PERFORMANCE INVESTIGATIONS OF SOLAR PHOTOVOLTAIC WATER PUMPING SYSTEM USING CENTRIFUGAL DEEP WELL PUMP

by

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Photovoltaic technology is an effective, reliable and rapidly developing technology to convert solar energy into electrical energy. In the recent years, the need and demand of solar photovoltaic water pumping system has been increased as a stand-alone water pumping system to pump water in remote, desolate and mountainous region for end use of livestock watering and rural/urban water supply system. For a required pumping head, photovoltaic array configuration and its size (peak power rating, W_p) affect the flow rate of pumped water, economy and performance of solar photovoltaic water pumping system. The recent work is aimed to study performance of a directly coupled solar photovoltaic water pumping system at different pumping heads (2 bar, 3 bar, 4 bar, and 5 bar) and different photovoltaic array configurations (3S×2P, 4S×2P, 5S×2P, 6S, 7S, and 8S) for the real meteorological conditions of the Vidarbha region, central India (Nagpur). A comparative study has been done to investigate the head effect on the optimum photovoltaic array configuration, pump and pumping system total efficiency by performing experiment on the centrifugal deep well pump (SQF 5A-7), with 6-10 photovoltaic modules (200 W each) with various configurations and different heads. It is concluded that the 4S×2P and 5S×2P configurations are most optimized array to provide optimum energy at all pumping heads.

Key words: *solar water pumping system, photovoltaic, total head, centrifugal deep well pump, optimization*

Introduction

Water pumping need of human civilization has long history. Human developed many methods, which required either minimum effort or cost to pump water. The early power sources included: human energy, animal power, wind energy, and fossil fuels for pumping water to meet the basic needs. With the evolution of the technology, pumping systems were designed using solar energy. Photovoltaic (PV) technology thus evolved as a new and advance technology that converts solar energy directly into electricity, to pump out the wa-

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ter from the deep reservoir. This technology has been proved to be an effective and reliable method to utilize the solar energy reaching on the earth's surface to meet the pumping water needs. Solar PV water pumping system (SPVWPS) can serve as a stand-alone system to get water for end use of livestock watering, rural/urban water supply system, drip irrigation, surface irrigation like pasture, green house, and for industrial use. Solar energy has the advantage of abundant availability, sustainability, environmental friendly, and SPVWPS is straightforward to install the equipment and minimum long run cost. So, this makes solar energy most preferred input energy source for the WPS in remote, uninhabited and grid electricity starved regions of many developing countries like India [1, 2]. Moreover, pollution and GHG emission potential and ever-increasing cost of fossil fuels, lack of grid electricity and continuous depletion of oil reserves are other concerns associated with non-renewable sources [3, 4]. The SPVWPS is gaining worldwide acceptance due to gradual and continuous reduction in the cost of PV technology [5], advances in PV material technology, thus improving the overall efficiency. In India, the efforts are also made from the government and its policies such as: low taxes, goods and service tax (GST) at 5% on PV modules [6], incentives for PV pumping, and other initiatives like Jawaharlal Nehru National Solar Mission (JNNSM) [7] to promote the use of SPVWPS. The SPVWPS consists of solar PV array, motor and a deep well submersible pump. It can be classified as directly and indirectly coupled PV pumping system (PVPS). In directly coupled PVPS, PV array is directly connected to a DC motor to drive the pump. It is the cheapest, simplest, and most reliable of all the different PVPS. The system stores water rather than storing electricity.

Early research in this area reported in mid-seventies. Being an interdisciplinary area, researchers from various engineering domain contributed in the design, system sizing, and study of performance parameters, efficiencies of components, economic viability, and cost optimization [8-10]. Waddington and Herlevich [11] compared pumping system with power supply from conventional electric motor and PV array. They concluded that PV powered system performed satisfactorily at low operational cost. Many location or area-based study has been performed with the SPVWPS. Manakbadi and Ayad [12] investigated the technological viability of PV, solar thermal and SPVWPS under the meteorological conditions of Egypt. Chowdhury *et al*. [13] studied the performance and reliability of seven different capacity SPVWPS for various locations of Wyoming, USA. They found SPVWPS as cheaper alternative for pumping water in remote areas, with high performance and more customer satisfaction. Whitfield *et al.* [14] investigated the pumping performance of low power rating, 300-500 peak watt, [W_p] SPVWPS with capacity of 40 m^3 per day at 10 m head. They reported that the efficiency of pump/motor/controller system increased from 40% to 60-70%, on daily basis. The researchers [15, 16] investigated the effect of total dynamic head and insolation distribution on the pumping efficiency of SPVWPS. They reported that the optimum size SPVWPS showed highest efficiency at higher operating head and insolation values. Chinathambi, *et al*. [17] investigated the performance of SPVWPS under the influence of solar PV panel cooling using air-flow over top and bottom surface of the panel. They concluded that air cooling of panel resulted in SPVWPS efficiency by 1.8%.

Vick *et al*. [18] found higher efficiency with wind electric WPS over the SPVWPS for 30 m head, under the environment conditions of Bushland, Tex., USA. They also concluded that, the SPV alternating current (AC) system pumped three times more water than the SPV direct current (DC) system. Protogeropoulos and Tselikis [19] investigated the performance of coaxial piston positive displacement (PPD) and centrifugal solar submersible pump of 200 W_p rating, powered by 220 W_p PV array under the outdoor conditions of Athens, Greece. They

concluded that the hydraulic efficiency of low capacity centrifugal pump (CP) pump at 65 m head was 12% higher than the high capacity pump at 28 m head. Lujara *et al.* [20] investigated SPVWPS with maximum power point tracking (MPPT), using permanent magnet DC (PMDC) motor and induction motor (IM) drive systems. They reported that the system with PMDC was more efficient than IM. Fraidenraich and Vilela [21] proposed utilizability method to calculate the maximum discharge at different locations in Brazil. They calculated the averaged volume flow of water using the derived analytic expression. The results of the derived expression and calculated pumped water volume over 10 years were in acceptable range. Mahmoud *et al*. [22] investigated the performance of two similar AC PVPS, one with load control system and other without it, under the desert climates of Jordan. They conclude that, the controlled PVPS delivered 7.4% more water than the uncontrolled system annually.

Michela *et al.* [23] studied performance of a SPVWPS with a brushless DC motor in the MATLAB/Simulink environment. They reported SPVWPS with MPPT configuration delivered more volume of water and found more versatile. Odeh *et al*. [24] studied the cost effectiveness of the five different size PVPS (2.8 kW_p to 15 kW_p) and 5 diesel WPS of comparable sizes, under the outdoor conditions of Jordan. They found PVPS system was cost effective than diesel WPS for hydraulic energy below 2100000 m^4 per year but diesel WPS were more suitable for wider applications.

India is bestowed with high solar radiation all around the year because of its location in the solar belt (40°S to 40°N) [25]. Nagpur, is situated at the center of the country and falls in the solar hot spots zone of West Coast Plains and Ghat region with high solar radiations availability in the range of 4-7 kWh/m^2 per day. The meteorological conditions of the city make it worthy for water pumping using solar energy. Hence, the authors have attempted to study the performance of SPVWPS using centrifugal submersible pump. Solar insolation and PV array size and its arrangement affect the flow rate of pumped water. A significant part of the system cost of a SPVWPS is the cost of the PV array (40-60%). Oversizing of the array size results in significant increase in cost whereas under sizing results in reduction in volume of pumped water and system efficiency [26]. Therefore, proper selection of size and type of the array is of paramount importance to improve the cost effectiveness of SPVWPS. Some of the investigations are reported in the literature on these issues. Researchers [27-32] investigated the effect of optimum size of PV array configuration, Series×Parallel (S×P), to maximize the delivered water at given location and head. They reported that optimum PV array configuration affects the optimum quantity of water required for the worst month, energy requirement of the loads, radiation intensity level and location and water consumption profile of the site. The literature survey reveals that the optimum PV configuration and performance of SPVWPS are location and type of pumping system dependent. Very few studies are reported under Indian climatic conditions at different heads, PV configurations, subsystem and system efficiencies of the SPVWPS. Therefore, this research paper envisages following objectives:

– To study performance of a directly coupled SPVWPS at different pumping heads (2 bar, 3 bar, 4 bar, and 5 bar) and different PV configurations (3S×2P, 4S×2P, 5S×2P, 6S, 7S, and 8S) for the Vidarbha region, Central India (Nagpur).
– To carry out a comparative study to investigate the head effect on the optimum PV panel configuration, pump and pumping system total efficiency by performing experiment on the CP with various configurations and different heads. The SPVWPS is tested for each head and PV configuration for the daily pumped water volume, L, hydraulic and electrical input energy.

– To decide the optimal PV module configuration (optimum cost of configuration) at different heads under consideration, for the optimal performance (maximum discharge) of SPVWPS.

Description of the experimental set-up

Experimental data were collected at the PVPS research facility for measuring the performance of directly coupled SPVWPS installed at Nagpur, Maharashtra, India (latitude 21.15 °N, longitude 79.09 °E, altitude 310 m). The tropical savannah climatic conditions prevails throughout the year with average ambient temperature of 20 °C and 32 °C in the month of January and June [33]. The city receives solar irradiation of 4-7 kWh/m^2 per day, on a tilted PV surface [34]. Monthly and daily variation of solar radiation for Nagpur is shown in fig. 1.

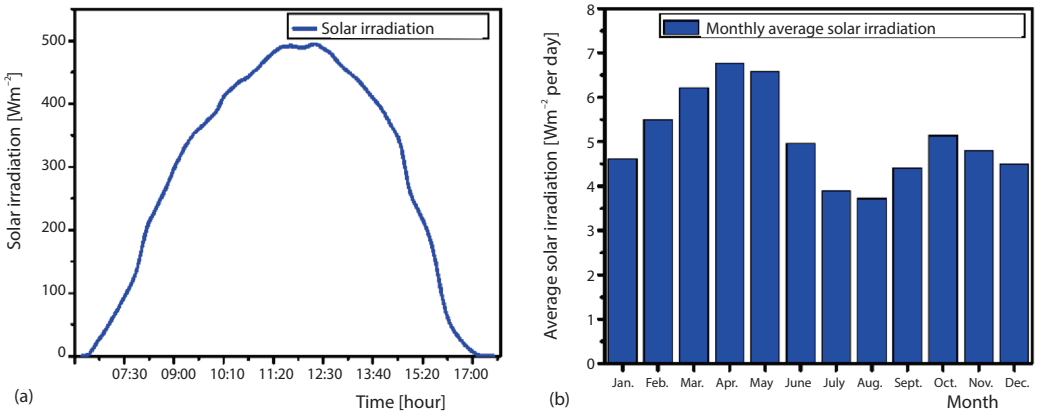

Figure 1. (a) Monthly average irradiance of Nagpur site, (b) variation of daily solar radiation [35]

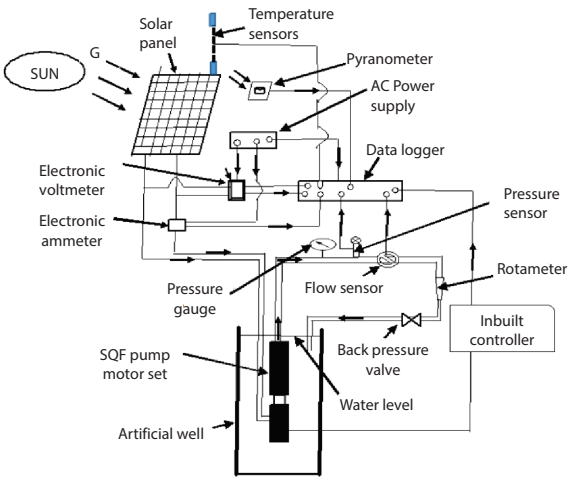

Figure 2. Experimental set-up for performance evaluation of directly coupled SPVWPS

The symbolic representation of the experimental set-up for directly coupled SPVWPS along with all the control, measuring and data acquisition system is shown in fig. 2. The major components of the set-up are Grundfos (Model SQF 5A-7) deep well CP driven by inbuilt permanent magnet brushless direct current (PMBLDC) motor and PV modules. The pump is installed in a cylindrical shaped tank to serve as artificial well. The water discharged by the pump forms a closed loop cycle and is made to return to tank. Other components are pressure and flow sensors and pyranometer to measure the pressure head [bar], discharge from the pump in liter per hour [Lph] and global radiation [Wm^{-2}], respectively. The pressure gauge and Rotameter have been fitted to crosscheck the readings of pressure and flow sensors, respectively. In addition, electronic voltmeter and ammeter are also installed to measure DC voltage and DC current. A backpressure valve is fitted in the pipe-line to regulate the pressure

head. All the components are connected to the data logger which is capable of recording values of all parameter on per second basis. Detail of all the components is given in tab. 1.

Table 1. Detail of components used in experimental set-up

Component	Model (make)	Technical specifications
Pump	SQF5A-7 (Grundfos)	Multistage deep well CP with 7 stages
PMBLDC motor	MSF3 (Grundfos)	Power input – P1: 1.4 kW Rated voltage and current: 30-300 V, 8.4 A
PV Module	ASP-72C-200 (Akshaya Solar)	Maximum power, P_{max}: 200 W V_{max}: 36.72 V, I_{max}: 5.45 A
Flow Sensor with meter	FT-650 (Aster)	Flow range (Min-Max): 0.05-500 m^3/hr
Electronic voltmeter	DTI	Range: 0-450 V DC, 4-20 mA output *Accuracy:* Standard: ±0.5% of Span
Electronic ammeter	DTI (MECO)	Range: 0-20 A DC; 4-20 mA output *Accuracy:* Standard: ±0.5% of Span
Pyranometer	SRR (Virtual Etx)	Calibration: 0.25 mV per W/m^2, Range: 0 -2000 W/m^2
Data logger	Unilog (PPI)	16 Channel data Recorder Accuracy: ±0.25% of reading

Pump and motor characteristics

In the study, Grundfos pump (Model SQF 5A-7) was used for experimentation. This pump is a deep well multistage submersible CP (4″), tab. 1. It has seven stages, each stage consisting of centrifugal impeller and diffuser blades attached, circular shaped stator casing, both made up of stainless steel. The SQF pump comes in a modular design consisting of pump, PMBLDC Motor – MSF 3, and accessories like cable with a water-level electrode, socket and cable guard. The pump can run at temperature range of zero to maximum + 40 °C. The dry-running protection is provided via a water level indicator placed at 0.3-0.6 m above the pump. The pump duty point is optimized in accordance to the input power availability using a built-in MPPT [34].

The Grundfos pump is driven by the MSF 3 motor and the characteristics are provided in tab. 1. The motor cuts out when voltage exceeds beyond the permission range and automatically starts when the voltage reaches the permissible range. Overload protection is ensured by controlling the speed [34].

The PV module and configuration

The multi-crystalline Silicon PV modules (each 200 W/36 V) were connected in series and parallel to make different array configurations to supply the required DC power to the CP pump. All the PV modules are installed facing towards south with 21° of tilt angle almost same as the latitude angle of the Nagpur city. The modules are arranged in series (S) and parallel (P) combinations. The numbers before S and P denoted the units of PV modules. The six different PV array configurations namely PVC1 (3S×2P), PVC2 (4S×2P), PVC3 (5S×2P), PVC4 (6S), PVC5 (7S), and PVC6 (8S) are used for study and their characteristics are shown in tab. 2.

Table 2. The PV array configuration characteristics

Configuration name	Configuration/ arrangement	Panel combine power rating [W_p]	Cumulative max voltage (MPPT), V_{max}	Combine Max current (MPPT), I_{max} [A]	Total panel area, A_{PV} [m^2]
PVC1	3S x 2P	1200	108	11.1	9
PVC2	4S x 2P	1600	144	11.1	12
PVC3	5S x 2P	2000	180	11.1	15
PVC4	6S	1200	216	5.55	9
PVC5	7S	1400	252	5.55	10.5
PVC6	8S	1600	288	5.55	12

Methodology

Solar water pumping data collected from experimental set-up. At one instance of time, the pump remained connected to one particular PV array configuration and different pressure heads were simulated and other parameters recorded. The backpressure valve controlled the pumping heads of 2, 3, 4, and 5 bar and constant head was maintained by continuously varying valve control element position. For each PV array configuration and total head combination, pump was tested during sunny days (from December 1, 2017 to March 15, 2018). The solar radiation variation on monthly and daily basis is shown in fig.1. Measurements for each set of experiments were recorded through data logger for different parameters namely: hourly flow rate Q [Lph], voltage, [V] and current, [A] instantaneous solar radiation intensity, G. Extensive data analysis was done to investigate performance parameters of the SPVWPS. The analysis for the solar energy incident on PV array, DC electrical power input to the pump, hydraulic power output from the pump, the pump and total efficiency of the SPVWP are calculated using the equations given below. All these quantities were calculated for ideal 7-8 hours of pumping operations using following relations:

– solar energy incident on PV array, E_G:

$$E_G = A_{PV} \int_{8h} (G)\,\mathrm{d}t \quad \text{where } G\ [\mathrm{Wm}^{-2}] \text{ is incident solar iradiance} \tag{1}$$

– electrical power input, E_e, to the pump:

$$E_e = \int_{8h} (VI)\,\mathrm{d}t \tag{2}$$

– hydraulic power output from the pump, E_h:

$$E_h = \rho g H \int_{8h} (Q)\mathrm{d}t \quad \text{where } Q\ [\mathrm{Lph}] \text{ is volume flow rate of water} \tag{3}$$

– pump efficiency, η_p:

$$\eta_p \frac{E_h}{E_e} \tag{4}$$

– system total efficiency, η_{sys}:

$$\eta_{sys} = \frac{E_h}{E_G} \tag{5}$$

Results obtained from experimentation carried out on SPVWPS at four different heads and powered by six different PV configurations are discussed in this section. Various comparative studies have been presented to select optimal PV configurations to supply power to the pump operating at different heads. Studies are also carried out on the daily variation of pump and system total efficiency and effect of operating head on the PV configuration performance.

Daily pumped water quantity and its variation fordifferent PV configurations at different heads

The comparative study on the performance of the SPVWPS for daily pumped water at four different operating pressure heads (2 bar, 3 bar, 4 bar, and 5 bar) and powered by different PV configurations have been done. The minimum and maximum average pumped water quantity by the SPVWPS is 5487 L per day and 47535 L per day, respectively at the head of 2 bar and 5 bar, respectively, from different PV configurations. The comparative study of the daily pumped water quantity obtained from all the six PV configurations and variation of discharge over the day at 2 bar, 3 bar, 4 bar, and 5 bar is given in fig. 3.

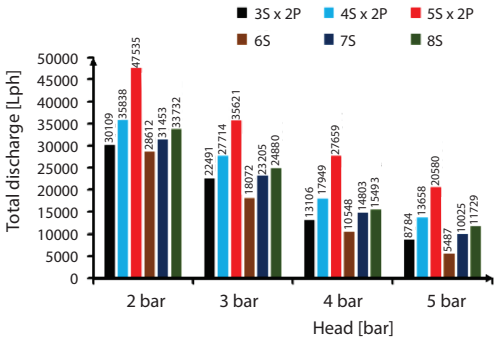

Figure 3. Total pumped water quantity per day with different PV configurations

The SPVWPS delivered a minimum average water quantity per day for the PVC1 and PVC4 configurations (each consisting of 6 PV modules) followed by PVC5 module configuration (7 PV modules) at all four heads. For PVC3 configuration consisting of 10 PV modules, pumping system delivered maximum average discharge at all heads. After PVC3, for PVC2 and PVC6 configurations, SPVWPS pumped maximum discharge in a day at all operating heads. The reason for the low discharge by the PVC1 and PVC4 configurations is that they consist of minimum number of PV modules and hence they provided minimum PV electrical power to operate the CP. However, for PVC1 configuration, discharge is more than the PVC4 and increased by 5.23%, 24.75%, 24.25%, and 60.1% at 2 bar, 3 bar, 4 bar, and 5 bar, respectively. The SPVWPS shown similar performance characteristics for PVC2 and PVC6 configurations where pump output was increased for PVC2 by 6.24%, 11.40%, 15.85%, and 16.44% at 2 bar, 3 bar, 4 bar, and 5 bar, respectively. For a two different configuration consisting of same number of PV module, S×P arrangement supplied more water than the all modules connected in series. This could be attributed to the fact that series arrangement of PV panels provide lower current ratings which is directly proportional to the solar intensity. In series configuration, PV array generally does not utilize the increase in the solar intensity over the day period. For PVC3 configuration SPVWPS pumped maximum water quantity which is significantly high as compared to the other PV configurations. This due to the fact that current rating and total panel area is very high for the arrangement.

Figure 3 clearly depicts that for all PV configurations, total discharge from the pumping system decreases with increase of head. The information shown in fig. 3 can also be used to select optimal PV array configuration. At 2 bar, 3 bar, 4 bar, and 5 bar head PVC3 configuration supplies 32.3 %, 28.5%, 54.09%, and 50.7% more water than the PVC2 configuration, respectively, however, increase in the cost of the PVC3 is 25% as compared to the cost of the PVC2.

This analysis can be quite useful to decide whether PV configuration selection is aimed at increase in discharge or saving in cost of the pumping system. However, selection of optimum PV configuration considering seasonal variations, radiations and effect of temperature will be carried out in future studies.

Variation of discharge rate with time over a day

The variation of discharge provided by all the six PV configurations at different operating heads (2 bar, 3 bar, 4 bar, and 5 bar) under study is shown in fig. 4. The trend of variation of discharge of all the PV configuration is similar. For all PV configurations and head, discharge increases significantly during early in the morning, variation rate is minimum or negligible (almost constant discharge) in the mid hours of the day and further decreases drastically in the later part of the day. Discharge increases till 10.30 a. m. remains constant (or low variation in discharge) till 2.30 p. m. and then decrease till the pumping system stops. For all four heads minimum discharge rate is provided by PVC4 and maximum discharge rate by PVC3. Minimum and maximum discharge of water per day by these two configurations at all heads are shown in fig. 3 could be attributed to these discharge rate variations.

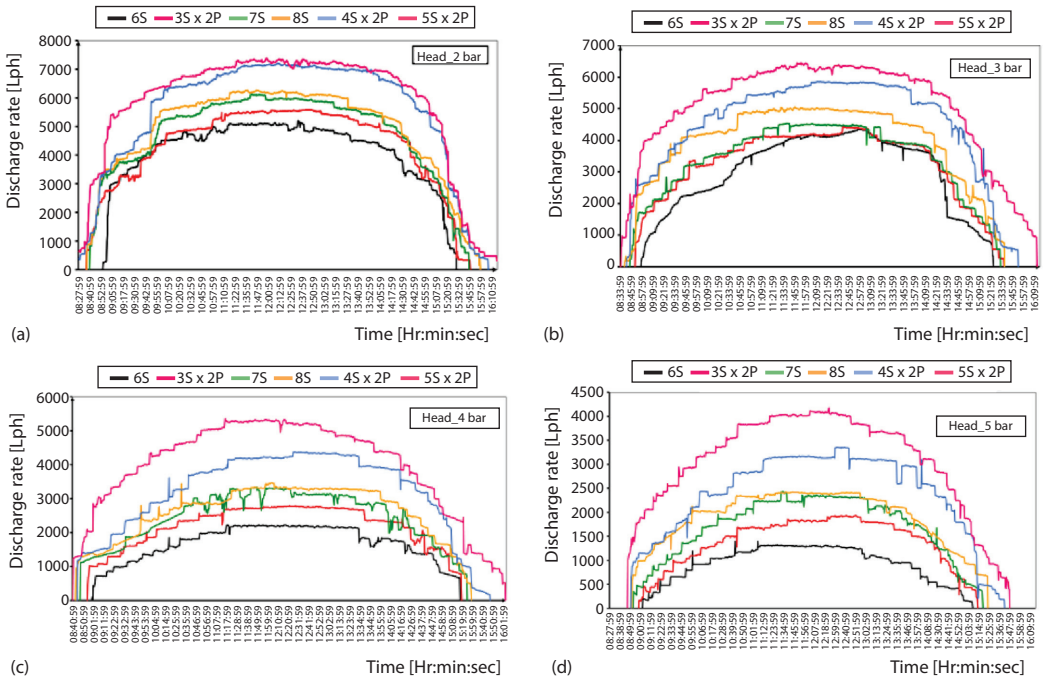

Figure 4. Variation of discharge rate over the day for different PV configurations and head

Relationship between discharge and radiation threshold

Radiation threshold is defined as the intensity or level of radiation at which solar pumping system starts its pumping operation at desired head [31]. The threshold radiation of a PV pumping system depends on the characteristics of the system components. Furthermore, after starting the pump, its water pumping rate depends upon the intensity of the radiation. Table 3 and fig. 5 show value of radiation threshold and its variation for six PV configurations and four heads. It can be shown that for particular PV configuration, radiation threshold increas-

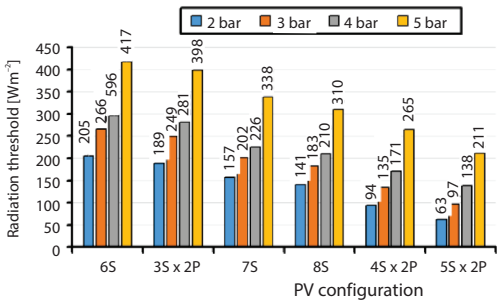

Figure 5. Radiation threshold for different PV configurations and head

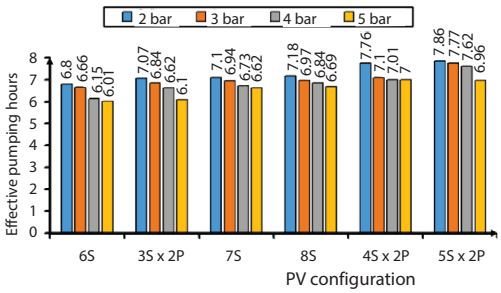

Figure 6. Effective pumping hours for different PV configurations and heads

Table 3. The performance of the SPVWPS for different PV configurations and heads

PV configuration name and arrangement	Head	Actual starting time (head achievement time), STT	Actual pump stopping time (due to non-achievement of head), SPT	Effective pumping hours (SPT-STT) (hours)	Radiation threshold, $G_{thresold}$ [Wm^{-2}]	Total quantity of pumped water [L per day]
PVC1 (3S×2P)	2 bar	8.36 a. m.	3.43 p. m.	7.07	189	30109
	3 bar	8.50 a. m.	3.34 p. m.	6.84	249	22491
	4 bar	8.55 a. m.	3.17 p. m.	6.62	281	13106
	5 bar	9.00 a. m.	3.10 p. m.	6.1	398	8784
PVC2 (4S×2P)	2 bar	8.27 a. m.	4.03 p. m.	7.76	94	35838
	3 bar	8.40 a. m.	3.50 p. m.	7.1	135	27714
	4 bar	8.45 a. m.	3.46 p. m.	7.01	171	17949
	5 bar	8.51 a. m.	3.40 p. m.	7.0	265	13658
PVC3 (5S×2P)	2 bar	8.27 a. m.	4.13 p. m.	7.86	63	47535
	3 bar	8.33 a. m.	4.10 p. m.	7.77	97	35621
	4 bar	8.40 a. m.	4.02 p. m.	7.62	138	27659
	5 bar	8.47 a. m.	3.45 p. m.	6.98	211	20580
PVC4 (6S)	2 bar	8.55 a. m.	3.37 p. m.	6.8	205	28612
	3 bar	8.56 a. m.	3.22 p. m.	6.66	266	18072
	4 bar	9.00 a. m.	3.15 p. m.	6.15	296	10548
	5 bar	9.04 a. m.	3.05 p. m.	6.01	417	5487
PVC5 (7S)	2 bar	8.40 a. m.	3.42 p. m.	7.1	157	31453
	3 bar	8.44 a. m.	3.30 p. m.	6.94	202	23205
	4 bar	8.48 a. m.	3.21 p. m.	6.73	226	14803
	5 bar	8.54 a. m.	3.16 p. m.	6.62	338	10025
PVC6 (8S)	2 bar	8.37 a. m.	3.55 p. m.	7.18	141	33732
	3 bar	8.38 a. m.	3.35 p. m.	6.97	183	24880
	4 bar	8.43 a. m.	3.27 p. m.	6.84	210	15493
	5 bar	8.52 a. m.	3.21 p. m.	6.69	310	11729

es with increase of pumping head. Furthermore, radiation threshold deceases with increase of PV configuration power rating. Moreover for same PV power rating, modules arranged in S×P configuration require less radiation threshold as compared to all the modules arranged in series combinations. In addition, low radiation threshold resulted pumping system to start pumping water at desired head early in the morning. This increased the effective pumping hour, fig. 6, which in turn result more daily discharge from the system for PV configuration.

Pump and pumping system total efficiency

The economy of SPVWPS depends upon how the system components utilize input power to convert it into pumping power. Pump is heart of any SPVWPS, and its efficiency depends upon how it utilizes the input PV electrical energy to increase the hydraulic energy of the water to obtain desired discharge and pumping head. Similarly, the total pumping system efficiency depends upon the effective utilization of the solar radiation energy to obtain desired discharge and pumping head. Hence, pump and total system efficiency evaluation plays a vital role in the selection of most cost-effective PV configuration power the SPVWPS to get desired discharge at different pumping heads. This section evaluates the variations of pump and pumping system total efficiency with respect to different PV configurations at different head. The family of curves are shown in figs. 7 and 8. Using the eqs. (4) and (5), respectively, the pump and total efficiency were calculated.

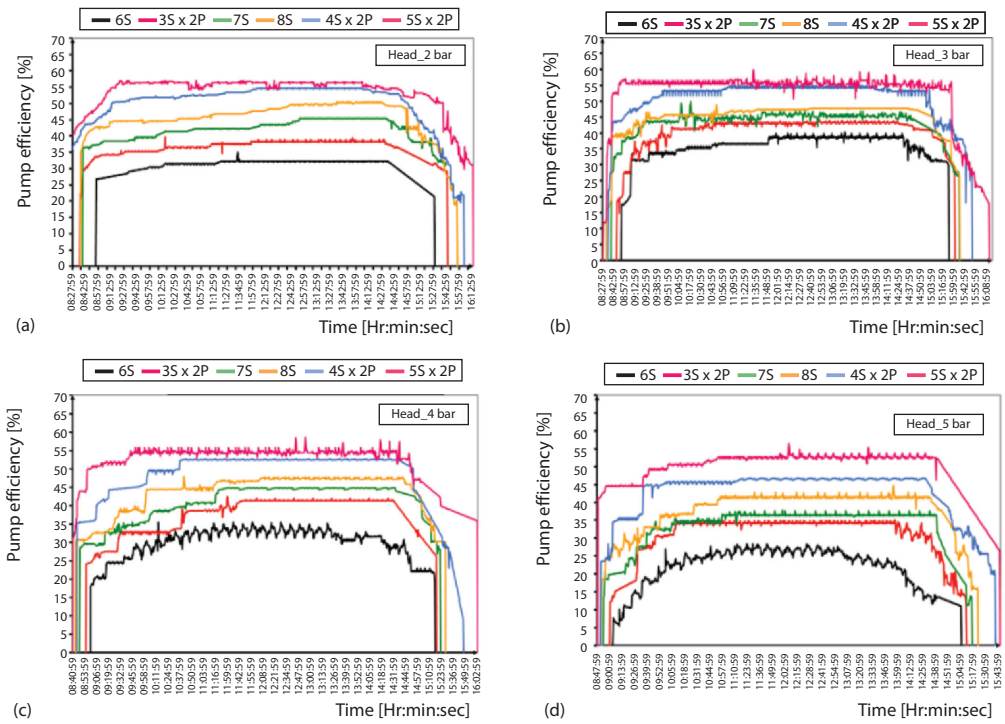

Figure 7. Pump efficiency variation for different heads at different configurations

Figures 7(a)-7(d) show the variation of pump effciency for all six PV configurations at four different heads under study. The pump effciency variation trends are similar for all the PV configurations at all heads. The pump efficiency increases rapidly in the early morning hours (till 9.00-9.30 a. m.), remains constant (5-10% variations) for long hours in the afternoon (2.30-2.30 p.m.) and then decreases rapidly till the pump stops pumping water at desired head, as shown in fig. 7. At all pumping heads pump showed highest efficiency for PVC3 followed by PVC2. At lower heads 2 and 3 bar, pump efficiency and its variation is almost same for both PVC2 and PVC3 as compared to the other configurations. This is because power input by both configurations at these two heads can reach operational point of the pump. The variations

shown in pump efficiency is significant for all configurations at 4 and 5 bar heads. Moreover, for the same power rating of the configurations (PVC1 and PVC2 both 1200 W_p and PVC2, PVC4 both 1600 W_p) pump powered by modules connected in series and parallel arrangement showed higher efficiency than those connected in series combinations.

The total system efficiency of all the six configurations (PVC1, PVC2, PVC3, PVC4, PVC5, and PVC6) at 2 bar, 3 bar, 4 bar, and 5 bar heads are shown in figs. 8(a)-8(d). The trends of total efficiency variation for all PV configurations at all heads are like that of pump efficiency. At all heads PVC3 powered SPVWPS showed highest total efficiency, though this efficiency decreased with increase of pumping head. This is because the SPVWPS under study used the CP which is more suitable for high discharge and medium head pumping requirements.

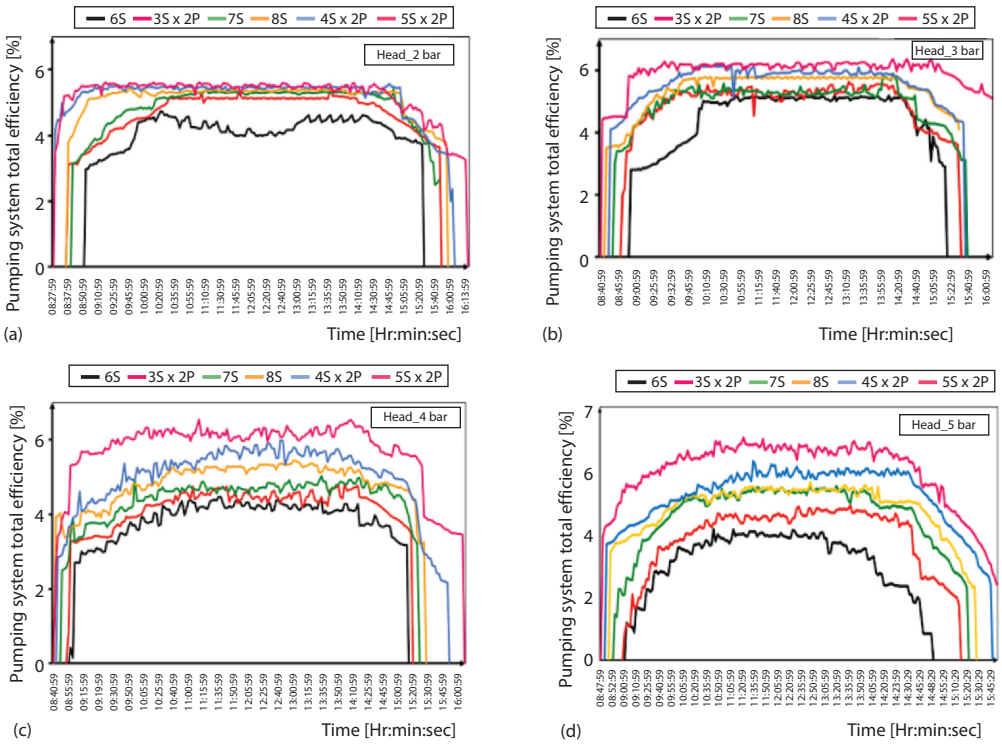

Figure 8. Pumping system total efficiency variation for different heads at different configurations

Conclusions

In this study, performance analysis of SPVWPS using solar PV operated submersible DC CP (model SQF 5A-7, make Grundfos) has been carried out. The performance of the pumping system has been analyzed in terms of water discharge per day, effective pumping hours, radiation threshold and pump and system total efficiency. The SPVWPS was tested extensively for six different PV configurations (PVC1, PVC2, PVC3, PVC4, PVC5, and PVC6) and at 2 bar, 3 bar, 4 bar, and 5 bar heads under the outdoor conditions of VNIT Nagpur and comparative studies for aforementioned parameters have been done. Through the analysis of different performance parameters following conclusions can be drawn:

- The PVC2 and PVC3 emerge best PV configurations to power SPVWPS under study. Though PVC3 provided maximum discharge at all heads, system average total efficiency is almost same for both the configurations.
- Selection of particular array configuration is done based on whether maximum discharge or optimum system cost is the requirement. At 2 bar, 3 bar, 4 bar, and 5 bar head, PVC3 configuration supplies 32.3%, 28.5%, 54.09%, and 50.7% more water than the PVC2 configuration, respectively, however, increase in the cost of the PVC3 is 25% as compared to the cost of the PVC2. Hence for more discharge PVC3 is suitable configuration whereas from optimum system cost point of view PVC2 is best option.
- For two different array configurations consisting of same number of PV module (*i. e*. same power rating), S×P arrangement supplied more water than the all modules connected in series. This could be attributed to the fact that series arrangement of PV panels provides lower current rating which is directly proportional to the solar intensity. In series configuration, PV array generally does not utilize the increase in the solar intensity over the day period.
- Low value of radiation threshold helps PVPS to start pumping water early in the morning which in turn increases daily effective pumping hours and results in more discharge from the system. Moreover, for same PV power input from configuration, effective pumping hours have been increased for modules arranged in S×P as compared to all the modules arranged in series combinations. For example, at 2 bar head and 600 W_p input, effective pumping head for PVC1 (3S×2P) is 7.07 hrs whereas for PVC4 (6S) is 6.8 hours. This could be attributed to low value of radiation threshold for PVC1.

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