abundantly. In addition, the cost of PV system hardware has dropped by 80.0 percent in the past 2 decades. The levelized cost of energy has decreased by 75 percent in the past 10 years [42]. These developments provide a base for rapid installation of PV systems, especially stand-alone PV systems. Considering cost and maintenance, a PV water-pumping system is very simple as compared to other traditional electric- or diesel-pumping systems. A PVWPS consists of a PV module, an inverter/VFD, and an electric motor-pump set. The PV strings are designed by connecting several PV modules together in series. VFD is an important component of a PV system because it converts the direct current (DC) output from the PV modules into the alternating current (AC) so that it can operate an electric pump set for groundwater extraction [43]. The management of the power flow is necessary due to the variety of models and energy sources in order to assure the protection of all equipment [44]. Furthermore, the current PV water-pumping system uses electronic technologies, which helps to improve the performance, efficiency, and output power of the system. The controller can also track the water level in the water storage tank, control and manage the motor speed, and provide efficient output using maximum power-point tracking technology [45]. In addition, the performance of a PV system used to operate drip-irrigation systems depends on the size of the PV array, operating head, and the irradiation coefficient [46].

The efficiency and installation cost of the PV-operated drip irrigation system depends not only on the efficiency of the water pump, electric motor and its driver (VFD), but also on the effective use of irrigation water [47]. PV-operated drip-irrigation systems have a number of benefits, including effective use of both water and energy resources in the agricultural sector. As a result, PV-operated drip-irrigation system have become more and more common. The most important factor in the adoption and growth of these systems is their high efficiency and low cost [48,49].

Due to its location on the solar belt, Pakistan has tremendous sun irradiance, which ranges from 5.0 to 8.0 kilowatt-hour/m^2/day and can produce 2.9 million MW of energy. However, despite having exceptional irradiance, Pakistan's total installed capacity is still 1600 MW and at the 27th position with respect to total new added PV capacity all over the world.

In the province of Punjab, 85% of farms are up to 12 acres only. There are 771,638 diesel and 223,818 electric tube wells in Punjab province, and the total number of agriculture tube wells all over Pakistan is 1,149,447, with a depth of water table ranging from 10 ft to more than 400 ft in different areas. Nearly 27 million acres of cultivated area depend on tube wells and canals for irrigation. As a huge number of agriculture farms are not connected to the national grid, the tube-well operation mainly depends on diesel fuel. This dependency on diesel for tube-well operation significantly increases the cost of agriculture products. Moreover, irrigation with the flood irrigation method is less efficient, i.e., 40–50%. A heavy volume of water goes to waste because of less efficient flood irrigation, which ultimately threatens the limited resource of ground water. Water tables are declining rapidly, and aquifers are being depleted due to the hold irrigation practice. The irrigation sector in the country uses almost 90% of fresh water. The drip-irrigation systems, referred to as high-efficiency irrigation systems, are far more efficient than flood irrigation systems, i.e., by more than 80%. This unique idea to install a drip-tied solar system is to improve farm water management and use precious water resources wisely.

The key objective of this research is optimal designing of a PV drip irrigation (PVDI) system, to analyze the comprehensive energy generation pattern and calculate the potential available water. Therefore, a PVGIS simulation tool was used to analyze the potential of power generation with optimal PV modules tilt angle and orientation on a monthly and annual basis. Furthermore, SoSiT was used for load and supply optimization.

2. Materials and Methods

2.1. Sizing of the PVDI System

Oversizing would result in additional unnecessary expenses, while under sizing would result in poor system performance. This is extremely important in the application for powering a drip-irrigation system: the soil does not store water as in flood irrigation, so a daily availability of power is required in critical times of the crop. This is why each component of the system needs to be optimally designed and sized in order to meet the specific requirement of the site. It is the only approach to ensure system stability, durability and sustainability while also achieving the expected performance. Table 1 shows the steps that must be followed in the sizing process of a water pumping system operated by a PV system.

Table 1. System sizing variables.

Assessment	Variables	Output
Water resource	i. Delivery capacity ii. Water level	Capacity of water Available pump type
Total head	i. Dynamic head ii. Static head	Water pump size
Water demand	i. Storage capacity ii. Consumption profile	Storage size
Solar resources	i. Sun peak hours per day ii. Solar irradiance (Wh/m^2)	PV size
Flowrate		Pump size
System Sizing	**Input Data**	
Water Pump	• Total head • Flow rate	
PV Array	• Meteorological data • Pump size	

2.1.1. Water Resource

The depth of the water well determines whether a surface pump is used. For wells deeper than 7.0 m below ground level, it is recommended to use a submersible pump [50,51]. The submersible pump's position is determined by the water level. Between the bottom of the borehole and the pump, there must be enough space. The capacity of a water source to provide water in the sustainable manner is measured by delivery capacity (tested delivery capacity). Pumping out more water than the tested delivery capacity can cause the borehole to dry up because the discharge rate exceeds the water replacement rate.

2.1.2. Total Head

The total head is calculated by adding the distance between the storage delivery sites and the pump's submerged depth, as well as head losses across the piping system. It is the sum of major losses head, and minor losses head and elevation head. The height between ground level and the storage capacity is known as the static head (D). It should be kept to a minimum to reduce pump head requirements, but also consider storage location suitability. One meter of dynamic head is equal to one meter of height [52,53].

To calculate the dynamic head, an approximate value is calculated by measuring the horizontal distance covered by pipes from ground level to the storage volume. Only 5% of the total distance is accounted for on a perfectly horizontal path, indicating that if the pipe runs horizontally for 200 m with no inclination, the dynamic head is increased by 10 m. The height difference should be accounted for in the storage height value if there is an incline.

If the water quality is unstable, a safety factor of 20.0% to 30.0% is recommended. To do this, the pump head must be at least 20.0% higher than the calculated total head.

2.1.3. Water Demand

The size of the pumping system is mainly determined by the amount of water demanded. It is determined as a daily consumption rate, as well as an hourly rate in some cases. The storage capacity refers to the amount of water that must be stored in order to maintain a steady supply of water to end consumers. Depending on the region and usage patterns, storage tanks typically have a capacity of 3 to 10 days of storage [54,55]. For example, if the daily requirement is 3000 L, the storage volume should be at least 9000 L, and in extreme cases as much as 30,000 L.

2.1.4. Required Flowrate

Flowrate is based on water demand and peak sunshine hours per day and measured in m^3 per hour (flow is demand (cubic meters) divided by peak sunshine hours (hours).

2.2. Designing of PV Systems and Pump Set for Particular Site

2.2.1. Monthly Crop Water Requirement

The particular drip-irrigation site has two zones, zone 1 (2.67 acres) dedicated for row crops and zone 2 (2.67 acres) dedicated for orchards. Maximum water requirement for zone 1 is 50,918.40 L per day in month of June and minimum water requirement is 9792.0 L per day in month of December as shown in Table 2. Maximum water requirement for zone 2 is 56,908.80 L per day in month of June and minimum water requirement is 10,944.0 L per day in month of December as shown in Table 3.

Table 2. Monthly crop water requirement for row crops.

	January	February	March	April	May	June	July	August	September	October	November	December
Eto (mm/day)	1.60	2.50	3.90	5.50	7.20	7.80	6.50	5.80	5.00	3.60	2.20	1.50
Kc	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
CWR (mm/day)	1.36	2.13	3.32	4.68	6.12	6.63	5.53	4.93	4.25	3.06	1.87	1.28
Irrigation Efficiency %	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00
Canopy factor	64.00	64.00	64.00	64.00	64.00	64.00	64.00	64.00	64.00	64.00	64.00	64.00
Application Rate mm/hour	2.30	2.30	2.30	2.30	2.30	2.30	2.30	2.30	2.30	2.30	2.30	2.30
No. of Zones	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Operation time (hrs/day)	0.42	0.66	1.02	1.45	1.89	2.05	1.71	1.52	1.31	0.95	0.58	0.39
Total operational time (hours)	0.42	0.66	1.02	1.45	1.89	2.05	1.71	1.52	1.31	0.95	0.58	0.39
Flow rate (lps)	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9
Daily water requirement (Litres)	10,444.8	16,320.0	25,459.2	35,904.0	47,001.6	50,918.4	42,432.0	37,862.4	32,640.0	23,500.8	14,361.6	9792.0

2.2.2. Pump Set Designing

Normally submersible and surface pumps are installed for operating drip- irrigation systems. The selection of a water pump depends upon the depth of the water table and the desired discharge and head to operate the irrigation system. These pumps are run by induction motors operated with a three-phase AC power supply. The main reason for selecting these pumps was that they are very efficient and have the potential to provide the desired discharge and head for a specific agricultural field based on crop-water requirements and drip-system design.

Table 3. Monthly crop water requirement for orchards.

	January	February	March	April	May	June	July	August	September	October	November	December
Eto (mm/day)	1.60	2.50	3.90	5.50	7.20	7.80	6.50	5.80	5.00	3.60	2.20	1.50
Kc	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
CWR (mm/day)	1.52	2.38	3.71	5.23	6.84	7.41	6.18	5.51	4.75	3.42	2.09	1.43
Irrigation Efficiency %	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00
Canopy factor	64.00	64.00	64.00	64.00	64.00	64.00	64.00	64.00	64.00	64.00	64.00	64.00
Application Rate mm/hour	2.30	2.30	2.30	2.30	2.30	2.30	2.30	2.30	2.30	2.30	2.30	2.30
No. of Zones	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Operation time (hrs/day)	0.47	0.73	1.15	1.62	2.11	2.29	1.91	1.70	1.47	1.06	0.65	0.44
Total operational time hours	0.47	0.73	1.15	1.62	2.11	2.29	1.91	1.70	1.47	1.06	0.65	0.44
Flow rate (lps)	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9	6.9
Daily volume requirement (Liters)	11,673.6	18,240.0	28,454.4	40,128.0	52,531.2	56,908.8	47,424.0	42,316.8	36,480.0	26,265.6	16,051.2	10,944.0

Motor power (HP) to run the irrigation systems is computed by using Equation (1) [56].

$$\text{Motor Power (HP)} = \frac{\text{Operating Discharge of Pump (LPS)} \times \text{Operating Head (m)}}{\text{Pump Set Efficiency (\%)} \times 745.7 \times 9.8} \times 100 \quad (1)$$

For particular selected site, operating discharge of pump is 6.9 LPS, operating head 55 m, pump set efficiency is 55%. By using above Equation (1) motor power is calculated as shown in Table 4.

Table 4. Design of a PV system for 10 HP motor.

Pump Set Data							
Manufacturer		Hyrdromech		Model No		6SP30-8	
Pump Type (Submersible/Centrifugal)		Submersible		Pump Set Efficiency (%)		55%	
Operating Discharge of pump (LPS)		6.9		Motor power calculated (HP)		9.02	
Maximum Discharge of pump (LPS)		12		Motor power selected (HP)		10.00	
Operating Head of pump (m)		55		Motor power selected (kW)		7.46	
PV Module Data (Electrical Data at STC)				**VFD/Controller Data (Electrical Data at STC)**			
PV Module Manufacturer	Canadian Solar	Model No	CS6U-325P	VFD Manufacturer	JnTech	Model No	JNP11-KH
Peak Power Watts-Pmax (Wp)	325	Maximum Power Current-Imp	8.78	Maximum input DC Voltage to controller (V)	900.0	MPPT Voltage range (V)	450~850
Power Tolerance-Pmax (W)	0~+5	Open Circuit Voltage -Voc	45.5	Max. Power can be connected (kW)	17.2	Per String Current (A)	8.78
Maximum Power Voltage-Vmp	37	Short Circuit Current -Isc	9.34	Selected VFD Size (kW)	11.0	Total Current (A)	17.6
PV Array Sizing							
Motor Capacity (hp)	Motor Capacity (kW)		PV Array Design Factor	PV Array Size (kW) based on motor rated voltage			
				For 340 V		For 380 V	
10.00	7.46		1.35	-		10.07 KW	
No. of PV Modules				**VFD Sizing**			
For 340 V	For 380 V			For 340 V	For 380 V		
-	32.00			-	11.00 kW		
No. of Strings			**Voc (DC Volt)/String on STC (Input DC Voltage) to VFD**		**Vmp (DC Voltage)/String on STC**		
For 340 V	For 380 V		For 340 V	For 380 V	For 340 V	For 380 V	
-	2		-	728 V	-	592 V	

2.2.3. DI Head Unit

The head unit of a drip irrigation (DI) system has different components such as motor pump set, filtration system (hydro cyclone, filter etc.), control valves and flow meters as shown in Figure 1.

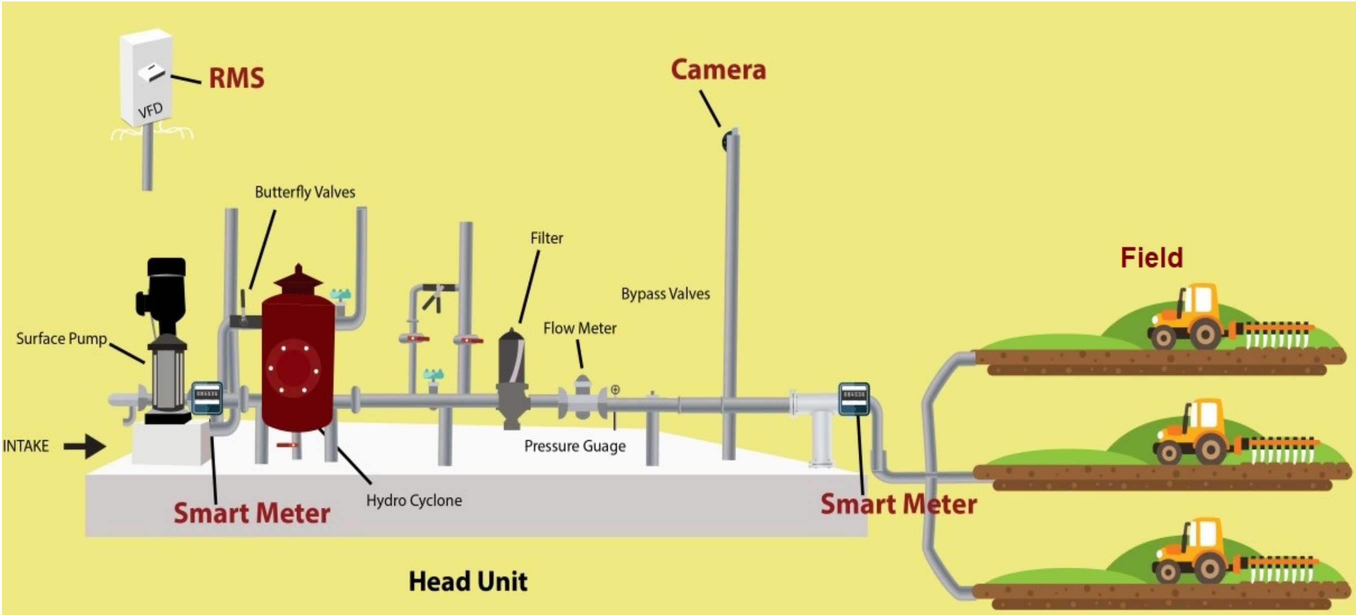


Figure 1. Head unit of drip irrigation system.

2.2.4. PV System Designing

The design of the PV system is based on calculated motor power. For present study the drip systems are designed for three categories of motor power, i.e., 5.50 HP, 7.50 HP and 10.0 HP. Design of the PV system for a particular selected site having 10 HP motor power is shown in Table 4. Design shows that the submersible pump having pump set efficiency of 55% with operating discharge of 6.9 LPS is installed. The operating head of the site is 55 m. Canadian Solar (CS6U-325P) 325.0 W polycrystalline PV modules and 11 kW JnTecH (JNP11KH) VFD are used in the design.

When planning and designing the size of a solar photovoltaic system, the PV array design factor is used. Depending on the climate of the site, it can vary (depending upon global geographic location). Actually, the PV system designed for drip-irrigation system is an off-grid system. Approximately 35% of losses occur in PV system due to climatic conditions, and the rest are because of effects such as shadows between the PV modules, wiring losses, and AC losses. To operate the system at maximum efficiency Punjab Energy Department, Pakistan, decided to use 1.35 PV Array Design Factor for the off-grid system. Equation (2) is used to calculate total PV system capacity.

$$\text{Total Watt} - \text{Hours (Wh)/Day} = \text{Total Wh/day required to operate motor} \times 1.35 \quad (2)$$

The flow rate of Hyrdromech pump (6SP30-8) integrated with PV system is shown in the Table 5. From Table 5 it is shown that flow rate of the pump increases with the increase in PV power (kW).

Table 5. Pump flow points.

Solar System Power (kW)	Pump Output Flowrate (LPS)	Solar System Power (kW)	Pump Output Flowrate (LPS)
0.00	0.00000	5.50	7.33000
0.50	0.00000	6.00	8.25000
1.00	0.00000	6.50	9.16600
1.50	0.00000	7.00	10.00000
2.00	1.66000	7.50	11.66000
2.50	2.50000	8.00	11.66000
3.00	3.16600	8.50	11.66000
3.50	4.00000	9.00	11.66000
4.00	4.75000	9.50	11.66000
4.50	5.50000	10.00	11.66000
5.00	6.33000	10.40	11.66000

Figure 2 shows a single line diagram (SLD) of a PV system for operating high-efficiency irrigation systems. We can see from SLD that there are two strings connected to the JnTech VFD (JNP11KH), and each string contains 16 PV modules (CS6U-325 P). Wiring arrangement is critical for a successful system installation because it decreases system loss and improves system operational safety. The PV modules are connected in series with 6 mm single cores. One DC circuit breaker (1000VDC, 16 ADC) and two AC circuit breakers (380~500 VAC, 32 A AC 3 Pole) are connected.

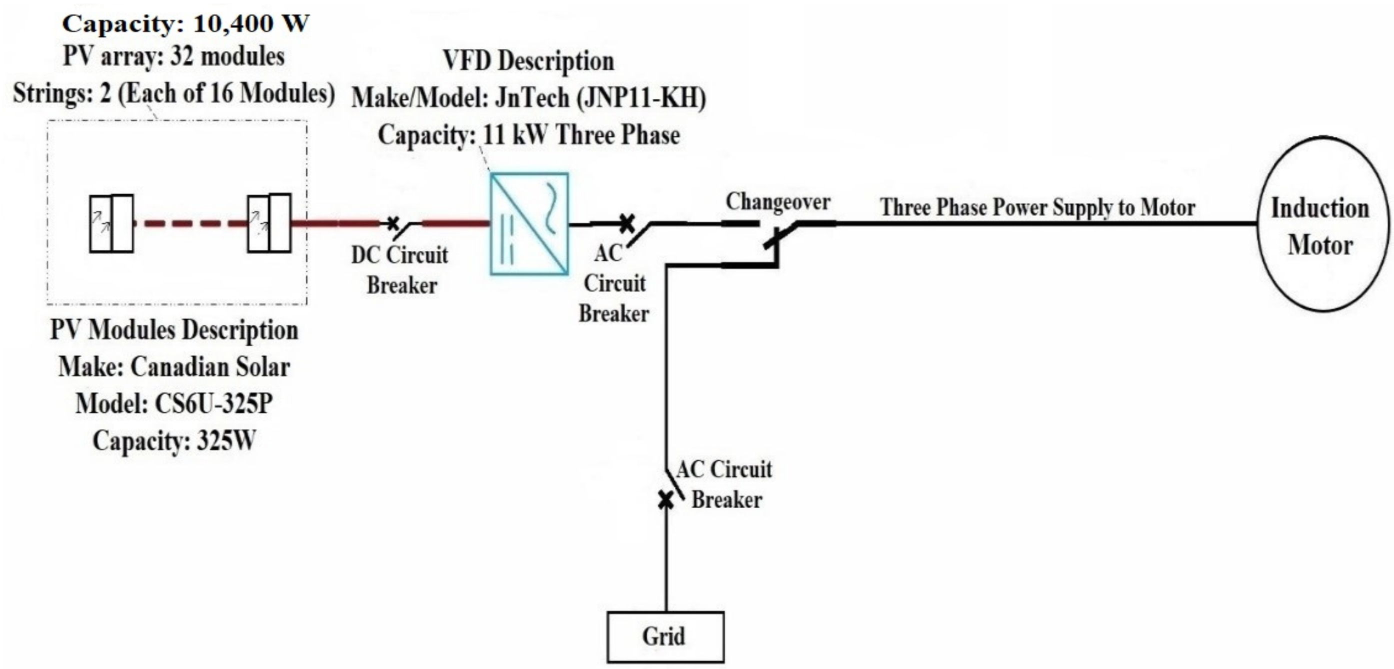


Figure 2. SLD of a Photovoltaic (PV) system for operating high-efficiency irrigation systems.

The complete PV drip irrigation system components installed at a particular selected site are shown in Figure 3.

Figure 3. PV drip irrigation system.

2.3. System Simulation

We simulate the performance of the system based on the selected technical concept in order to analyze the electricity generation pattern and the total electricity generated, and to calculate the potential available water. This number will be compared with the irrigation water requirement. The result of the simulation will provide an estimation of the potential power production of the solar power plant depending on irradiation, temperatures, the chosen design, pumped water and over/under watering. The important location-specific energy yield assessment is provided in a bankable format and includes:

- Analysis of overall shading situation (horizon) and detailed shading analysis of the nearby located objects as well as the internal shading between the PV module rows.
- Generation of climate-relevant datasets (irradiation and temperature) and comparison to other sources and long-term statistical data, including the assessment of differences.
- Simulation of yearly power production of the solar power plant using up-to-date bankable simulation Photovoltaic geographic information system (PVGIS) software considering irradiation, climatic conditions, shading situation, and soil conditions (albedo, array soiling). Standard design values for the losses related to Solar PV technology and VFD type and external cabling will be used.
- Uncertainty analysis of the simulation.

2.3.1. Simulation of PV System

The energy generated by designed PV installations for highly efficient irrigation systems is calculated using PVGIS software. This tool is used to design a grid-connected or standalone PV system. This software analyzes the potential of power generation from a PV system with optimal PV modules tilt angle and orientation on a monthly and annual basis.

2.3.2. Solar-Drip Simulation Tool (SoSiT)

Locally developed SoSiT was used for Load and Supply optimization. SoSiT combines the features of a PVsyst [57] that helps to design the solar water-pumping system and shows how different parameters affect system performance results, and CropWat [58] estimates the water needs of crops, which are very important in irrigation. Before implementation of SoSit, model is validated by a comparison between the practical performance data of working PVDI system and SoSiT analysis of that drip irrigation system. The purpose of comparing actual field data with simulated data using SoSiT is to evaluate the performance of a PVDI system in comparison to an ideal SoSiT simulated PVDI system.

SoSit is based on an hourly analysis for one year (8760 h). For every hour, input parameters are determined such as ambient temperature, solar irradiation, and water requirements. Based on these parameters, output values are calculated such as net generation by PV system and resultant water output of the irrigation system. Main input parameters for the SoSiT model are: Size of the solar system in kWp, expected hourly electricity yield of the solar power plant in Wh per hour for the years 2012–2016 for the specific site coordinates, monthly water requirement for the system netted of expected rainfalls broken in to hourly values and input/output efficiency of the Motor/Pump combination at different input power levels

As a result, the SoSiT model derives the decision parameters for every hour for 5 years such as expected water output of the system, shortfall/overcapacity of the system, monthly supply gap, rolling average weekly gap in %, annual water supply gap in CBM and Water output efficiency (Wh/CBM).

3. Results

3.1. Simulation Results of Energy Generation from PV Systems

The nominal power of the designed PV system is 10.40 kilowatt. The simulation results of PVGIS show that the loss caused by the local ambient temperature, temperature and low irradiance is 14.7%, the loss caused by the angular reflection effect is 2.9%, and other losses (cables, inverters, etc.) are 14.0%. PVGIS simulates and analyzes the potential of daily and monthly power generation from a PV system for three different cases, i.e., (i) fixed PV system installed at 22 degree inclination angle and 0 degree orientation, (ii) vertical axis tracking PV system installed at 0 degree inclination angle, and (iii) inclined axis tracking PV system installed at 22 degree inclination angle.

In the present work, the photovoltaic energy generation systems are installed to operate drip-irrigation systems on a cost-sharing basis. The farmer's share is 20% of the cost of PV systems, and the government covered the remaining 80% of the cost of the PV systems. In this study, an East–West Vertical axis tracker as shown in Figure 3 is used to increase the number of irrigation hours per day and provides a daily constant photovoltaic energy during irrigation period.

The output of the 10.40 kW Fixed PV system installed at an inclination angle of 22 degrees and 0 degree orientation is shown in Table 6. Maximum daily energy production of the PV system is 4.86 kWh and monthly energy production is 149 kWh during the month of May. This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, and the experimental conclusions that can be drawn.

Table 6. Fixed PV system installed at 22 degree inclination angle and 0 degree orientation.

Month	Average Daily Energy Generation (kWh)	Average Monthly Energy Generation (kWh)	Average Daily Sum of Global Irradiance (kWh/m^2)	Average Monthly Sum of Global Irradiance (kWh/m^2)
January	3.15	97.8	4.13	128
February	3.71	104	4.98	139
March	4.71	146	6.55	203
April	4.79	144	6.87	206
May	4.82	149	7.13	221
June	4.44	133	6.60	198
July	4.07	126	5.94	184
August	4.18	130	6.02	187
September	4.37	131	6.26	188
October	4.25	132	6.00	186
November	3.65	110	4.97	149
December	3.52	109	4.63	143
Year	4.14	126	5.84	178
Total for year		1510		2130

The output of the 10.40 kW vertical axis tracking PV system installed at 0 degree inclination angle is shown in Table 7. Maximum daily energy production of the PV system is 5.0 kWh and monthly energy production is 155 kWh during the month of May.

Table 7. Vertical axis tracking PV system installed at 0 degree inclination angle.

Month	Average Daily Energy Generation (kWh)	Average Monthly Energy Generation (kWh)	Average Daily Sum of Global Irradiance (kWh/m^2)	Average Monthly Sum of Global Irradiance (kWh/m^2)
January	2.32	72.0	3.06	94.9
February	2.98	83.5	3.97	111
March	4.16	129	5.72	177
April	4.65	139	6.60	198
May	5.00	155	7.34	228
June	4.73	142	6.98	210
July	4.27	132	6.19	192
August	4.19	130	5.99	186
September	4.03	121	5.71	171
October	3.52	109	4.92	153
November	2.73	81.9	3.73	112
December	2.43	75.3	3.24	100
Year	3.75	114	5.29	161
Total for year		1370		1930

The output of the 10.40 kW inclined axis tracking PV system installed at 22 degree inclination angle is shown in Table 8. Maximum daily energy production of the PV system is 6.48 kWh and monthly energy production is 201 kWh in the month of May.

Table 8. Inclined axis tracking PV system installed at 22 degree inclination angle.

Month	Average Daily Energy Generation (kWh)	Average Monthly Energy Generation (kWh)	Average Daily Sum of Global Irradiance (kWh/m^2)	Average Monthly Sum of Global Irradiance (kWh/m^2)
January	3.94	122	5.15	160
February	4.78	134	6.41	179
March	6.25	194	8.69	269
April	6.40	192	9.15	274
May	6.48	201	9.51	295
June	5.86	176	8.64	259
July	5.10	158	7.38	229
August	5.31	164	7.62	236
September	5.68	170	8.13	244
October	5.51	171	7.76	240
November	4.63	139	6.27	188
December	4.46	138	5.83	181
Year	5.37	163	7.42	226
Total for year		1960		2710

From the simulation results of the PV system, it is shown that at an inclination angle of 22 degrees and 0 degree orientation, maximum daily energy production of the PV system is 4.86 kWh and monthly energy production is 149 kWh during the month of May. With a vertical axis tracking PV system installed at 0 degree inclination angle, maximum daily energy production of the PV system is 5.0 kWh and monthly energy production is 155 kWh during the month of May. With an inclined axis tracking PV system installed at 22 degree inclination angle, maximum daily energy production of the PV system is 6.48 kWh and monthly energy production is 201 kWh in the month of May. Therefore, we concluded that the inclined axis tracking PV system installed at a 22 degree inclination angle produces more energy as compared to the other two systems. The comparison of energy generation from three systems is shown in Figure 4. Simulation Results of Energy Generation from PV Systems is similar to results found in the research study conducted by Tamoor et al. [8].

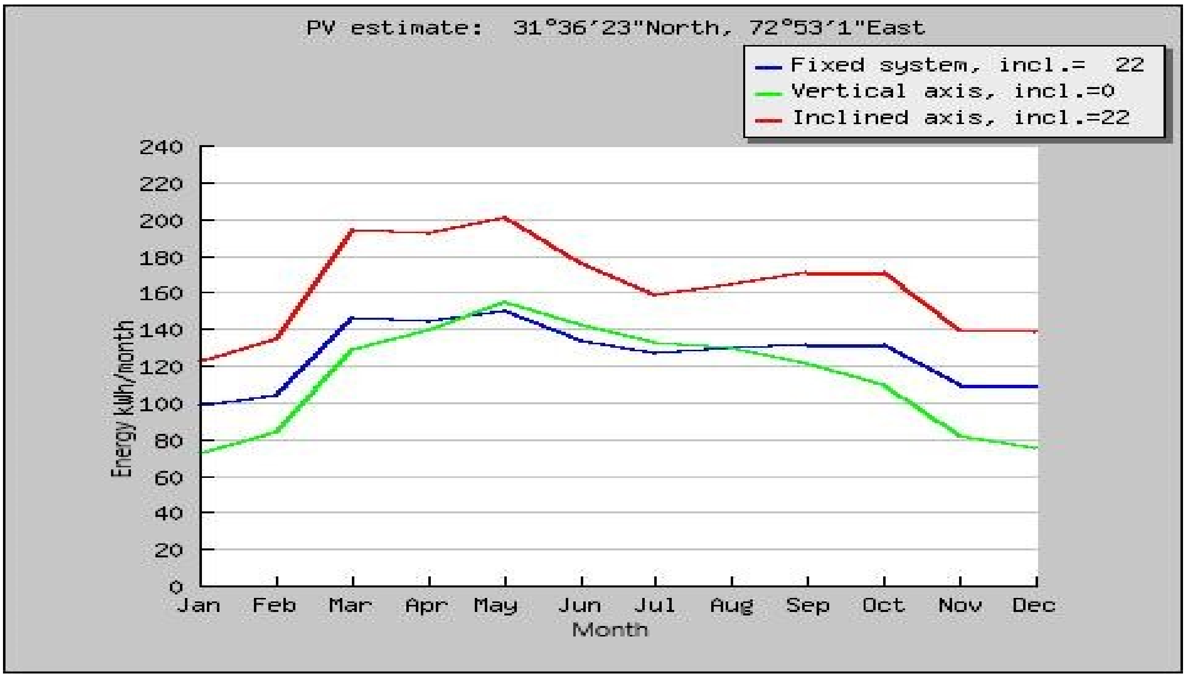
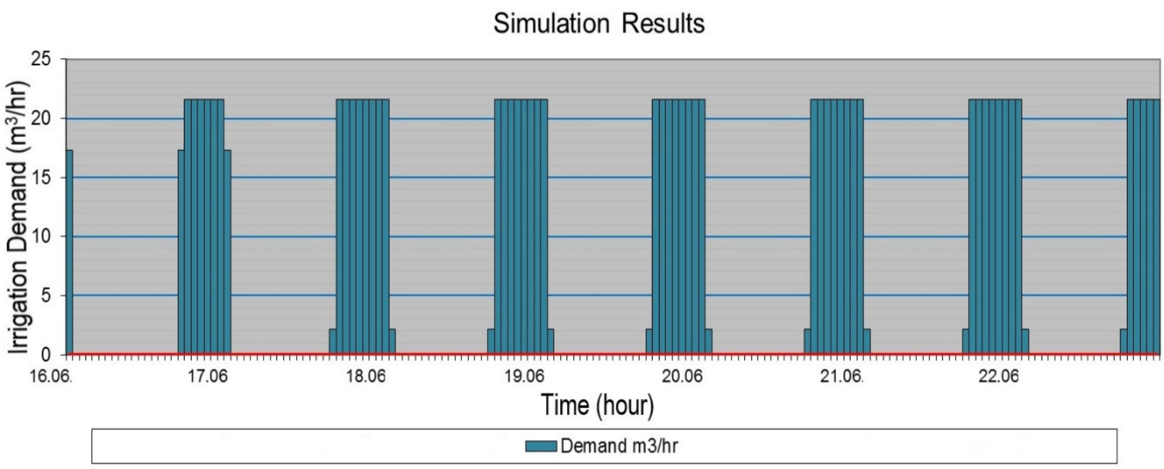


Figure 4. Monthly energy output of the PV system.

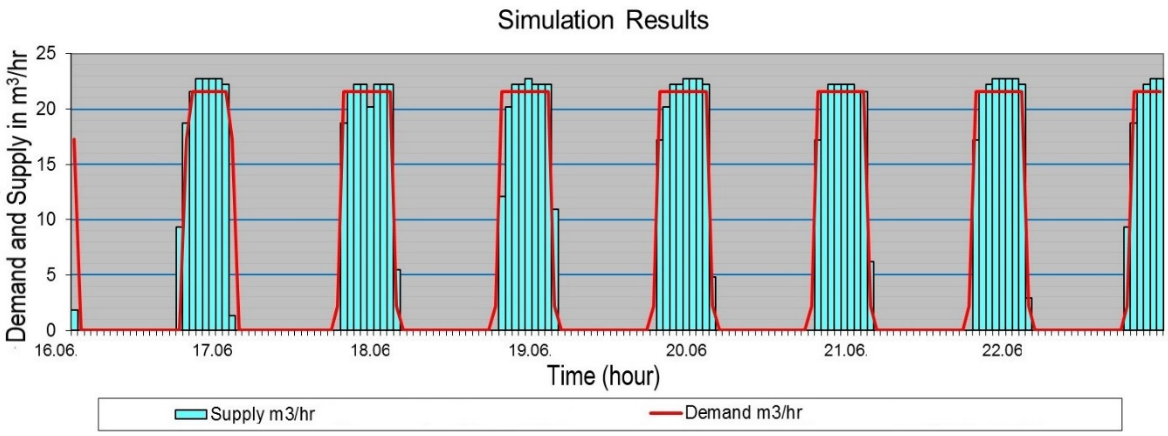
3.2. *Solar-Drip Simulation Tool (SoSiT) Output Results*

Simulation results of SoSiT are shown in Figure 5. A typical irrigation demand in m^3/hr in a selected week in the month of May is illustrated in Figure 5a. The next result in Figure 5b shows the same demand situation supplied by the PV system. It can be seen from Figure 5b that the solar energy system is starting a little later and also cannot fulfill the desired irrigation demand during that time (morning time). However, it can make up for that in other hours of the day. Figure 5c below shows the productive use of electricity from the PV system and unused electricity in white. Figure 5d shows that in all other seasons of the year this solar system is also providing sufficient water.

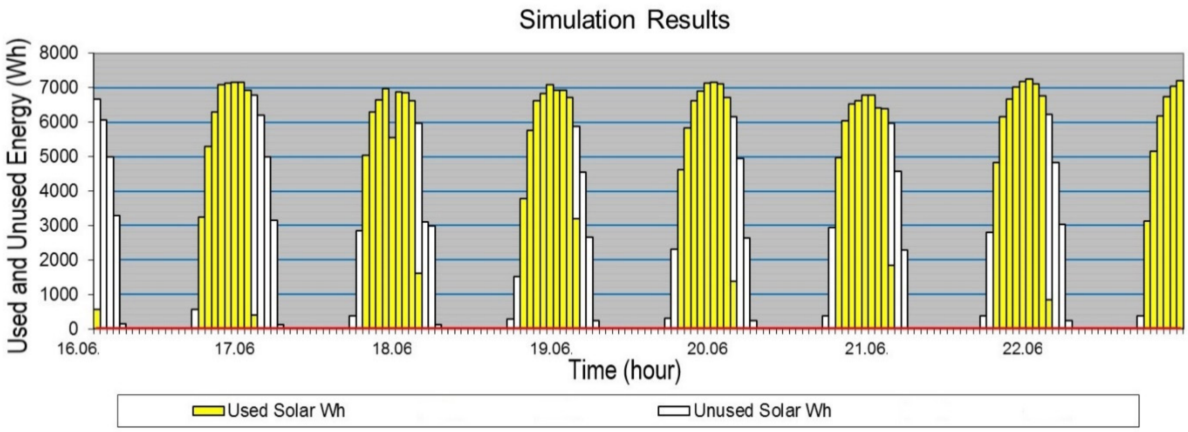


(**a**)

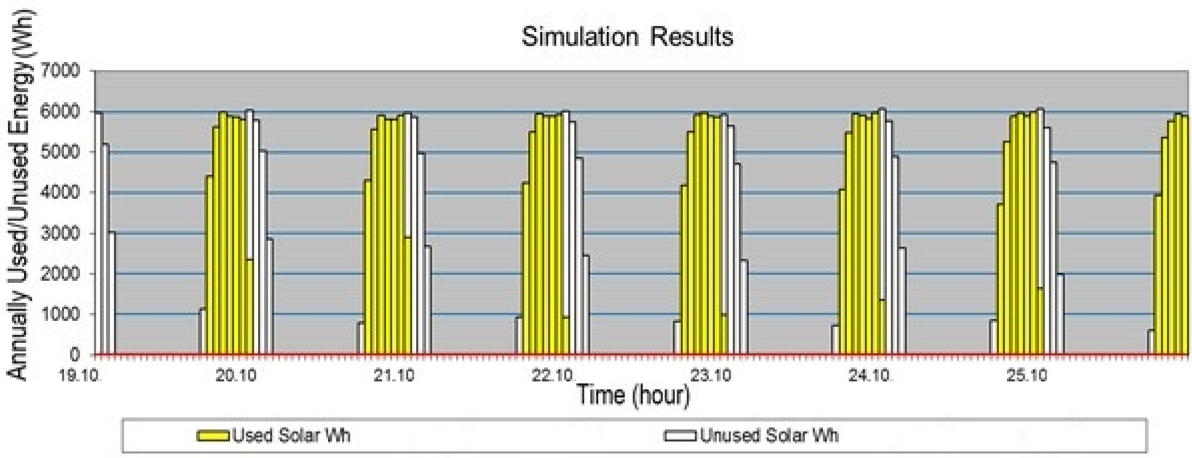
Figure 5. *Cont.*



(**b**)



(**c**)



(**d**)

Figure 5. Simulation results of SoSiT: (**a**) Irrigation demand m^3 per hour in a week; (**b**) Irrigation demand and supply by the PV system; (**c**) Productive used and unused electricity from PV system in May; (**d**) Productive used and unused electricity from PV system in all seasons.

The monthly water supply potential (m^3) of a particular selected site having 10 HP motor operated by PV system is shown in Figure 6.

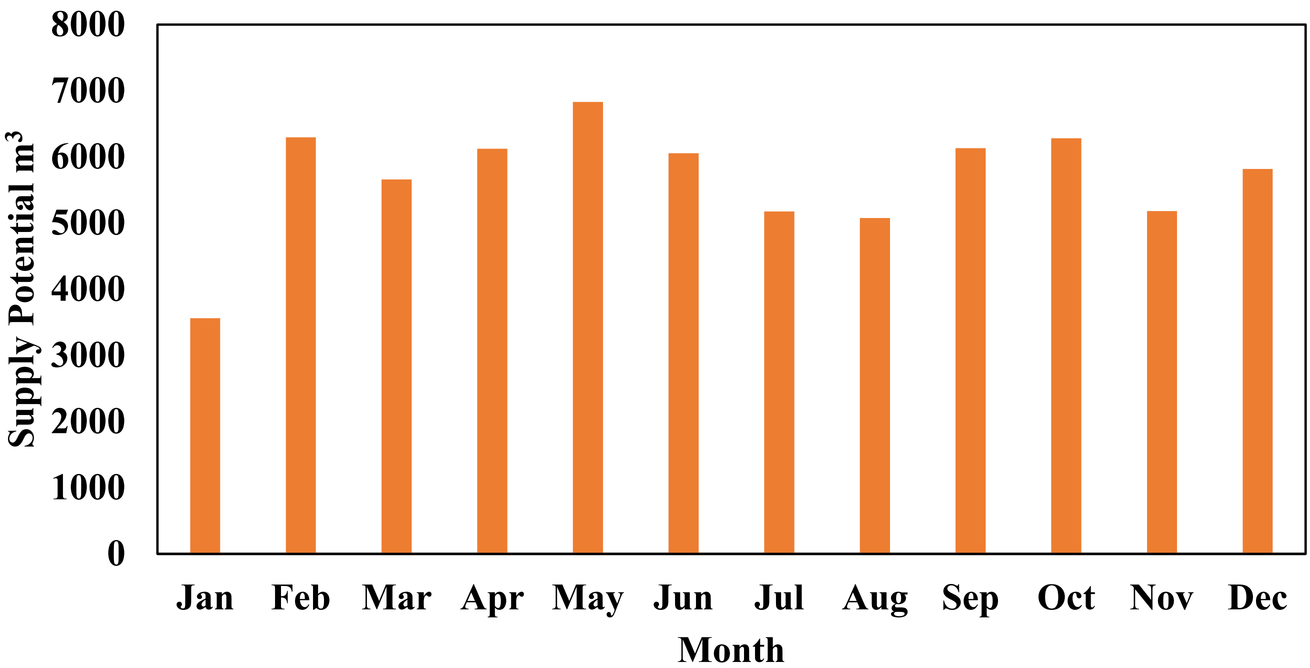


Figure 6. Potential water supply of the selected system at the project location.

Figure 7 shows the actual water demand and supply by the designed PV system. It shows that that the PV system fulfills the required crop water requirement and has a good match. For example, in the month of June, total water requirement is 3234.816 cubic meters and the PV system fulfills this demand. PV Systems fulfill the required crop water requirement, similar to results found in the research study conducted by Raza et al. [35] and Tamoor et al. [56].

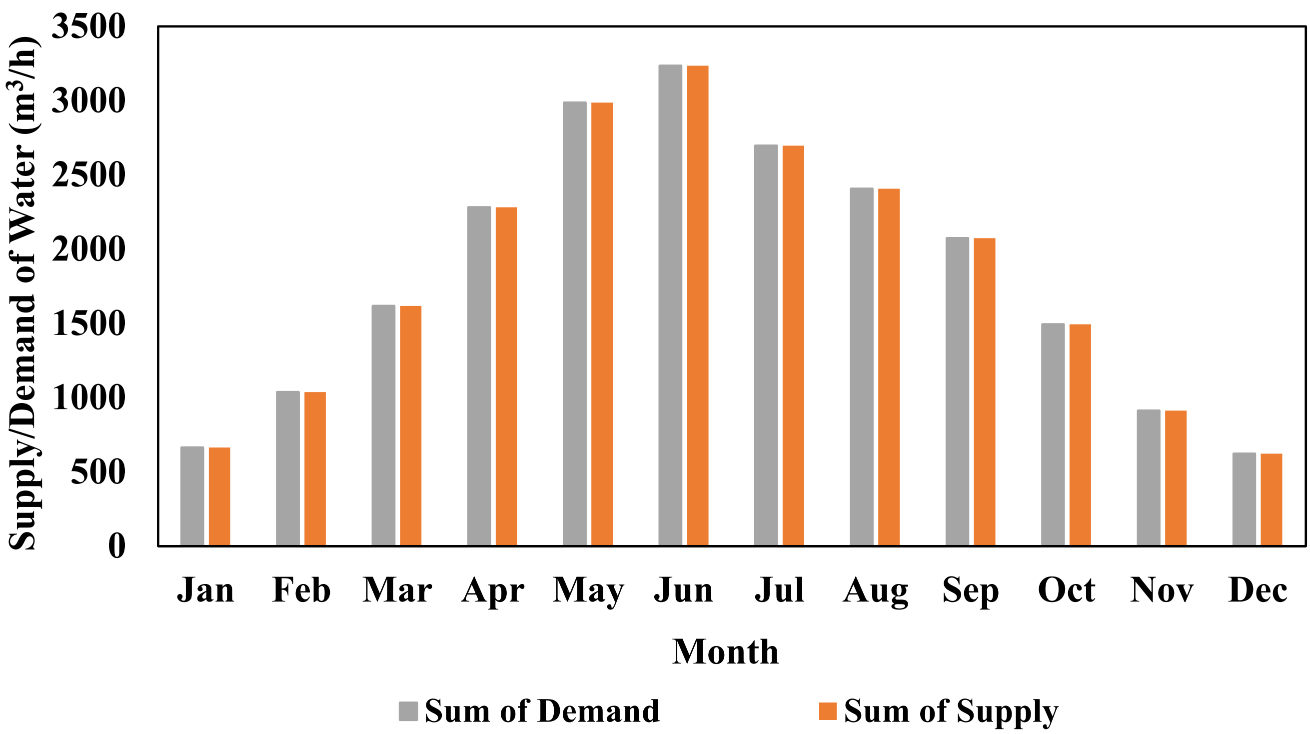


Figure 7. Crop water demand and supply by solar-powered pump.

If we compare Figures 6 and 7, we see that the PV system fulfills the required crop requirement by only using 28% of potential water supply, and 72% of the potential water supply has not been used. This value is high and it is recommended to grow more or different crops to utilize the fuel-free electricity from the PV system. Fuel-free electricity from the PV system means that total initial capital expenses for the PV system are higher than those for diesel- and electricity-operated drip irrigation systems. But after this, the operational and maintenance cost of the PV system is almost negligible as compared to other two systems (diesel and electricity) as shown in Table 9. Second, this PV system is designed as per water requirement. Therefore, it is an optimal system for a drip-irrigation system. Oversizing would result in additional unnecessary expenses, while under sizing would result in poor system performance.

3.3. Installed Experimental System Energy Generation

The energy generation for one month of the installed PV system used to operate a drip-irrigation system is shown in Figure 8. The monthly yield of the PV system is 667 kWh.

Figure 8. Energy generation of installed PV system for 1 month.

3.4. Comparison of Pumping Systems Operating on Electricity, Solar, and Diesel

A cost comparison was made for a 7.46 kW pump system driven by electricity, the PV system, and diesel. The cost of the pumping unit, solar system, diesel generator, etc., is taken from the local vendors. The unit cost of the PV-powered drip irrigation is USD 0.1013/kWh, which is 4.74% and 66.26% lower than the cost of subsidized electricity and diesel, respectively, as shown in Table 9. The total cost per hour (USD/h) for the solar system is 0.76 USD, which less than the total cost of the system operated by electricity and diesel as shown in Figure 9.

Table 9. Comparison of pumping systems operating on electricity, solar, and diesel.

Cost Break Up	Electricity	Diesel	Solar
Cost of pumping unit (USD)	1033.45	1033.45	1033.45
Motor (USD)	440.58	478.65	440.58
Transformer/Solar (USD)	1246.67		7718.25
Housing (USD)	543.92	543.92	543.92
Total capital expenses (P)	**3264.62**	**2056.02**	**9736.20**
Parameter-fixed cost			
Assumed Life (L; Years)	15	15	20
Salvage value, %	10	10	20
Interest rate (i), %	10	10	6
Taxes on P, %	0	0	0
Insurance on P, %	0	0	0
Fixed Cost			
Depreciation incl Housing	195.88	123.36	389.45
Average Interest on Investment	163.23	102.80	292.09
Taxes (No tax on Tubewell operation)	0	0	0
	0	0	0
Total fixed costs per annum	**359.11**	**226.16**	**681.53**
Parameter-variable cost			
Average working hour per day	3	3	3
Unit cost of energy source used	0.054 USD/kWh	0.60 USD/L	
Units of energy resources consumed/h	7.46 kWh/h		
Oil change duration, h		50	
Cost of lubricant, dosage		8.16	
No. of Lubricant change per annum		22	
Repair & Maintenance % of Capex	2%	4%	2%
Labor charges/h; min wages	0.54	0.54	0.54
Variable Cost			
Electricity/Fuel charges	444.31	1965.46	0
Lubrication cost	0	178.68	0
Repair and Maintenance	65.29	82.24	146.04
Labor charges@ USD 54.39/month	0	0	0
Total variable cost per annum	**509.61**	**2226.38**	**146.04**
Total Cost			
Total cost per annum (USD)	868.71	2452.54	827.58
Total cost per hour (USD/h)	**0.79**	**2.24**	**0.76**
Unit cost (USD/kWh)	**0.1063**	**0.30**	**0.1013**

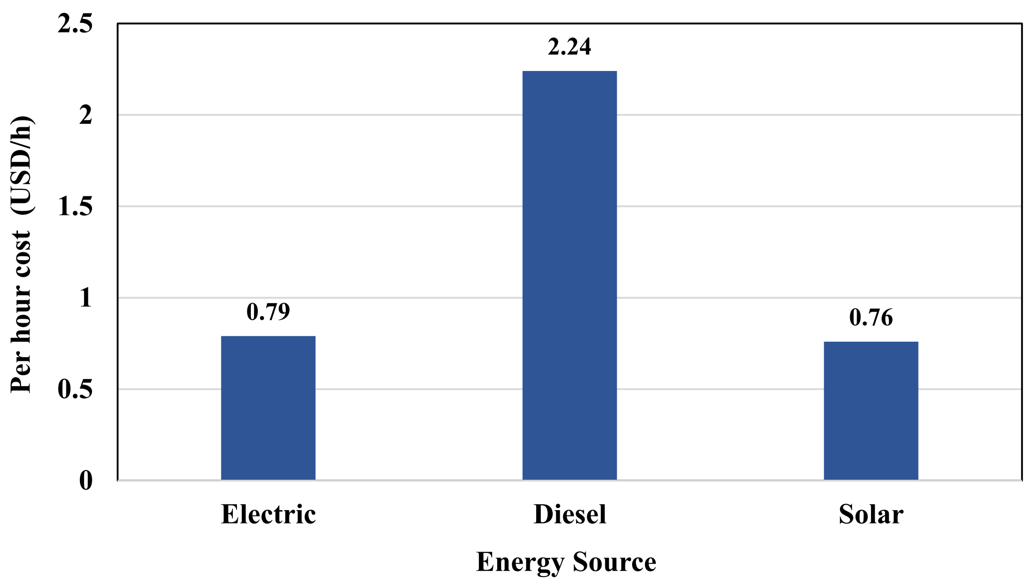


Figure 9. Total cost per hour for electricity, diesel and solar.

PV systems for operating drip-irrigation systems are more economically feasible than electric- and diesel-powered irrigation systems. This total cost per hour for electricity, diesel, and solar is similar to those found in the research study conducted by Raza et al. [32].

4. Conclusions

In this study, water requirement of the crop was calculated for two zones of a drip-irrigation site. It was found that for zone 1 the maximum calculated water requirement is 50,918.40 L per day in the month of June and the minimum water requirement is 9792.0 L per day in the month of December. However, for zone 2 the maximum water requirement is 56,908.80 L per day in the month of June and the minimum water requirement is 10,944.0 L per day in the month of December.

Furthermore, the PV system is designed based on calculated motor power, irradiance, and other meteorological parameters at a certain geographical position. The energy generated by designed PV systems for a drip-irrigation system are calculated by using the PVGIS simulation tool. Maximum daily energy production of the PV system is 6.48 kWh and monthly energy production is 201 kWh in the month of May. A locally developed Solar-Drip Simulation Tool (SoSiT) was used for load and supply optimization. Based on ambient temperature, solar irradiation, and water requirements, SoSiT calculates net generation by a PV system and resultant water output of the irrigation system. Simulation results of SoSiT show the typical irrigation demand in m^3/hour, the same demand situation supplied by the PV system, and in all seasons of the year this solar system is providing sufficient water.

Finally, a cost comparison was presented for a 7.46 kW pump system driven by electricity, the PV system, and diesel. The unit cost of PV-powered drip irrigation is USD 0.1013/kWh, which is 4.74% and 66.26% lower than the cost of subsidized electricity and diesel, respectively. The total cost per hour (USD/h) for the solar system is 0.76 USD, which is less than the total cost of systems operated by electricity and diesel.

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Abbreviations

PVDI	Photovoltaic Drip irrigation
VFD	Variable Frequency Drive
PVGIS	Photovoltaic geographic information system
SoSiT	Solar-Drip Simulation Tool
TDH	Total Dynamic Head
kW	Kilowatt
kWh	Kilowatt-hour
MW	Megawatt
USD	United State Dollar
LPS	Liter per second

HP	Horse Power
PV	Photovoltaic
DI	Drip Irrigation
OFWM	On Farm Water Management
CBM	Cubic meter
DC	Direct Current
AC	Alternating current

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