Performance analysis of photovoltaic based submersible water pump

Shiv Lal, Pawan Kumar, Rajeev Rajora
Department of Mechanical Engineering, Rajasthan Technical University Kota, India
Email:shivlal1@gmail.com

Abstract:
The performance of a photovoltaic (PV) array based water pumping system situated at Kota Rajasthan (25.18 N and 75.83 E), India has been studied. A 2hp DC motor with 2200W (10 panels of each 225W) have been used for discharge 30 m water head. The maximum discharge logged 163litre/minute between 11AM to 2PM at PV power output between 75 to 85W/m^{2}and the system is operating approximately 8 hours in the of November of the winter season. The full day discharge has found 70995litre and it is more than the average discharge given by the manufacturer at 50m depth. It is revealed that PV array based water pumping system is suitable and feasible option for off-grid and drip irrigation system like the interior area of Kota, where clear sky days are more than 250 in a year.

Keyword: PV system, submersible pump, energy conservation solar insolation etc.

Nomenclature:

P_i	Input power in W
I_s	Solar radiation in W/m^2
A_c	Effective module cell area in m^2
P_o	Photovoltaic array output power in W
V	D.C. output voltage in Voltage (V)
I	D.C. output operating current in A
P_h	Hydraulic power output of the pump in W
ρ	Water density in kg/m^3
g	Specific gravity in m/s^2
Q	Water discharge m^3/s
H	Total pumping head in m
E_a	Array efficiency
E_s	Subsystem efficiency
E_0	Overall efficiency
MNRE	Ministry on new and renewable energy
e.m.f.	Electromagnetic field
DC	Direct current
GOI	Government of India

1. Introduction:

The Indian electricity generating capacity (installed capacity) including both the shares of central and state sectors is 210951.72MW in the year of 2012. The Figure shows the rational production of electricity according to energy resources as 57.3% coal, 8.96% gas, 0.57% DSL, 2.27% nuclear, 18.65% hydro, and 12.26% renewable sources [http://www.cea.nic.in/]. And the energy consumption by industry 23%, agriculture pumping 18%, residential appliances 18% (among which fan is 6%, television are 3% and the refrigerator is 3%) residential lighting 13% and services 12% and small amount is consumed by transportation like Railway. [Rue et al. 2009]

The conventional energy resources mainly are coal, oil and gas. But hydro and renewable energy sources play an important role in developing countries like India where solar energy available abundantly and sufficiently. The energy is divided into two categories as: commercial and non-commercial. The most important commercial energy is electricity others are petroleum products and coal. The commercial energy form depends on industrial, agricultural, transport and commercial development in the modern world. The energy which is not available in the commercial market is called non-commercial energy e.g. Firewood, cattle dung, agricultural waste, solar energy, animal power for transport and wind energy. The non-commercial energy which can be harnessed without release of harmful pollutants called renewable energy for e.g. solar power, wind power, geothermal power, tidal power, and hydroelectric power etc.

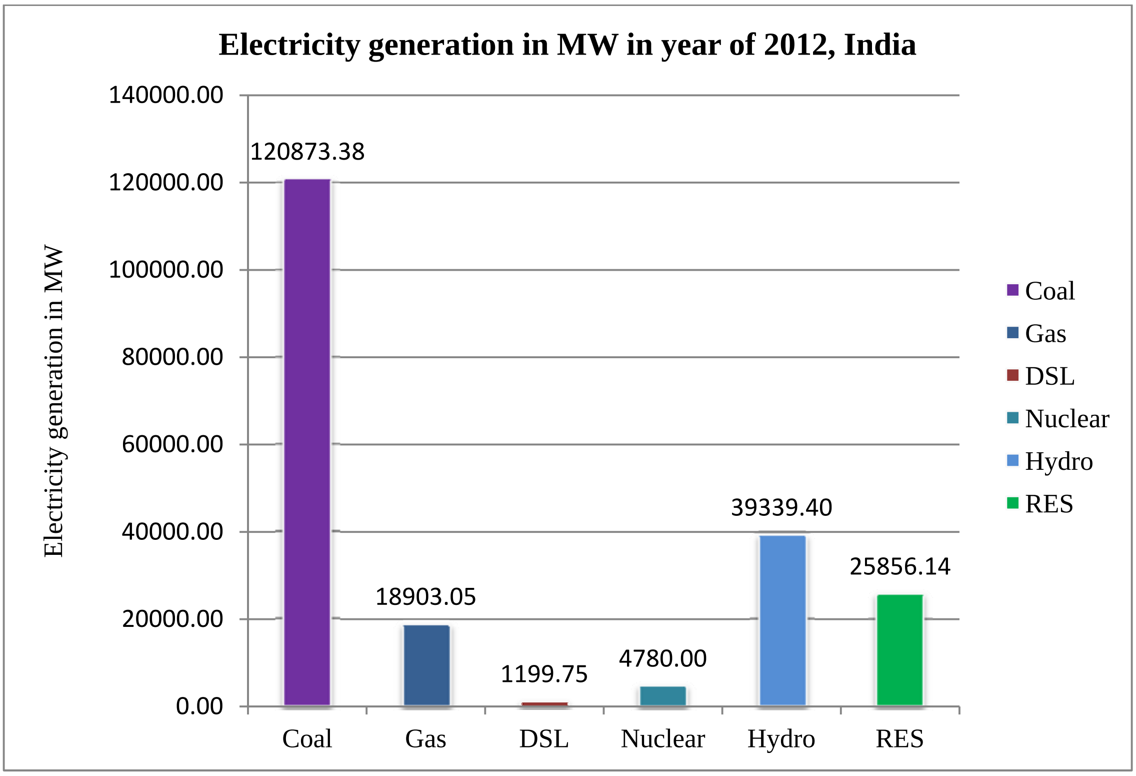

Figure 1: Installed electricity generation capacity in the year of 2012 in India [22]

The benefits of renewable energy systems were realized in an international renewable energy conference held in Bonn, June 2004 as a follow up to the world summit 2001 on sustainable development in Johannesburg, where the political declaration agreed by 154 government representatives. The major factors motivating the use of renewable energy are economic reason, energy security and climatic change mitigation. Other factors included equity and development, improved health, overcoming peak oil price fluctuations, provision of clean water and common belief that “there will be no need for war over solar energy” [Philibert, 2004].

The agricultural consumption is less but it is necessary to supply electricity in peak load time also because the production of agricultural products (food) is a necessary thing for a human being. The farmers are placed everywhere in the world at each point on earth. The electricity available or not, the vegetation is there. To grow the product where the grid energy doesn’t reach in the hands the PV system plays an important role. Another important reason of using PV based pumping systems is: conventional electricity not supplied for sufficient time (6-8 hour supplied to farmers in Rajasthan India), the cost of conventional energy, government subsidy in solar pumping systems and it is difficult to extend the electric grid to every location where it is needed for every farmer. Therefore the factors affect to lead down the use of diesel engine [Akela et al. 2007]. The cost of conventional fuel increasing day by day and the operating cost of a diesel engine will be increasing. Due to the high fuel cost, operating the PV system above 7.2 kW is feasible and having less operating cost than a diesel engine. The decentralized system is feasible where the population is living at a small bunch in far the distance [Aligah, 2011]. Many countries are adopting the decentralized grid system to supply the electricity in rural areas [Hiremat et al. 2007].

Most cost effective solution is the photovoltaic system based water pumping station and it can be used in water pumping for the low or high head. The PV system is basically working on the principle where solar radiation falling on the silicon based P-n Junction and the number of free of electrons moving and generating e.m.f. The 1.5 volt e.m.f. is generated by one cell and many cells attached in series and to develop combined effectively. The total power required by the pump will decide the capacity of the PV system.

The type of the pump having an important role in the efficiency of the system where Fiaschi et al. [2005] studied the modular centrifugal pump with variable speed for improving effectiveness of solar pumping systems. They used 30 m^2 PV systems and 46 stage commercial submersible pumps in 100 m depth well and found the payback time was very less as 0.5 to 2.5 years and sale price was 1.1- 0.6 Moe/m^3. The AC motors are not suitable for PV based water pumping system because it required inverters and batteries which increase cost and maintenance and it is less efficient. The most efficient motor system is a permanent magnet DC motor it replaced the carbon brushes. If a brushed DC motor is used then the equipment will need to be pulled up from the well to replace the brushes in approximately every two years. Many researchers have emphasised their study of the steady state performance of PV water pumping system in which centrifugal pump has been driven by separately excited DC motor (Appelbaum and Bany, 1979) or by series shunt motor (Hamid et al. 1996) and brushless permanent magnet motor (Firatoglu and Yesilata, 2004) and induction motor (Daud and Mahmoud, 2005).

A large number of papers on sizing [Odeh et al. 2006], matching [Salas et al. 2006] and optimizing [Kaldellis et al. 2009] have been published during last two decades. Hamza and Taha [1995] analysed the submersible PV solar pumping systems under the condition of Sudan (Average solar radiation is 6kWh/m^2/day). Three SP4-8 Grundfos submersible pumps used for study and these were run by M-51 and M-53 PV systems and found 10-25% less efficient than the manufacturer claims. It is necessary to taste every system on the field and it is universal truth the actual/field performance found less than the theoretical or the manufacturer claim performance which depends on ideal condition. A time dependent model of a complex PV water pumping system has proposed by Badescu [2003] for PV array and storage tank operation. It is found that the system operation improves by using water storage tank and the fraction of the power which supplied by the battery have been constant during the day, month and year. The fraction of the solar energy collected in water tank is higher in cloudy as compared to the clear sky and it is also higher in winter as compared to the summer season.

Odeh et al. [2006] studied on the economic viability of a photovoltaic water pumping systems, it compared with the diesel engine pumping system and found it is a viable option for off-grid water pumping.

Mokeddem et al. [2011] analysed the performance of a direct coupled PV water pumping system which 1.5kW PV array, DC motor and centrifugal pump. It is revealed that the motor-pump system did not exceed 30%, it means direct coupled systems are suitable for low head irrigation in the remote area. Benghanem et al. [2013] studied the performance of the helical pump (SQF2.5-2) used in a deep well and run with PV systems in Madinah, Saudi Arabia. It is found that 8Sx3P and 6Sx4P are suitable for delivering maximum average volume of water needed (22m^3/day).

The paper presents the performance analysis of the PV based solar pumping system situated in a farmhouse in Kota city of Rajasthan state, India. Our study depends on the data collection of a PV cell, Submersible pump and solar radiation availability in the Kota city of Rajasthan state in India for a particular day on November 2012.

2. Photovoltaic based water pumping system:

The water pumping system is used to pump the water at particular head. The pump can be operated by mechanical or electrical motor. The mechanical pump is classified into two groups as: centrifugal and reciprocating based on working principle. The centrifugal pump or axial flow pump is used in submersible pumping systems. The PV system used to generate electricity and it supplied to the pump and the system will run to lift the water.

The PV based water pumping system shown in Figure 2 having following parts: Solar PV panel, Water pump (One of the following motor- Pump set compatible with the photovoltaic array, Surface mounted centrifugal pump set, Submersible pump set, Floating pump set, Any other type of motor-pump set, after approval from MNRE.) and Pipes.

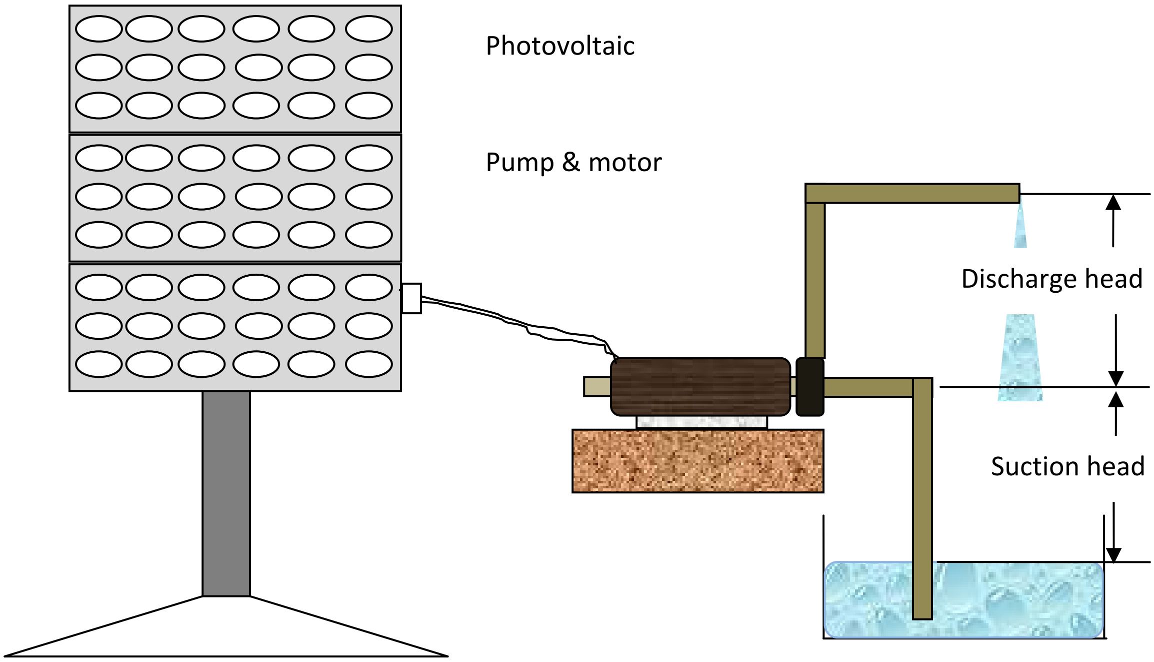

Figure 2: SPV based water pumping system

The basic principle behind solar water pumping is that the radiation energy of the sun is converted into electric energy with the help of photovoltaic cell and this electric energy are used to run the water pump to lift the water from ground level or deep well. In this phenomenon the solar energy is also stored in batteries as chemical energy for the use of system in night time when solar radiation is not present. The efficiency of solar water pump is depending upon the intensity of the solar radiation. Therefore many advantages of the system occur at a point to approve its uses in rural areas as: No fuel cost - as it uses available free sunlight, No electricity required, Long operating life, Highly reliable and durable, Easy to operate and maintain.

2.1 Utility:

A system with 1800 watt PV array capacity and 2 HP pump can give a water discharge of 1.4 lakh litres per day from a depth of 6 to 7 meters. This quantity of water is considered adequate for irrigating about 5-8 acres of land holding for several crops.

2.2 Approximate Cost:

Total cost of the system	- Rs. 4,50,000/-
GOI subsidy through MNRE	- Rs. 1,80,000/-

2.3 Classification:

Solar water pumps may be classified into three types according to their application;

1. Submersible pumps: They draw water from deep wells.
2. Surface pumps: They draw water from shallow wells, spring, ponds, river or tanks,
3. Floating water pumps: They draw water from reservoirs with adjusting heights ability.

The solar water pumps also classified according to discharge head and output, power required, and types of PV panels used {Solar cells could be classified into three categories according to the type of crystals: mono-crystalline (17% efficiency), polycrystalline (15% efficiency), and amorphous (7%efficiency)}.

2.4 Operating Parameters:

The main operating parameters are intensity of solar radiation falls on the PV panel, output power and discharge head. Electricity generated by PV panel is directly depends on the intensity of solar radiation and this DC output can be directly used to run the induction motor based DC submersible pump in my study.

2.5 Effects of Weather Conditions:

Effect of atmosphere is a great role in the operation of solar water pumps. With a clear sky, the efficiency of solar water pump is maximum or more water discharge. But in cloudy day and rainy season indirect and diffused radiation are available in which efficiency is low and less water discharged.

2.6 Specification:

In this study silicon cell based PV panel is used to operating the system. The efficiency of the system is based on the selection of type of PV panel and the solar radiation availability. A 50 m head SPV based pump working in a farmhouse of Mr. Jasvindar Singh, situated at Thekda, Ladpura Kota, Rajasthan. The system specification and cost of the systems according to the discharge head and quantity is shown in table 1 and 2 as below.

Table 1: The specification of the system is given in the table as below

S. No.	Specification	Remark
1	Motor	2 hp/2200 W
2	PV Pannel power	225 W
3	No. of pannels	10
4	Place	Jasvinder Singh Farm house, Thekda, Ladpura Kota.
5	Yojna	RKVY/JLNNSM 2011-12
6	Date of Installation	8-Apr-12
7	Subsidised by	RHDS, UdyanVibhag, Rajasthan
8	Manufacturer	Jain irrigation system ltd.

Table 2: System cost according to head and discharge provided by manufacturer [24]

S.No.	Head	Cost / discharge of 2200 W	Cost/discharge of 3000W
1	20 m	399300 Rs. 119000 lt.	468300 Rs. 163000 lt.
2	50 m	405000 Rs. 50000 lt.	481800Rs. 80000 lt.
3	75 m	411300 Rs. 28000 lt.	485100 Rs. 40000 lt.

The actual view of SPV based water pump is shown in Figure 3 and which shows as ten panels are needed for 2200 W and 15 panels are needed for 3000W owing which one panel power is indicated by 225 W.

Figure 3: SPV based water pumping system at the Jasvindar Singh Farmhouse, Kota

3. Mathematical methodology:

The incident solar irradiation power to hydraulic power circuit is shown in Figure 4.

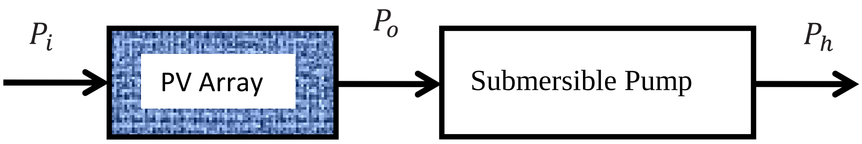

Figure 4: Input output power circuit

Incident solar radiation to the PV array gives the input power (in W) to the system which is given by

$P_i = I_s \times A_c$-------------------------------(1)

The D.C. output power from the photovoltaic array is given by

$P_o = V \times I$--------------------------------(2)

The hydraulic power output of the submersible pump (P_h) is the power required to lift a volume of water over a given head or it is equivalent to total hydraulic power in discharge at particular head from the suction point.

$P_h = \rho \times g \times Q \times H$--------------------(3)

Array efficiency (E_a) is the measure of how efficient the PV array is in converting sunlight to electricity.

$E_a = P_o / P_i$------------------------------(4)

Subsystem efficiency (E_s) is the efficiency of the entire system components (inverter, motor, and pump).

$E_s = P_h / P_o$------------------------------(5)

Overall efficiency (E_0) indicates how efficiently the overall system converts solar radiation into water delivery at a given head;

$E_0 = P_h / P_i$------------------------------(6)

It can be written in the form of efficiencies as:

$E_0 = E_a \times E_s$---------------------------(7)

4. Results and discussions

The daily solar radiation was measured along with the discharge measurement as dated on November 28, 2012 at the Jasvindar Singh farmhouse, Thekda Ladpura Kota situated at latitude 25.18 N and longitude 75.83 E.

Daily solar radiation is shown in graphical Figure5 and found a clear sky day in the winter season. The highest solar radiation 691W/$m^2$is found at mid of day and no more variation in the pattern shows clear sky condition. The sufficient radiation availability shows the sufficient running power availability for the PV array generation which fulfil the energy requirement of submersible pump.

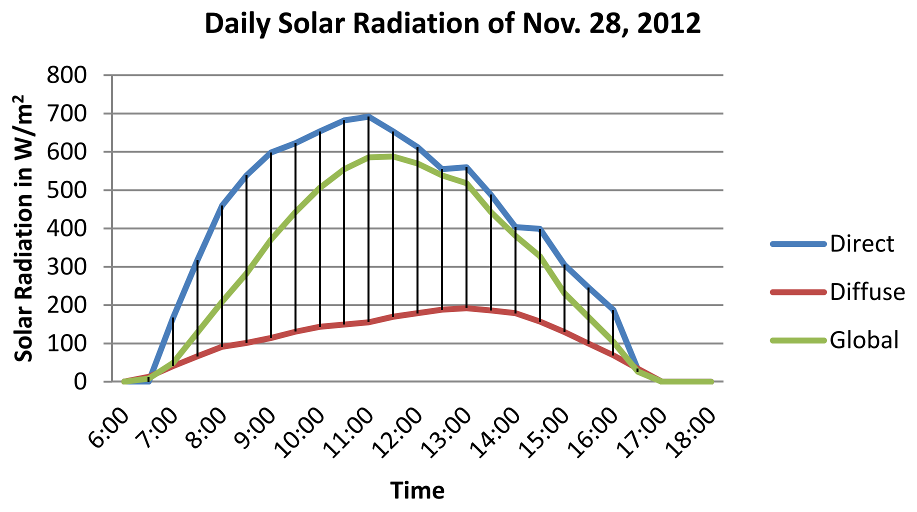

Figure 5: Daily solar radiations on November 28, 2012 in Kota city.

The three dimensional graphical representation Figure 6 of solar radiation and discharge w.r.t. time shows that the discharge has been increased from morning to middle of the day or noon after that discharge will be decreasing. It clearly indicates that the peak solar radiation in winter day will provide sufficient energy for maximum discharge. This discharge is slightly higher than the prescribed 50000 lt. per day because it is fixed at 30 m depth rather than 50 m depth. It means if total head increases mean the discharge being decreases accordingly.

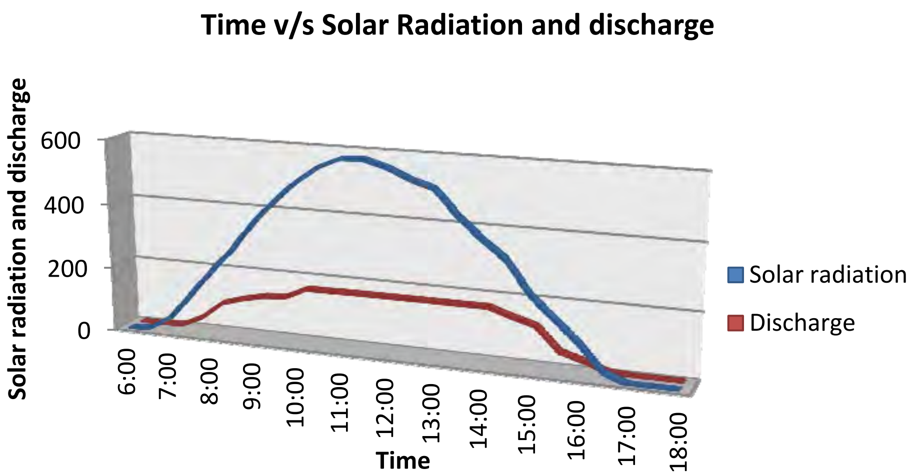

Figure 6: Three dimensional representations of time v/s radiation and discharge

Figure 7 represents time v/s array efficiency, subsystem efficiency & overall efficiency. It shows that all efficiencies will be increased from morning time approximately 8 AM to 9 AM and it is constantly up to 4:30PM after that abruptly decreases it means system is designed for constant efficiency and it is clear that these efficiencies are depends on the solar radiation intensity availability or availability of solar radiation for maximum power output from the PV array.

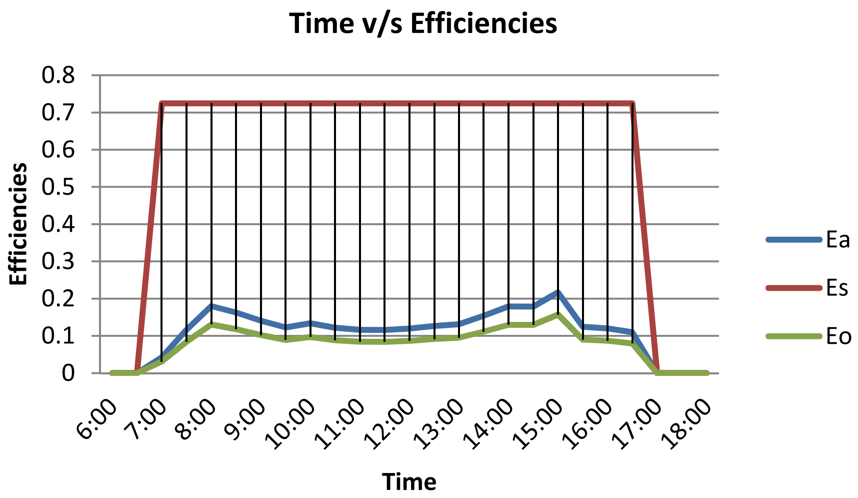

Figure 7 Time v/s efficiencies

The maximum power is generated at noon time at which discharge found maximum it is clearly indicated by Figure 8. The PV power output w.r.t. time is also shown in Figure 8 where solar insolation gradually increases up to noon and after that decreases and power output from PV cell increases and decreases in pattern of solar insolation. The power output is a function of pump discharge.

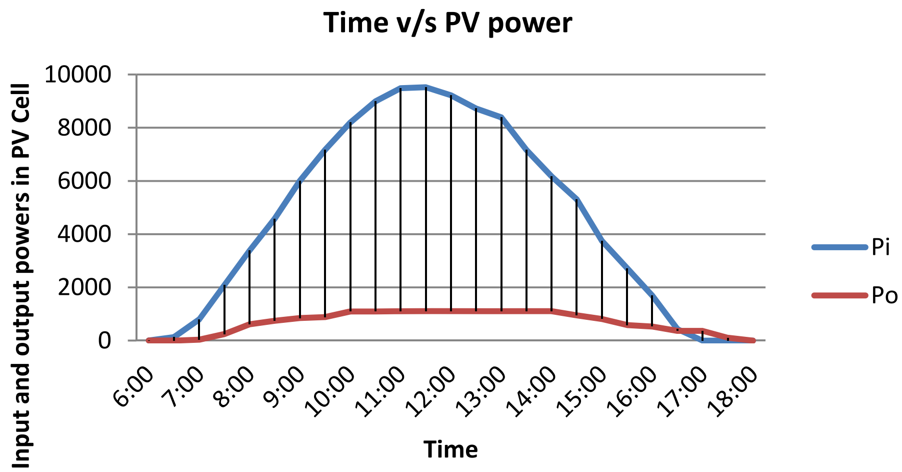

Figure 8 Time v/s power input and output in PV cell

5. Conclusions:

All the variations of radiation, discharge, power and efficiencies with respect to daily times were shown in the last paragraph. The conclusions of this study are found as follows.

1. This system is designed for 50 m head and gives better performance. But the performed system is installed for 30 m water head and it is clear that the discharge of the system is more than the discharge at high head. It stated that the discharge is depending on the water head.
2. The system is economically feasible in interior areas where no electricity or it is an alternate source of electricity.
3. The initial cost is high but if subsidy is provided by government (86% shown by the literature) then it is a best option.
4. It is a good alternate because the demand is in the face of solar radiation availability.
5. Peak load can be reduced by using this technology.

References:

[1] Hamza and A. Z. Taha, "Performance of submersible PV solar pumping systems under conditions in the Sudan", Renewable energy, vol. 6, no. 5-6, p. 491-495, 1995.

[2] Akella, M. Sharma, and R. Saini, "Optimum utilization of renewable energy sources in a remote area", Renewable and Sustainable Energy Reviews. Vol.11 no.5 pp. 894–908, June 2007.

[3] Aligah M Abu, "Design of Photovoltaic Water Pumping System and Compare it with Diesel Powered Pump," Jordan Journal of mechanical and industrial engineering, vol. 5, no. 3, pp. 273–280, 2011.

[4] Daud Abdel-Karim, Mahmoud Marwan M. Solar powered induction motor-driven water pump operating on a desert well, simulation and field tests. Renew Energy, vol. 30, pp. 701–714, 2005.

[5] Fiaschi, R. Graniglia and G. Manfrida, "Improving the effectiveness of solar pumping systems by using modular centrifugal pumps with variable rotational speed", Solar energy, vol. 79, pp. 234-244, 2005

[6] G. Belgacem, "Performance of submersible PV water pumping systems in Tunisia," Energy for Sustainable Development, vol. 16, no. 4, pp. 415–420, Dec. 2012.

[7] Hamidat, B. Benyoucef and T. Hartani, "Small-scale irrigation with photovoltaic pumping system in Sahara regions", Renewable Energy, vol. 28, no. 7, pp. 1081–96, 1996.
Odeh, Y. G. Yohanis, and B. Norton, "Economic viability of photovoltaic water pumping systems," Solar Energy, vol. 80, no. 7, pp. 850–860, Jul. 2006.

[8] Odeh, Y. G. Yohanis, and B. Norton, "Influence of pumping head, insolation and PV array size on PV water pumping system performance," Solar Energy, vol. 80, no. 1, pp. 51–64, Jan. 2006.

[9] J. Appelbaum and J. Bany, "Performance analysis of DC motor—photovoltaic converter system, part I—separately excited motor", Sol Energy, vol. 22, no. 5, pp. 439–45, 1979.

[10] J. K. Kaldellis, G. C. Spyropoulos, K. a. Kavadias, and I. P. Koronaki, "Experimental validation of autonomous PV-based water pumping system optimum sizing," Renewable Energy, vol. 34, no. 4, pp. 1106–1113, Apr. 2009.

[11] J.S. Ramos and H. M. Ramos, "Solar powered pumps to supply water for rural or isolated zones: A case study, Energy for sustainable development", vol. 13, pp. 151-158, 2009.

[12] M. Benghanem, K. O. Daffallah, A.A. Joraid, S. N. Alamri, and A. Jaber, "Performances of solar water pumping system using helical pump for a deep well: A case study for Madinah, Saudi Arabia," Energy Conversion and Management, vol. 65, pp. 50–56, Jan. 2013.

[13] M. Hamid, B. Metwally and W. R. Anis, "Dynamic performance of directly coupled photovoltaic water pumping system using D.C. shunt motor", Energy Convers Management, vol. 37, no.9, pp. 1407–16, 1996.

[14] Mokeddem, A. Midoun, D. Kadri, S. Hiadsi, and I. a. Raja, "Performance of a directly-coupled PV water pumping system," Energy Conversion and Management, vol. 52, no. 10, pp. 3089–3095, Sep. 2011.

[15] P. E. Campana, H. Li, and J. Yan, "Dynamic modelling of a PV pumping system with special consideration on water demand," Applied Energy, Jan. 2013.

[16] Philibert, "Case study 1: concentrating solar power technologies," International Energy Technology Collaboration and Climate Change Mitigation, OECD Environmental Directorate, IEA, Paris 2004.

[17] R. Hiremath, S. Shikha and N. Ravindranath, "Decentralized energy planning, modelling and application", Renewable & sustainable energy review, vol. 11, no5, pp. 729, , 2007.

[18] Rue du Can S. de la, McNeil M., and J. Sathaye, "India Energy Outlook: End Use Demand in India to 2020", LBNL, DOE California USA. ies.lbl.gov/iespubs/india_energy_outlook.pdf

[19] S. Ould-Amrouche, D. Rekioua, and a. Hamidat, "Modelling photovoltaic water pumping systems and evaluation of their CO2 emissions mitigation potential," Applied Energy, vol. 87, no. 11, pp. 3451–3459, Nov. 2010.

[20] V. Badescu, "Time dependent model of a complex PV water pumping system," Renewable Energy, vol. 28, no. 4, pp. 543–560, Apr. 2003.

[21] V. Salas, E. Olías, A. Barrado, A. Lázaro, "Review of the maximum power point tracking algorithms for stand-alone photovoltaic systems", Sol Energy Mater Sol Cells, vol. 90, no. 11, pp. 1555–78, 2006.

[22] www.cea.nic.in/

[23] www.jainirrigation.com

[24] www.wikipedia.com