Analysis of Solar Photovoltaic-Based Water Pumping System in Sehore, India

Shubham Mishra, Shrey Verma, Ambar Gaur, Subhashree Mohapatra, Subhankar Chowdhury, and Gaurav Dwivedi

1 Introduction

In rural areas and remote places where electrical energy supplied from the grid is minimal or unavailable due to various constraints [1], solar photovoltaic (SPV) system can be utilized to meet the energy requirement of the growing population all across the world as the availability of solar energy is abundant in almost all regions [2–4]. Earlier in the absence of energy from the grid to power the water pupping system, diesel generators were used which are not only expensive but also causes harmful emission to the environment [4]. Solar photovoltaic-based water pumping system (SPBWPS) requires no fuel for its operation and is environment friendly [5–7].

Energy generation from the SPV system depends on climatic conditions and energy from it is generated only during the availability of sunlight only [6]. Hence to ensure a reliable operation of water pumping system, battery energy storage unit, biodiesel-based generator, etc., are required [7]. The biodiesel-based generator has lower emissions levels as compared to the conventional diesel generator system [8].

The efficiency of SPBWPS depends on several factors including climatic conditions, SPV panels, energy storage energy backup units, power controllers, power converters and inverters, and pumps and motors [9–12]. The software used for simulation helps in system design and optimization of the available energy resources to get the best results [10]. Analysis of design and simulation results gives a brief view of the performance of the system and problems that needed to be rectified before deploying it on the field [11]. There are a lot of software options available to design SPBWPS including PVsyst software [13, 14]. The designing of the system is easy in PVsyst, and performance study of the system based on several parameters can be done using the graphical approach [15].

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In this work, PVsyst 7.1 is used to design the system for a location in Sehore, Madhya Pradesh, India. The groundwater information of the selected location is taken from [14]. The paper is divided into four sections. Section 2 contains the theoretical analysis of system design and simulation of the system using PVsyst 7.1, and Sect. 3 has a detailed discussion of the results. This work is done to perform design and simulation analysis of a SPBWPS. This work can be further extended to on-field implementation of the system and evaluate the difference between design performance and on-field performance of the system.

2 Methodology

2.1 Theoretical Analysis

This includes analysis of hydraulic power, sizing of PV array, sizing of the motor, and calculation of the system efficiency. Figure 1 shows the generalized representation of SPWPS [15]. As all the systems are interconnected in SPWPS with feedback using water level sensors in tank and groundwater, to control the working of whole system to make it more efficient. Controller unit controls the level of water in tank to avoid overflow, has maximum power point tracker (MPPT) to maximize the output of PV system with the variation of solar irradiance level, and controls the ON/OFF of pump based on the solar irradiance presence and water level in both ground and tank.

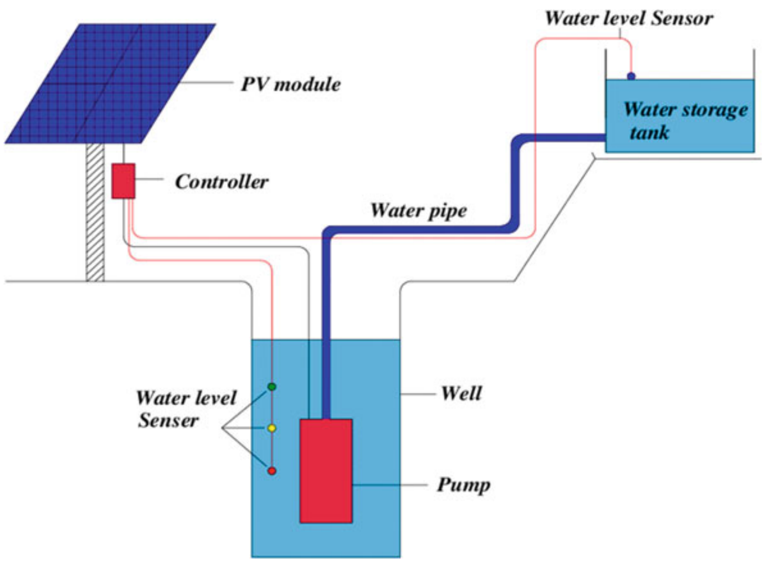

Fig. 1 Generalized representation of solar-powered water pump

Calculation of required Hydraulic power. Ideally, the hydraulic power required to drive the pump depends on.

- Mass flow rate of liquid
- Liquid density
- Differential height.

$$\text{Hydraulic power } P_H(\text{kW}) = \frac{\rho * Q * g * h}{3.6 * 10^6} \tag{1}$$

where

ρ = water density (kg/m^3).

Q = discharge of water (m^3/h).

g = acceleration due to gravity (9.8 m/s).

h = differential head (m), which is the difference in level of groundwater and tank upper level with the addition of frictional loss.

Motor sizing. The power generated by the PV array is fed directly to the DC motor with the help of controller that operates the pump. The amount of power required for the driving of (direct current) DC motor is depending on the pump efficiency as the motor drive the pump.

$$\text{Power required by motor } P_M(\text{kW}) = \frac{\text{Hydraulic power required by pump}}{\text{Efficiency of the pump}} \tag{2}$$

PV array sizing. The PV array sizing defines the total size of the solar PV system. The total power required also depends upon the system's efficiency.

$$\text{Total power required from PV array} = \frac{\text{Power required by motor}}{\text{Efficiency of the system}} \tag{3}$$

The input power to the system is calculated with the help of incident solar radiation of the solar panel surface.

$$P_i = G_i * A_c \tag{4}$$

where

G_i = Incident solar irradiance (W/m^2).

A_c = Effective area covered by cells in module (m^2).

The unit PV module power output is given by

$$P_o = V_{OC} * I_{SC} \quad (5)$$

No. of PV module required for array

$$\text{Total no PV module in array} = \frac{\text{Power output required from PV array}}{\text{Power output form unit module}} \quad (6)$$

PV array efficiency η_p is given by

$$\eta_p = \frac{\text{Total power used from PV array}}{\text{PV array capacity}} * 100 \quad (7)$$

PV array input power depends on the area covered by the array and the average total solar irradiance incident on the plane surface of the PV.

Theoretical mathematical calculation. Approximate water requirement for the day is 40m^3 for agriculture use, taking peak sun hour of 8 h/day. Duration of pumping = 6 h.

$$\text{Flow rate } Q\left(\text{m}^3/\text{h}\right) = 40/6 = 6.66 = 7\,\text{m}^3/\text{h}$$

$g = 9.8$ m/s^2, $\rho = 1000$ kg/m^3, $h = 33$ m (static head of 30 m with 10% of friction loss = total head of 33 m)

$$P_H = \frac{1000 * 9.8 * 7 * 33}{3.6 * 10^6} = 628.833\ W = 0.628\ \text{KW}$$

Pump power requirement (if pump efficiency is 49%) = 628.833/0.49 = 1283.33 W.
Total power required from PV array (if system efficiency is 81.4%) = 1283.33/0.814 = 1576.57 W = 1.576 kW.
Input power to the system from annual solar irradiance, where $G_i = 5.18$ W/m^2/day and $A_c = 16$ m^2.
Then $P_i = 5.18*16 = 82.88$ kWh/day.
The unit PV module power output, where $V_{OC} = 14.7$ V and $I_{SC} = 8.84$A.
Then $P_o = 14.7*8.84 = 130$ W.
No of PV module required = 2000/ 130 = 15.38 ≈ 16 panels approx.
Efficiency of PV array = 1576/ 2000 = 0.788 = 78.8%.

2.2 Simulation of Design Using PVsyst 7.1

Details of water well location. The detailed location of the water well is presented in Table 1. Water level and depth of the well are decided based on the data Ground Water

Table 1 Location and water well information

Name of location for system installation	Sehore, Bhopal, Madhya Pradesh
Latitude	23.21° N
Longitude	77.08° E
Altitude	496 m
Name of water resource	Deep well to storage
Application	Irrigation
Diameter of well	15 cm
Static level depth	30 m
Pump level	50 m

Information Booklet, Sehore District, Madhya Pradesh. Sehore District is nearby of Chambal and Narmada river basin, which makes the predominately agriculture-based economy in this district. As the major of the irrigation sources are groundwater either by tube wells or dug wells [14].

Details of the pump, water storage, and piping network. There are variety of pumps available in market such as submersible, floating and surface water pump which is further divided into helical, diaphragm type, centrifugal, positive displacement type, divided shaft pump type, whose efficiency varies from 40 to 60% [16]. Table 2 represents the details of the pump, water storage, and piping network. In simulation, a centrifugal multistage-type pump is used powered by DC brushless motor of 1500 W with a head of 20–70 m, flow rate at 7.7–4.07 m^3/h. Water tank is assumed made up of fibreglass reinforced plastic of capacity 45m^3 and kept at height of 1 foot, to make gravity flow of water to the irrigation fields, connected with a polyethylene (PE50) category of 2-inch piping system.

Details of PV array. PV array made up of silicon cells system utilizes the visible length spectrum rays of sun ranging from 300 to 1100 nm (nanometres) to generate electricity. PV array is made up of by combining various modules in series and

Table 2 Pumping system details

Type of pump	Centrifugal multistage
Supply type	DC, brushless
Power rating	1500 W
Name of manufacture	Generic
Volume of storage tank	45 m^3
Water requirement	40 m^3
Diameter	4.4 m
Height	3.0 m
Feeding altitude	4 m
Size of pipe	2"

Table 3 Information about PV array

Name of manufacture	Vikram solar
Model name	Generic Mono 130Wp 36 cells
Type of cell	Si-mono
No of modules	16
Power rating per unit module	130 Wp
Voltage rating	14.7 V
Current rating	8.84 A
Total power capacity of PV array	2 kW

parallel connections as per voltage and current requirements at converter level [6]; here we have used 8 modules in series and 2 modules in parallel covering an area of 16m^2. Table 3 describes the detail of the PV array used.

Monthly climatic data of the location. The climatic data include global horizontal radiation, diffuse, direct radiation, and temperature of the SPWPS site location in Table 4. Data is collected from Sehore_MN73.SIT Meteonorm 7.3 (1981–2010), Sat = 100%. With the help of metrological data, the annual solar irradiance level of 5.18 W/m^2/day is assumed. And based on the variation in season, a seasonal tilt adjustment of 20° in summer and 50° in winter with 0° azimuths is assumed.

Table 4 Monthly climatic data

Month	Global horizontal radiation (kWh/m^2/mth)	Diffuse radiation (kWh/m^2/mth)	Direct radiation (kWh/m^2/mth)	Ambient temperature (°C)
January	137.5	38.70	98.8	17.7
February	147.8	45.41	102.39	20.9
March	195.6	57.84	137.76	26.6
April	200.8	72.27	128.53	31.2
May	211.1	85.48	125.62	33.6
June	169.8	96.01	73.79	30.4
July	131.5	89.66	41.01	27.0
August	121.0	79.99	41.01	25.7
September	145.4	79.00	66.4	26.4
October	165.1	57.79	107.31	26.1
November	138.1	43.59	94.51	21.1
December	126.4	41.92	84.48	19.1
Total	1890.3	787.64	1102.66	25.6

Table 5 Main results obtained from simulation

Main simulation results		
System production	Water pumped—14,210 m^3	Specific—1945 m^3/kWp/bar
	Energy at pump—2898 kWh	Specific—0.20 kWh/m^3
	Water needs—14,600 m^3	Missing water—2.7%
	Unused PV energy—539 kWh	Unused fraction—15.1%
	System efficiency—81.4%	Pump efficiency—48.5%
Investment	Global (incl. of 5% GST)—553,686 INR	Specific—266 INR/Wp
Yearly cost	Annuities (loan at 6% for 20 years)—19,309 INR/year	Running cost—10,100 INR/year
Water cost	*2.06 INR/m^3*	

3 Results and Discussion

3.1 Output of System Design Calculation

The system efficiency for the designed system from PVsyst7 is 81.4%. This result shows that most of the energy generated through PV strings is utilized by the submersible pump set and only 15.7% of generated energy is not utilized. The water pumping cost from the designed system is 2.06 INR/m^3, which is very feasible in comparison with a conventional diesel engine water pumping set. Table 5 describes the result obtained from the simulation of PV-based water pumping set.

3.2 Performance Ratio

The performance ratio (PR) is the ratio of the measured output energy of the PV system to the expected output energy with the standard term and condition based on the system nameplate rating. For the designed system, PR is 0.656. Here for the calculation of PR includes the optical losses (Shadings, IAM, soiling), the array losses (PV conversion, ageing, module quality, mismatch, wiring, etc.), and the system losses (inverter efficiency in grid-connected, or storage/battery/unused losses in stand-alone, etc.). Figure 2 shows the PR for the year.

3.3 Normalized Production

Figure 3 shows the energy balance of the proposed solar water pumping system for the Sehore region, Bhopal site. As the figure explains, there is very low unused

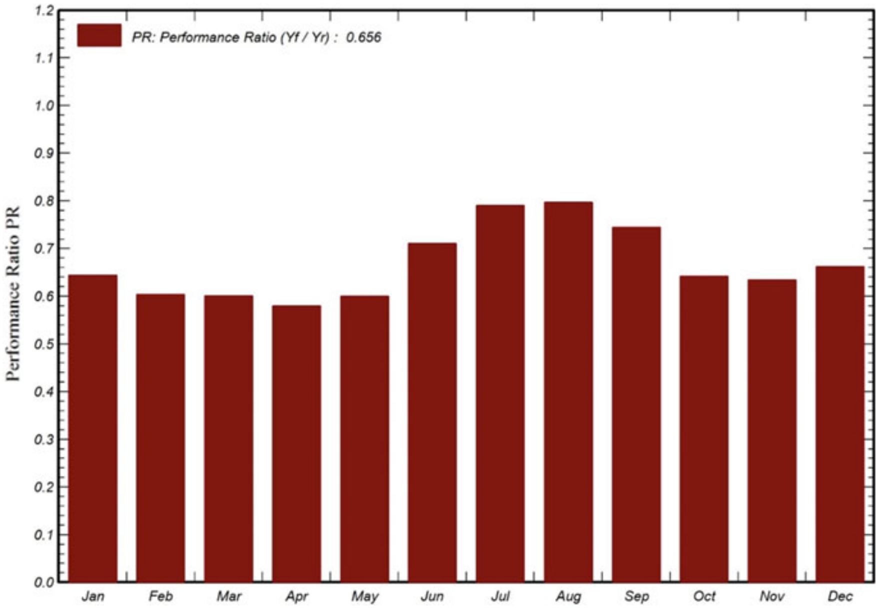

Fig. 2 Performance ratio of the system

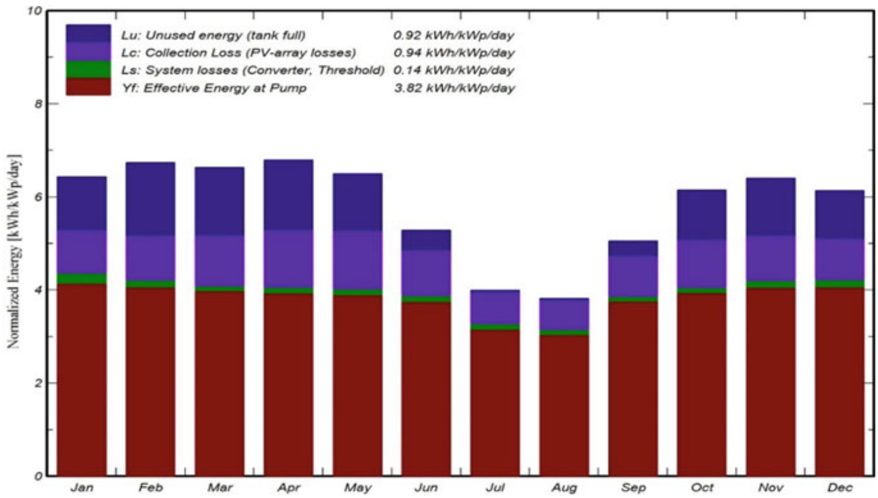

Fig. 3 Energy balance of the SPWPS for Sehore site: Nominal power 2080 Wp

energy for the given site, due to the system is designed based on the maximum water production volume within a year. It shows the normalized value of unused energy (tank full), collection loss (PV array loss), system loss and the effective energy at the pump. Unused energy in the system is minimum in comparison with the addition of collection and system loss, as the system is designed to deliver the maximum amount of water per day using all available energy resources. When it is desired to maximize the water, the output is subject to high losses, but if all of the losses are minimized, it will reduce the water output on a per-day basis and unused energy will be maximized.

3.4 Flow Rate Function of the Pump

Figure 4 shows the relationship between energy available at the pump and the average flow rate of the pump. It shows the almost linear relationship between the flow rate and the available energy at the pump. It shows how the flow rate, size of the pump depends on the availability of power. As there is a requirement for the pump controller for adjusting the size of the pump according to the available power at the pump.

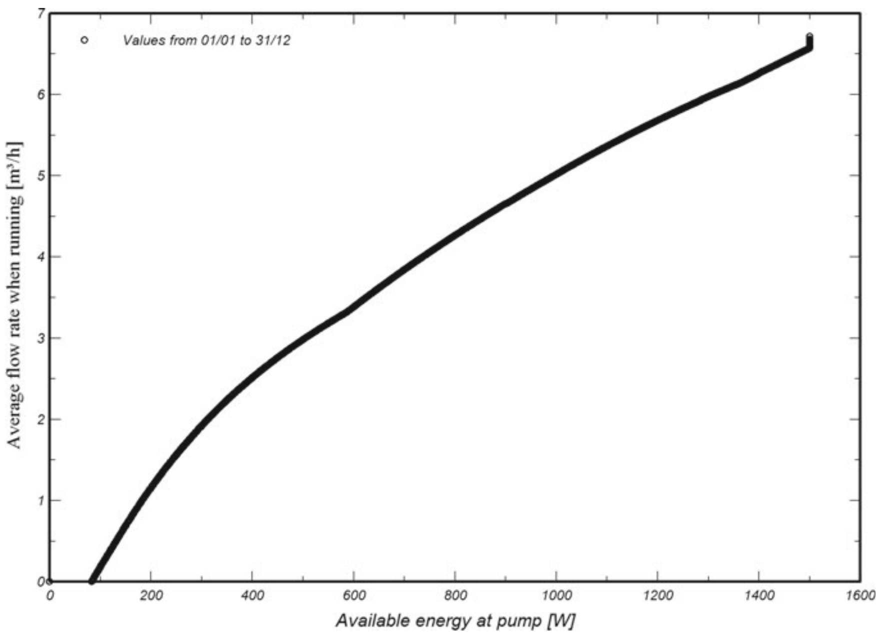

Fig. 4 Flow rate function of pumps power

Table 6 System summary, water and energy cost

Total installation cost	553,686 INR
Operating cost	10,000 INR/year
Energy used for pumping	2898 kWh/year
Excess energy (tank full)	539 kWh/year
Water pumped	14,210 m^3
Cost of pumped water	

3.5 *Economic Calculation*

Economic calculation of SPWPS has been accessed using PVsyst software to calculate the energy and water cost. The factors used for economic evaluation are installation cost, operating cost, depreciation and financial cost. Table 6 describes the system summary, water and energy cost.

Installation cost:

PV modules: 16 units * 5000 INR/unit = 80,000 INR.
Support for modules: 16 units * 145 INR/unit = 2320 INR.
Pump including controller (with a life span of 20 years): 1 unit = 35,000 INR.
Tank and hydraulic system: 260,000 INR.
Transport, engineering and drilling cost: 150,000 INR.
Overall cost (5% GST) = 553,686 INR.

Financing: It includes the depreciation cost, loan amount and interest.

Depreciation assets cost: 117,320 INR.
Subsidy: 332,211 INR (govt. provide 60% subsidy to promote the PV pump set for approaching towards renewable energy adoption).
Loan: 221,474 INR (at 6% interest rate for 20 years).
Water is a sale at the rate of 4 INR/m^3.

Return on investment: As the pumped water is sold to the villages for irrigation at the rate of 4 INR/m^3, as assumed the 20 years of project lifetime period.

Payback period: 15 years.
Net present value: 550,612.39 INR is the difference between the present value of cash inflows and the present value of cash outflows over a period of time.
Return of investment: 99.4%.

4 Conclusion

The present work shows an excellent and simplified approach for design optimization of the SPBWPS by employing a theoretical approach and using simulation software (PVsyst 7.1). The efficiency of the system which is designed on simulation software is calculated to be 81.4%. Also, the cost of water pumping from the designed system is 2.06 INR/m^3, which highly feasible when compared with a conventional diesel engine water pumping set. The design analysis part plays a very crucial role in evaluating the system efficiency and cost of pumping the water. The simulation results help in understanding the system's performance before deploying it on the field. This study will be very helpful for budding scholars and researchers working in the field of SPBWPS. This work can be further extended to employing a tracking system for solar PV to increase the energy output and analysing the impact of using an energy storage system on increased operating hours of pumping operation.

Credit authorship contribution statement Shrey Verma: Simulation and writing the original draft. Shubham Mishra: Writing—review and editing. Ambar Gaur: Investigation, Subhashree Mohapatra: Data curation, Subhankar Chowdhury: Data curation Gaurav Dwivedi: Final drafting and conceptualization.

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