ISSN 1808-8546 (ONLINE) 1808-3765 (CD-ROM)

CONVERSION OF SOLAR PHOTOVOLTAIC ENERGY INTO HYDRAULIC ENERGY APPLIED TO IRRIGATION SYSTEMS USING A MANUAL SUN TRACKING

VANESSA DE FÁTIMA GRAH PONCIANO[1]; ISAAC DE MATOS PONCIANO[2]; DINARA GRASIELA ALVES[3]; EZEQUIEL SARETTA[4] E RUBENS DUARTE COELHO[5]

[1] Professora Doutora, Instituto Federal de Educação Ciência e Tecnologia Goiano, Av. Oeste, 350, Loteamento Parque União, 76200-000, Iporá, Goiás, Brasil, vanessa.grah@ifgoiano.edu.br.
[2] Professor Doutor, Faculdade de Iporá, Rua Serra Cana Brava, 512, Jd. Novo Horizonte II, 76200-000, Iporá, Goiás, Brasil, ponciano.i.m@gmail.com
[3] Doutora, Departamento de Engenharia, Universidade Federal Rural do Rio de Janeiro, Rod. BR 465, km 7, 23890-000, Seropédica, Rio de Janeiro, dinara_alves@hotmail.com.
[4] Professor Adjunto, Universidade Federal de Santa Maria, Rua Ernesto Barros, 1345, Santo Antônio, 96506-322, Cachoeira do Sul, Rio Grande do Sul, Brasil, ezequiel.saretta@ufsm.br.
5 Professor Titular, Departamento de Engenharia de Biossistemas, Escola Superior de Agricultura Luiz de Queiroz, Av. Pádua Dias, 11, 13418-900, Piracicaba, São Paulo, Brasil, rdcoelho@usp.br.

1 ABSTRACT

Brazil has an unexplored solar energy potential, and only 1.2% of the energy matrix come from photovoltaic energy. Besides, water pumping is an important form of development in rural areas (family farmers) mainly because of the distance from distribution centers. Therefore, this paper aims to evaluate the energy conversion in a water pumping system applied to irrigation, powered by photovoltaic energy, and compare with a static system with a single axis manual three-steps sun tracking system. Two arrays of panels were installed in the field at 22° 42’30” S; 47°38’00” W; 546 m above sea level. One photovoltaic module was static and the other a manual sun tracking device. Each module was connected to an individual water pump to simulate an irrigation system. The results showed that the pumping system with manual tracking device had better performance in the energy conversion from photovoltaic to hydraulic, with increments of 177 MJ m^{-2}, 50.87 more pumping hours, and 66,135 L. However, the conversion energy efficiency from solar energy to water pumping was 4.55% and 4.77% for tracking and static modules, respectively. The manual sun tracking systems used in the photovoltaic module feeding a pumping system to irrigation was a technical alternative to improve the performance of the photovoltaic system.

Keywords: renewable energy, water pumped, pumping time, global efficiency.

GRAH PONCIANO, V. F.; PONCIANO, I. M.; ALVES, D. G.; SARETTA, E.; COELHO, R.D.

CONVERSÃO DA ENERGIA SOLAR FOTOVOLTAICA EM ENERGIA HIDRÁULICA APLICADA A SISTEMAS DE IRRIGAÇÃO UTILIZANDO UM RASTREADOR SOLAR MANUAL

Recebido em 16/05/2020 e aprovado para publicação em 13/07/2020
DOI: http://dx.doi.org/10.15809/irriga.2020v25n3p508-520

2 RESUMO

O Brasil tem um potencial solar energético pouco explorado, apenas 1,2% da matriz energética é proveniente da energia fotovoltaica. Aliado a isso, o bombeamento de água é uma importante forma de desenvolvimento nas áreas rurais (pequenos agricultores) principalmente, devido a distância desses locais aos centros de distribuição de energia elétrica. Este trabalho tem por objetivo avaliar a conversão da energia em um sistema de bombeamento de água aplicada a irrigação, movido por energia fotovoltaica, comparando um sistema estático com um sistema rastreador solar manual com três ângulos de ajuste de eixo único. Dois conjuntos de módulos foram instalados no campo na localização de 22° 42’30” S; 47°38’00” W; 546 m acima do nível do mar. Um módulo permaneceu estático e o outro módulo com um sistema de rastreador solar manual. Cada módulo foi conectado a uma motobomba individual, simulando um sistema de irrigação. Os resultados mostraram que o sistema de bombeamento com o rastreador manual teve melhor desempenho na conversão da energia solar para hidráulica, com um incremento de 177 MJ m^{-2}, 50,87 h a mais no tempo de bombeamento, e 66.135 L. Contudo, a eficiência da conversão da energia solar para o sistema de bombeamento foi de 4,55% e 4,77% para o módulo rastreador e estático, respectivamente. O sistema manual de rastreamento solar utilizado no módulo fotovoltaico, alimentando um sistema de bombeamento para irrigação, foi uma alternativa técnica capaz de melhorar a desempenho do sistema fotovoltaico.

Palavras-chave: energia renovável, água bombeada, tempo de bombeamento, eficiência global.

3 INTRODUCTION

Years after years, the cost of photovoltaic (PV) energy systems has been decreasing, much of impetus for adoption of clean energy technologies is a manifestation of policies driven by concerns of energy security, prevention of local pollution and increasing climate benefits (RIZI; ASHRAFZADEH; RAMEZANI, 2019). This cost reduction allows installing PV generators as a source to rural electrification and water projects (CATON, 2014; AISSOU et al., 2018). Additionally, the activation of water pump by PV energy turns out to be financially viable, helping the dissemination of the technology (FEDRIZZI; SAUER, 2002).

One of the most commons application of PV systems in the development countries is water pumping, which promotes social and economic development (KORDZADEH, 2010), mainly in isolated rural areas to cover human needs (RUBIO-ALIAGA et al., 2019). Such pumping application can be directed to irrigation in rural areas (SONTAKE; KALAMKAR, 2016), especially for family farmers not served by public services. Furthermore, irrigation is a major user of power and during recent decades has progressively required greater amounts of energy (RUBIO-ALIAGA et al., 2019). Besides costs reduction, innovations in renewable energy turns solar PV pumping irrigation a feasible technology to the progress (GAO et al., 2018).

Irrigation system require constant pressure and flow rate in order to uniformly deliver water to plants, so the pump and motor demand constant power. If a PV is used as the energy source, variations on solar radiation through the day may affect operation. As photovoltaic panels generate electricity in DC mode, the simplest way to use solar energy is to direct wire the panels to a DC motor (VERA et al., 2019). In this case, a sufficient level of solar irradiance is needed in order to exceed the motor power (METWALLY; ANIS, 1996; KOLLING et al., 2004; BIONE; VILELA; FRAIDENRAICH,2004). Thus, to a pumping system operating with an established energy demand to start running, there are some possibilities to reduce the problem of critical irradiance level, such as: increase the nominal power of PV modules or use solar trackers to up the irradiance level that reaches the PV modules.

Clouds may reduce daily pumping time as the global radiation on the surface is lower than on the top of the atmosphere (KASTEN, 1965), and therefore this ratio should be considered. Batteries and a charge controller equalize demand and generation, especially in cloudy skies. In complete clear sky, these equipment allow accumulating energy to be use when solar radiation decreases below the critical level. Another possibility to explore solar energy is to install a DC-AC converter after the panels, since AC motors are most popular used for irrigation, enlarging the possibilities to select a pump (AISSOU et al., 2018). Considering all these devices connected along the way, it is clear that the total net energy available to pumping is lower than the global energy that reaches the panels.

The current photovoltaic cells present a low efficiency of transforming solar energy into electricity (DEMAIN; JOURNEÉ; BERTRAND, 2013). Attempts to improve photovoltaic energy generation consist in constantly adjust panels to have sunlight falling perpendicularly throughout the day (KALDELLIS; KAVADIAS; ZAFIRAKIS, 2012). This way, the energy-generating cells obtain a constant maximal power. To do so, a control system is necessary to track the sun and adjust the angles of the generators. A single-axis tracking system adjust only the horizontal angle, and usually the tilt angle is fixed according to the local latitude. The most accurate system is the double-axis, which also moves the panel as the solar declination changes across seasons (AI et al., 2003). A control system may be necessary to track the sun and automatically adjust the angles of the generators.

Previous studies reported increments around 20% in irradiance absorbed on the panels using single-axis tracking system in comparison to a static array (KOLHE; JOSHI; KOTHARI, 2004; CLARK; VICK, 1997). For a double axis, this electricity conversion can be increased in 40% (CHUN-SHENG et al., 2008). The selection criteria for each type of tracking system, as well as automatic or manually operated, depend on many factors, which are based on the increment in productivity of the PV generator. Such as financial resources, availability of technical assistance for constant maintenance and repairs, and available of manpower to movement the PV generators (ALVARENGA, 2006; AI et al., 2003). In terms of automatic tracking systems, many problems happens that do not occur in the manual system, like complicated operation of the control system, higher consumption of energy, higher cost of maintenance, and less reliability (AI et al., 2003).

The global efficiency of a photovoltaic pumping system, i.e. the ratio between total energy used by the pump and total solar energy that arrives on the panels, are considered lower and is not expected to exceed 10% (VERA et al., 2019; TIWARI; KALAMKAR, 2018; KOLLING et al., 2004) even in the solstices and clear sky (MICHELS et al., 2009). Therefore, the purpose of this study was to evaluate a manual sun tracking photovoltaic panel to power an irrigation pump and compare the results with a fixed PV array.

4 MATERIAL AND METHODS

The photovoltaic water pumping system (PVWPS) was installed at the experimental area of Biosystem Engineering Department of Luiz de Queiroz College of Agriculture, São Paulo, Brazil, located in Piracicaba-SP. The site's coordinates are 22° 42' 30''S, 47°38' 00''W, altitude of 546 m above sea level. The experiment was carried out from June to August 2014, period with usually lowest rainfall index in this region.

4.1 Description of the tracking and static systems

Two identical arrays of PV systems were evaluated:

- A static photovoltaic module (SPVM) compound by 10 static photovoltaic generators (without movement), surface tilted with an angle equal to the latitude, north orientated; one pyranometer (Kipp & Zonen Company-SP - lite model) installed on the top of the front set, on the same plane of the modules surface;
- A solar tracking photovoltaic module (TPVM) compound by 10 generators fixed side-by-side, also tilted at the latitude; a single axis allowed the rotation to track sunlight at three angles: 50° east at the beginning of the day until 10 a.m., 0º north from 10 a.m. to 2 p.m, and 50° west until dawn; another pyranometer that moved together with panels.

For more details about the solar tracking manual system and the electric-electronical system of the PV see Grah et al. (2015).

4.2 Water pump system design

As the objective of using a water pumping was to simulate the direct supply of an irrigation system operation powered by photovoltaic energy, a setup was mounted to recirculate water and avoid wasting. This way, a metallic cylinder tank pressurized by a compressor simulated a pressure requirement downstream the pump. A pressure control system (PCS) maintained pressure constant at 220 kPa inside the tank, reading a pressure sensor (MPX 5700DP-Freescale) and triggering two solenoid valves, one between the air compressor and the tank and the other from the tank to atmosphere. As pressures raised or fell down, the control system opened and closed the solenoids to retain pressure.

The PCS worked as follows: the response of the sensor to the pressure variation inside the tank was given in potential difference (mva); this information was sent to the pressure controller which by means of an algorithm converted that information into pressure (error of ±0.5 m). According to the pressure reading inside the tank the controller drives the solenoid valves, so that if the pressure was below the desired pressure, the pressure controller promoted the opening of the solenoid valve that connected the air compressor to the tank, occurring an increase in pressure. If the pressure was higher than desired, the controller opened the solenoid valve that connected the tank to the atmosphere, occurring a relief in pressure inside the tank.

Two pumping systems were simulated, one with the supply from SPVM and the other supplied by TPVM, both system with the same flow and total head in the water centrifugal pump. Electrical connections from panels to the pump motors were done using a charger controller and a battery, and DC-AC converter with the characteristics shown in Table 1.

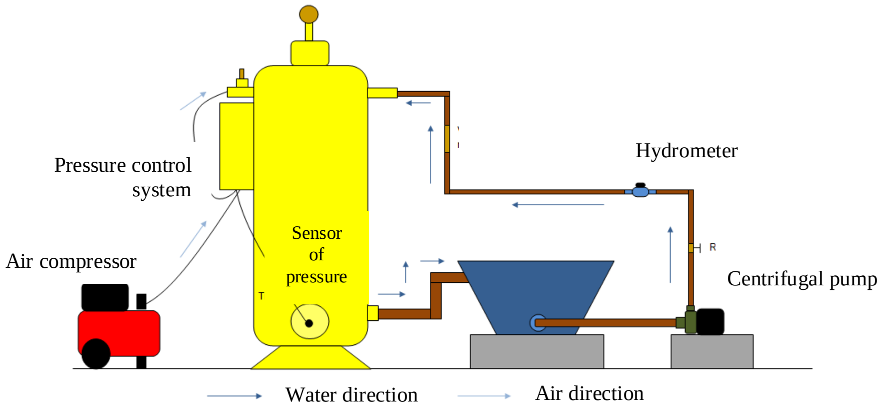
Table 1. Characteristic of selected electrical centrifugal pump (AC motor) and solar components.

	Descriptions	Characteristic
Pump	Type	BCR 2010 (Schneider)
	Power	362 W
	Head	25 m
	Flow	0.6 m³/h
	Efficiency	33%
	Impeller diameter	128 mm
Charger Controller	Type	C40- Xantrex
	Maximum input voltage	125 V
	Maximum motor current	40 A
	Maximum power	2000 W
Converter	Type	Prosine 1000 - Xantrex
	Output voltage (at no load)	120 V
	Output current (peak)	15 A
	Peak efficiency	89%
	Output power	1000 W
PV generator*	Type	KD 140 F- Kyocera
	Power at maximum point	140 W
	Voltage at maximum point	17.7 V
	Current at maximum point	7.91 A
	Cells type	Polycrystalline

*Standard Test Condition= 1000 W/m² irradiance, 25° module temperature, AM 1.5 spectrum

Both centrifugal pumps were powered by AC motors and was directly coupled to the PV system. It was selected for this small power application because of robustness, less maintenance, low-priced and more reliable compared with DC motors (RAGHUWANSHI; KHARE, 2018). Pumps withdrew water from a reservoir and discharged it into the tank (Figure 1), obtaining in this way a simulated irrigation system with constant flow and pressure.

Figure 1. Sketch of the irrigation simulated system shelter, in detail the water centrifugal pumps, pressure control system and air compressor.



Discharge flow from each pump was measured through a hydrometer with pulse counter of 10-L volume resolution. A datalogger totaled pulses and interval between signals, calculating the flow. The datalogger also monitored the pyranometers and voltage on the batteries, in order to automate the moment when the pumping system should be turned on/off.

The criteria for operating the pumps were as follows: to turn on, battery voltage should exceed 26,5 V and radiation in the pyranometer 350 W m^{-2}; to turn off the water centrifugal pump, battery voltage would drop below 23,5 V. The radiation value in the pyranometer was settled taking into account the water pump power, the number and efficiency of the PV module.

For every day that the SPVM and TPVM systems operated, the conversion efficiency was calculated. Pumping hydraulic energy (Eq. 1) divided by Radiation Solar (data from pyranometer sensor) results in the conversion efficiency.

$$E_p = \frac{\gamma H Q}{\eta} T_P \quad (1)$$

Where E_p is the pumping energy (J); γ is the water specific weight (N m^{-3}); H is the total head (m); Q is the flow rate (m^3 s^{-1}); η is the pump efficiency and Tp is the pumping time pumping (s).

In the tests, pumping head was set to 221 kPa (22.5 m), delivering a flow rate of 1.3 m^3. h^{-1} according to the pump curve and confirmed in the hydrometers. Operating at this point, pump efficiency was 22%.

5 RESULTS AND DISCUSSION

For the 34 days of data, 12 were sunny and both systems operated full time. Data form rainy days were not evaluated. The clouds presence was a major factor in the collected data, because the pump was directly coupled in the irrigation system. This means that batteries were used only to maintain the stabilized electric-electronical system. Thereby, in a cloudy day the photovoltaic system turn off when the voltage level dropped below the critical value (23.5 V).

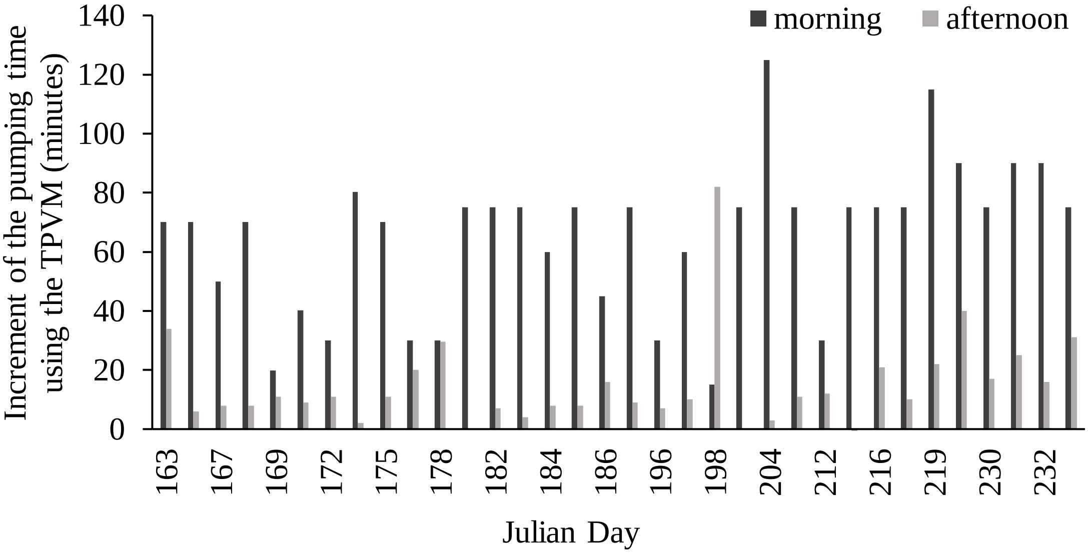
5.1 Increment of the pumping time

In the SPVM, at the beginning of the day, the solar rays were oblique in relation to PV modules, and consequently the tension and current were lower. How the controller deviated the current to the batteries, end the pump was connected into the batteries, there was not enough current to load the batteries and turn on the pump. Thus, the current oscillated until the radiation reach the critical level.

Wherefore, the pumping time in the SPVM was counted from the stabilization of the pumping system, which took 30 to 120 min. Michels et al. (2009), evaluating the performance of a pumping system with a 20 m of head, observed a system stabilization at the beginning of the day, after 60 to 80 min at the start of pumping.

In order to maintaining the stability of the system from the beginning of its operation, the PVWPS was automated to turn on the pump with a critical irradiance of 350 Wm^{-2}. Metwally and Anis (1996) that evaluated a system constituted by a photovoltaic array, DC motor and a centrifugal pumping, also observed a stabilization with a critical irradiance of 350 W m^{-2}. In Figure 2 it is presented the daily increment of pumping time using the manual solar tracking system for 34 days of experiment. At the beginning of the day the pumping time was always higher than at the end of the day.

Figure 2. Daily increment of pumping time using the manual solar tracking system for 34 days of experiment.



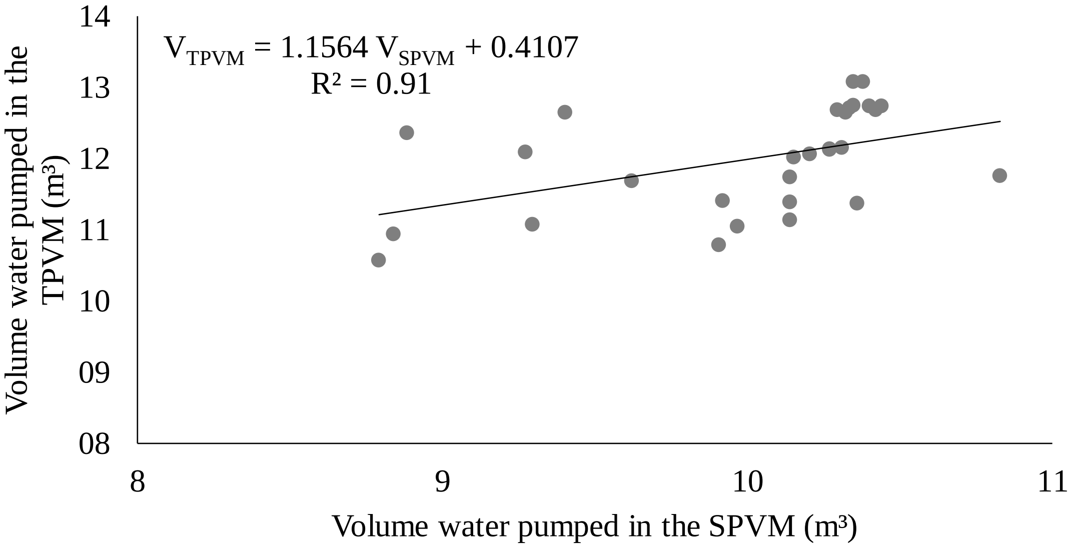
The manual tracking system incremented an average of 95.2 min per day in the pumping time in the period. In the morning, the average increment was 75 min, and in the afternoon, 20.2 min. This difference may be attributed to the use of batteries and the alignment of panels, enabling more radiation to fell on the generators from the early hours, recharging batteries and also starting pumping. In the afternoon, batteries were loaded in both SPVM and TPVM, than a lower increment was observed. Vilela, Fraidenraich, Tiba (2003) claims that tracking systems coupled in PV generator is a way to reduce the dependence of the start pumping time to a critical irradiance, increasing the range of pumping time.

According to Kolling et al. (2004) the total operation hours of a pumping system powered by PV generators depends on the total head as much as solar radiation. Thus, the greater the head, the higher the levels to start a pump, reducing time operations and, consequently the total water volume pumped. Those authors only considered the pump's head as a variable, however, pump's power is the main parameter to calculate operation hours, which depends on both pump's head and flow rate.

5.2 Increment of volume of water pumped

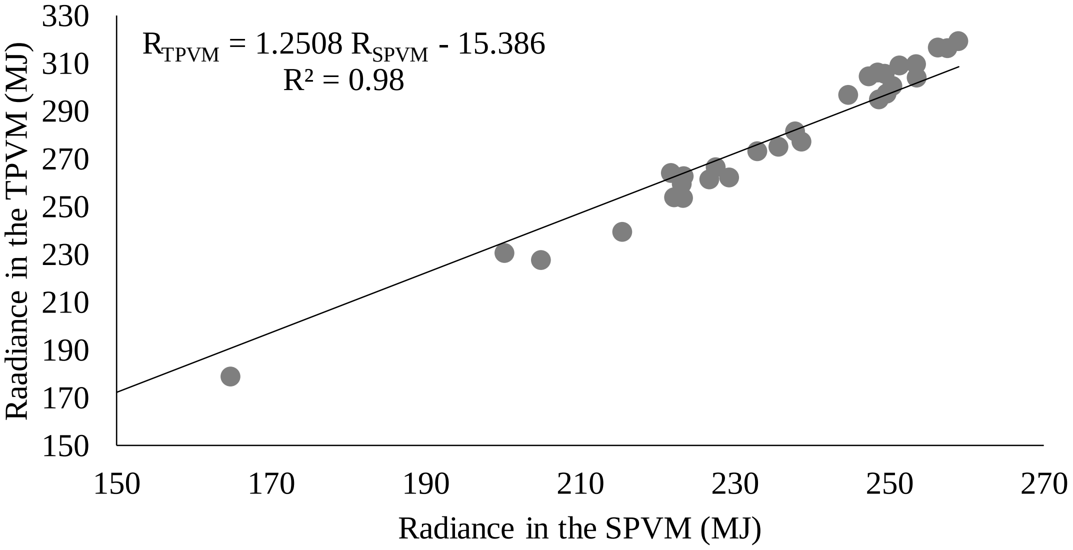
As a result of an increase of pumping time, there was an increase of the total volume pumped (Figure 3). For the entire period, TPVM was able to increment a volume average about 16% (1,945 L day^{-1}), identified by the line slope in the figure. Kolhe et al. (2004) observed that the pumped water was 20% greater in the manual tracking operation than in the fixed tilted PV array. The authors also used a manual tracking that changed orientation of PV panel three times a day, to keep the panels facing the sun.

Figure 3. Relation of volumes of water pumped in both SPVM and TPVM.



Vilela, Fraidenraich, Tiba (2003), claims that the increment of volume of water pumped, for many solar tracking strategies, can exceed the increment of solar radiance. However, Figure 4 shows that solar radiance was increased 25% by TPVM, superior than volume. Maybe, this difference in the increment of solar radiance and volume of water was effected by the batteries.

Figure 4. Daily solar radiance in both SPVM and TPVM systems, comprising10 modules each.

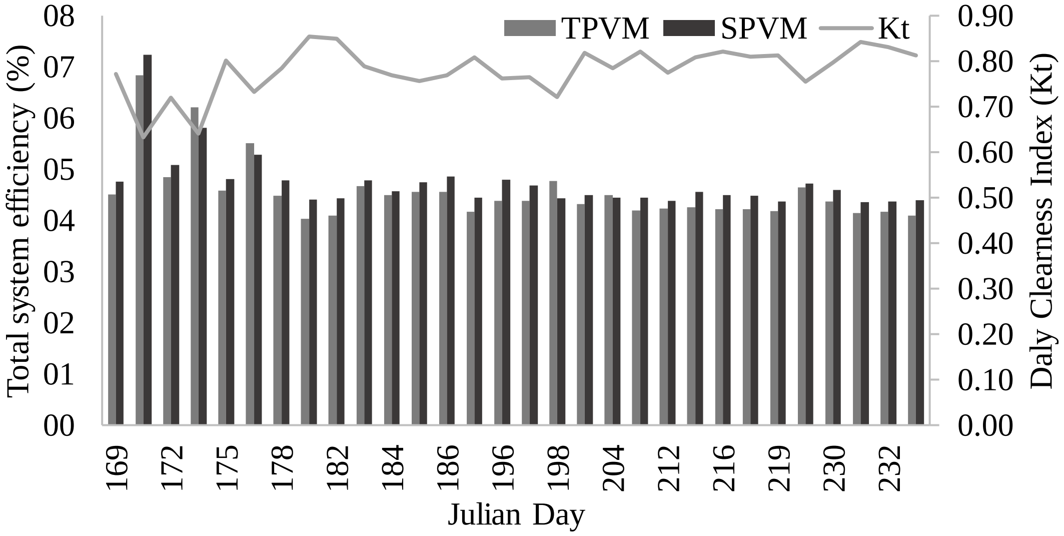


Using batteries is not a negative issue because they supply instant variations on voltage when clouds reduced radiation on panels. Additionally, due to the limitation of pump total head, the energy generated during peak radiation was not utilized by the pumping system which corroborates a greater increase in the solar radiance when compared to the pumping volume and time.

5.3 Global efficiency of the photovoltaic pumping system

The daily efficiency of the systems are plot in Figure 5, with average values of 4.73% for SPVM, and 4.55% for TPVM. The figure also shows the global atmospheric transmittance or clearness index (Kt), (KASTEN, 1965), which is the ratio between the global solar radiation and the radiation at the top of the atmosphere, indicating the percentage of cloud coverage in the sky (SOUZA et. al, 2010).

Figure 5. Total system efficiency to SPVM and TPVM for the 34 days of data.



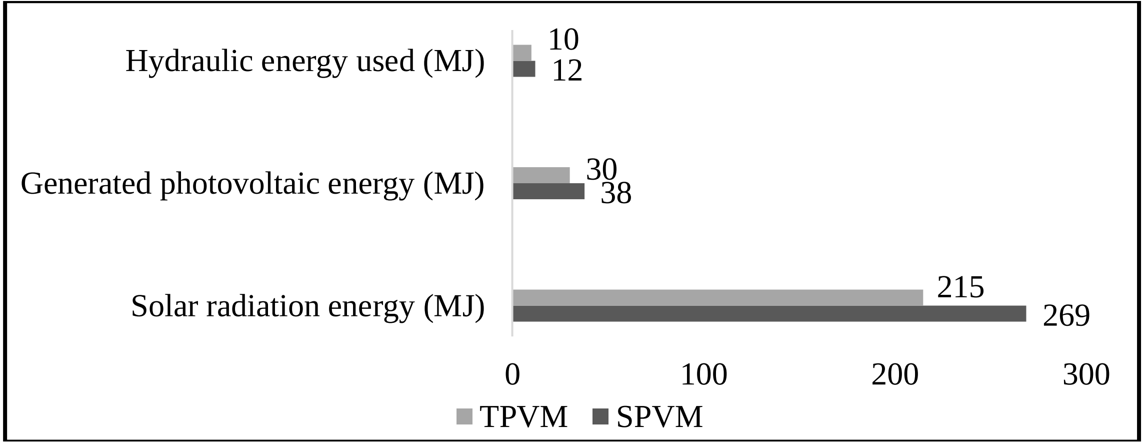
Efficiency in the TPVM was lower than SPVM and for the days with greater cloudiness the global efficiency was low for both PV systems (Figure 5). As irradiation increases, so does the energy generated on panels, than a greater volume is expected to be pumped. Days with a peak on radiation (Kt) presented higher efficiency, even if batteries drained current because this energy could be used during late hours.

In Peru, Vera et al. (2019) investigated a generation of electrical power using a photovoltaic energy system with DC/DC coupling for water pumping, and also found low global efficiency, around 6.5%. The authors pointed out that DC/DC systems can optimally harvest solar energy up to 8h per day.

Clark and Vick (1997) analyzing the efficiency of fixed and tracking system observed that the pump efficiency in a fixed system was greater in all months when compared to a tracking system. The authors explained that the controller restricted the power going to the pump, since it was set to run only when irradiation overcome 700 Wm^{-2}.

The energy reduction throughout the conversion process is shown in Figure 6. As explained before, besides the low conversion efficiency of the modules, the energy was subtilized because the limited power pump. With a limited total head the pump worked all day in the same power wasting a greater amount of energy.

Figure 6. Energy reduction along the process of PV to hydraulic conversion.



Tiwari and Kalamkar (2018) evaluating a photovoltaic pumping system in India (21.15° N, 79.09° E, altitude 310 m above sea level), observed that the efficiency of the system increased with the higher pumping head. They found efficiency between 5.27% (400-kPa head) and 7.68% (1000-kPa head), using helical pump, and concluded that a low pump efficiency at 400 kPa head was a result o underutilization of power produced by PV array. Same conclusion was presented by Michels et al. (2009) evaluating a pumps with total head of 20 m, with a maximum efficiency of 9.58% during winter solstice, and 8.57% in the summer solstice, considering sunny days without clouds. The difference in the efficiency was attributed to a saturation of the photovoltaic generator, so there was no increase in conversion and the excess irradiance is given as a loss. Low efficiency in the conversion of the panel may also decreases global efficiency, according to Kolling et al. (2004), who found 2.3% for a diaphragm pump.

A summary of the result is shown in the Table 2, with the increment of solar irradiance, pumping time, volume of water pumped and the global efficiency of the system by using a manual solar three steps tracking systems.

Table 2. Summary of the evaluated data for 34 days of the experiment

	Solar irradiance ($MJ\ m^{-2}$)	**Pumping time (hours)**	**Volume of water pumped (liters)**	**Global efficiency average (%)**
TPVM	1,182	262.48	407,359	4.55
SPVM	1,005	313.35	341,224	4.73
Increment	177	50.87	66,135	-

Despite of the high initial cost of the PV system installation when compared with diesel systems (ALVES et al., 2014), the reorientation of the panels allows a maximization of the solar irradiance. On the other hand, an increment o volume of water pumped might reduce the number of panels, therefore initial cost investments will be reduced to an acceptable value (CATON, 2014).

6 CONCLUSIONS

The photovoltaic module with manual three steps solar tracking system presented higher efficiency in the energy utilization when compared to static module, which reflected a significant increase of pumping time (40 to 160 min per day), in the volume water pumped (884 to 3,479 liters per day). However, the energy conversion efficiency was slightly lower (4.55% to 4.73%).

The use of the PV system with manual tracking device also had an advantage in the operation of the water pump when compared to static PV module, since batteries were not used for energy storage but only for the electrical stability of the PV module. In those periods where solar radiation is low (beginning and end of the day, and with intermittent clouds) the pumping system coupled to the manual tracking PV module presented higher operating stability.

7 ACKNOWLEDGMENTS

The authors acknowledge with thanks the financial support of Foundation for Research Support of the State of São Paulo (FAPESP), National Counsel of Technological and Scientific Development (CNPq), and the Ministry of Science, Technology and Innovation of Brazil (MCTI) by the National Institute of Science and Technology in Irrigation Engineering (INCT-EI), and the financial support of Coordination for the Improvement of Higher Education Personnel (CAPES).

8 REFERENCES

AI, B.; SHEN, H.; BAN, Q.; JI, B.; LIAO, X. Calculation of the hourly and daily radiation incident on three step tracking planes. **Energy Conservation & Management**, London, v. 44, n.1, p. 1999-2011, 2003.

AISSOU, S.; REKIOUA, D.; REKIOUA, T.; BACHA, S. Simple and low-cost solution system for a small scale power photovoltaic water pumping system. *In*: INTERNATIONAL RENEWABLE AND SUSTAINABLE ENERGY CONFERENCE IRSEC, 6., 2018, Rabat. **Proceedings** […]. Rabat: IEEE, 2018. p. 1-6

ALVARENGA, C. A. **Energia solar**. Lavras: UFLA: FAEPE, 2006.

ALVES, D. G.; PINTO, M. F.; DAMASCENO, A. P. A. B.; GRAH, V. F.; BOTREL, T. A. Cost analysis of water pumping using solar energy and diesel in drip irrigation. **Irriga,** Botucatu, v.1, n. 1, p. 125-133, 2014.

BIONE, J.; VILELA, O. C.; FRAIDENRAICH, N. Comparison of the performance of PV water pumping systems drive by fixed, tracking and V-trough generators. **Solar Energy**, Freiburg, v. 76, n.6, p. 703-711, 2004.

CATON, P. Design of rural photovoltaic water systems and the potential of manual array tracking for a West-African village. **Solar Energy**, Freiburg, v. 103, n.1, p. 288-302, 2014.

CHUN-SHENG, W.; YI-BO, W.; SI-YANG, L.; YAN-CHANG, P.; HONG-HUA, X. Study on automatic sun-tracking technology in PV generation. *In*: INTERNATIONAL CONFERENCE ON ELECTRIC UTILITY DEREGULATION AND RESTRUCTURING

AND POWER TECHNOLOGIES, 3., 2008, Nanjing. **Proceedings** […]. Nanjing: IEEE, 2008. p. 2586-2591.

CLARK, R. N.; VICK, B. D. Performance comparison of tracking and non- tracking solar photovoltaic water pumping systems. *In*: ANNUAL INTERNATIONAL MEETING, 1997, Paperno. **Proceedings** [...]. Paperno: ASAE, 1997. p. 1-12.

DEMAIN, C.; JOURNEÉ, M.; BERTRAND, C. Evaluation of different models to estimate the global solar radiation on inclined surfaces. **Renewable Energy**, Brighton, v. 50, n.1, p. 710-721, 2013.

FEDRIZZI, M. C.; SAUER, I. L. Bombeamento solar fotovoltaico, histórico, características e projetos. *In*: ENCONTRO DE ENERGIA NO MEIO RURAL AGRENER, 4., 2002, Campinas. **Anais** [...]. Campinas: UNICAMP: NIPE, 2002. p. 1-5.

GAO, Z.; ZHANG, Y.; GAO, L.; LI, R. Progress on solar photovoltaic pumping irrigation technology. **Irrigation and Drainage**, New Delhi, v. 67, n.1, p. 89 -96, 2018.

GRAH, V. F.; PONCIANO, I. M.; SARETTA, E.; ALVES, D. G.; BOTREL, T. A. Performance of single axis solar tracking system for photovoltaic energy generation. **Revista Energia na Agricultura**, Botucatu, v. 30, n. 2, p. 137-142, 2015.

KASTEN, F. A new table and approximate formula for relative optical air mass. **Archiv für Meteorologie Geophysik Bioklimatologie**, Berlim, v. 14, n.1, p. 206-233, 1965.

KALDELLIS, J.; KAVADIAS, K.; ZAFIRAKIS, D. Experimental validation of the optimum photovoltaic panel’s tilt angle for remote consumers. **Renewable Energy**, Brighton, v. 46, n. 1, p. 179-191, 2012.

KOLHE, M.; JOSHI, J. C.; KOTHARI, D. P. Performance analysis of a directly coupled photovoltaic water-pumping system. **Energy Conversion,** v. 19, n. 1, p. 613-618, 2004.

KOLLING, E. M.; SOUZA, S. N. M.; RICIERI, R. P.; SAMPAIO, S. C.; DALLACORT, R. Análise operacional de um sistema fotovoltaico de bombeamento de água. **Engenharia Agrícola**, Jaboticabal, v. 24, n. 3, p. 527-535, 2004.

KORDZADEH, A. The effects of nominal power of array and system head on the operation of photovoltaic water pumping set with array surface covered by a film of water. **Renewable Energy**, Brighton, v. 35, n. 5, p. 1098-1102, 2010.

METWALLY, H. M. B.; ANIS, W. R. Dynamic performance of directly coupled photovoltaic water pumping system using D.C. shunt motor. **Energy Conversion and Management**, Amsterdam, v. 37, n. 9, p. 1411-1416, 1996.

MICHELS, R. N.; RICIERI, R. P.; GNOATTO, E.; SOUSA, S. N. M.; SILVA, S. L.; FISCHBORN, M. Avaliação do bombeamento de água em um sistema alimentado por painéis fotovoltaicos. **Engenharia Agrícola**, Jaboticabal, v. 29, n. 3, p. 370-379, 2009.

RAGHUWANSHI, S. S.; KHARE, V. Sizing and implementation of photovoltaic water pumping system for irrigation. **IAES International Journal of Artificial Intelligence**, Yogyakarta, v. 7, n. 1, p. 54-62, 2018.

RIZI, A. P.; ASHRAFZADEH, A.; RAMEZANI, A. A financial comparative study of solar and regular irrigation pumps: Case studies in eastern and southern Iran. **Renewable Energy,** Brighton, v. 138, n. 1, p. 1096- 1103, 2019.

RUBIO-ALIAGA, A.; GARCIA-CASCALES, M. S.; SÁNCHES- LOZANO, J. M.; MOLINA-GARCÍA, A. Multidimensional analisys of groundwater pumping for irrigation purposes: Economic, energy and environmental characterization for PV power plant integration. **Renewable Energy**, Brighton, v. 138, n. 1, p. 174-186, 2019.

SONTAKE, V. C.; KALAMKAR, V. R. Solar photovoltaic water pumping system - A comprehensive review. **Renewable and Sustainable Energy Reviews**, London, v. 59, n. 1, p. 1038-1067, 2016.

SOUZA, A. P.; DAL PAI, A.; ESCOBEDO, J. F; GOMES, E. N. Estimativa da radiação global incidente em superfícies inclinadas por modelos isotrópicos e índice de claridade. **Pesquisa Agropecuária Brasileira**, Brasília, v. 45, n. 4, p. 339-350, 2010.

VERA, A. A. P.; BELTRÁN, H. J. C.; TOREES, J. C. Z.; GUZMÁN, J. J. M.; BRAGA, S. L. Experimental study of a photovoltaic direct current water pumping system for irrigation in rural-isolated region of Arequipa, Peru. **Renewable Energy**, Brighton, v. 141, n. 1, p. 1-11, 2019.

VILELA, O. C.; FRAIDENRAICH, N.; TIBA, C. Photovoltaic pumping systems driven by tracking collectors. **Solar Energy**, Freiburg, v. 74, n. 1, p. 45-52, 2003.

TIWARI, A. K.; KALAMKAR, V. R. Effects of total head and solar radiation on the performance of solar water pumping system. **Renewable Energy**, Brighton, v. 118, n. 1, p. 919-927, 2018.