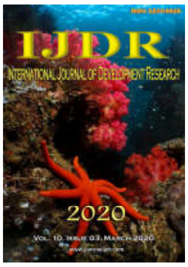
ISSN: 2230-9926

Available online at http://www.journalijdr.com

IJDR

International Journal of Development Research
Vol. 10, Issue, 03, pp. 34195-34203, March, 2020



RESEARCH ARTICLE OPEN ACCESS

PERFORMANCE EVALUATION OF TWO PV WATER PUMPING SYSTEMS IN THE STATE OF CEARÁ, BRAZIL

***Francisco Samuel Portela Vidal and Lutero Carmo de Lima**

State University of Ceará, Fortaleza, Brazil

ARTICLE INFO

Article History:
Received 10th December, 2019
Received in revised form
29th January, 2020
Accepted 14th February, 2020
Published online 30th March, 2020

Key Words:

Energy, PV System, Pumping Water, Performance.

Corresponding author:
Francisco Samuel Portela Vidal

ABSTRACT

The present study was developed with the purpose of evaluating the performance of two photovoltaic water pumping systems located at the State University of Ceará, Fortaleza, Brazil (latitude 3.40°S, longitude 38.33°W). One of the systems has 50 W_p of nominal power and the other 100 W_p of nominal power. The results presented were based on data collected weekly in 56 days, scattered in the months of April/2018, August/2018 and September/2018. The photovoltaic pumping system of 100 W_p had the highest daily average flow in liters, reaching a value of 3,223 liters/day, while the smaller system averaged 1,669 liters/day. The 50 W_p system had low power generation, with an average of 136.27 Wh/day, equivalent to only 39.24% of the average of the 100 W_p system. The efficiency of photovoltaic conversion was 6.18% in the 50 W_p system and 7.84% in the 100 Wp system.

Citation: ***Francisco Samuel Portela Vidal and Lutero Carmo de Lima.*** **2020.** "Performance evaluation of two pv water pumping systems in the state of ceará, brazil", *International Journal of Development Research*, 10, (03), 34195-34203.

INTRODUCTION

Water and electricity are two essential resources for the survival and quality of life of human society. However, in 2015, there were still 844 million people in the World (11% of the total) without access to a basic drinking water service (WHO, UNICEF, 2017, p.3). As for access to electricity, 1.1 billion people worldwide did not have it in 2016, 14% of the world population (IEA, 2017). The state of Ceará has the 5th worst GDP per capita in Brazil among the 27 states, but it has access to electricity rates above the national average, reaching 99.9% of households in 2017. Access to water is below average national, 7.4% of households did not have access to piped water (IBGE, 2017). Water pumping systems that use photovoltaic solar energy seek to offer a solution for access to water and electricity. In recent years, photovoltaic solar energy has undergone a drastic reduction of installation costs in the World, the weighted average installation costs fell from US$ 4.39 thousand/kW in 2010 to US$ 1.38 thousand/kW in 2017 (IRENA, 2017, p.23). Overall installed capacity jumped from 6.1 GW to 291 GW between 2006 and 2016 (IRENA, 2017, p.59).

The installed capacity of photovoltaic solar energy in Brazil has also been increasing rapidly in recent years. The country has 2.6 GW of installed power, but this represents only 1.57% of the national installed electric power from all sources (ANEEL, 2020). PV solar water pumping systems in rural communities have the potential to expand with the incentive provided by the cost savings of photovoltaic technology. Irrigation water pumping systems consume the equivalent of 62 terawatt-hours of electricity per year in the World (IRENA, 2016, p.8). India has developed an ambitious government subsidy program to purchase solar pumping equipment to replace diesel pumps and pumps connected to the grid. By the end of 2017, 147,500 photovoltaic pumping systems were installed in India from the government incentive program (MNRE, 2018, p.57). In semi-arid rural regions of northeastern Brazil, including regions of Ceará, photovoltaic pumping technology could be encouraged by the government, using India's expansion as a model. The rural communities of Ceará have levels of poverty and water scarcity far superior to urban communities. In Brazil, 9.9% of the general population lived below the poverty line in 2015 while in rural Ceará, 38.9% of the population was below the poverty line in the same year

(IPECE, 2017, p.87). Photovoltaic generation systems can help reduce energy costs by helping to remove households from the rural poverty line, in high energy consumption applications such as residential supply, irrigation, fish farming and drinking water supply to herds, the largest share of electric power consumption in many properties. The objective of this study is to evaluate the performance evaluation of two photovoltaic water pumping systems installed in Fortaleza, Ceará, one with a power of 50 Wp and one with a power of 100 Wp. The system with higher power is commonly used with the DC pump of the experiment in commercial pumping kits photovoltaic for sale in the Brazilian market, being considered the reference system. The lower power system will be considered the alternative system. The results will be used for future experiments in the rural area of the state of Ceará.

Literature review

The standard photovoltaic pumping system consists of a set of photovoltaic modules, a power conditioning device (inverter, controller), a motor pump unit and a water reservoir (FEDRIZZI, 2003, p.20). The positive displacement pumps used in photovoltaic systems are diaphragm pumps, for small manometric heights, and piston pumps for large manometric heights (PINHO; GALDINO, 2014, p.272). Positive displacement pumps require a higher electric current for starting the pump than the current required for starting the centrifugal pump. On the other hand, the decrease in solar radiation caused by clouds reduces the capacity of the pump to reach the required head. DC motors have advantages for small systems because they can be directly coupled to photovoltaic modules, which generate electricity in direct current, with low cost and complexity. In higher power systems, the use of AC motors with inverters that convert DC to AC power is more attractive due to the cost and availability of AC motors. Direct coupling is mainly used in systems up to 400 Wp (MORALES, 2011, p.53). The design of a photovoltaic water pumping system is a relative complex process, always searching for a lower cost system without generating insufficient supply during periods of lower solar irradiance. Morales (2011, p.152) proposes a methodology based on energy balance, where the energy demanded is equal to the energy generated for the work, considering the efficiencies of each element. This method has limitations caused by the variation of the parameters used, as for example, the pump can present a different level of efficiency for each level of current and voltage.

Muhsen, Khatib and Abdulabbas (2018, p.1003-1004) classify the methods of designing photovoltaic pumping in four types: intuitive, analytical, numerical and artificial. The intuitive method is based on the worst month of radiation or the average monthly radiation, this method is the simplest, with the risk of oversizing or undersizing the system. The analytical method is more precise and develops equations for the size of the photovoltaic system in terms of reliability. The numerical method is the most used, being based on hourly meteorological data to predict the performance of the system in different configurations. Among the configurations that meet the predetermined performance and reliability parameters, the lowest cost is chosen. The artificial method uses algorithms such as the genetic algorithm. A photovoltaic pumping system with oversized currents and voltage for the pump can burn the pump or the motor, while a system with low power can generate insufficient current for the beginning of the water pumping. A critical point of direct-coupled photovoltaic pumping is that the system operates outside the maximum power point of the photovoltaic generator most of the time, unlike conventional grid-connected photovoltaic systems which have inverters with maximum power point tracking (MPPT). The points where the I-V curve of the motor meets the I-V curve of the generator are known as working points (STEIGLEDER, 2006, p.41). In a well-designed photovoltaic pumping system the work points at low and high radiation levels are not too far from the maximum power point of the generator. Michels (2007) measured the performance of a system with two 56 Wp photovoltaic modules connected in series directly coupled to a Solarjack model SDS-D-228 pump. The study chose two days of clear skies to reap the results, one day in winter and another in summer. Winter day had a pumped flow of 2056 liters while summer day had a flow of 2377 liters. The efficiency of the system on winter day was higher than on summer day, in the morning (9.58% x 9.07%) and in the afternoon (9.34% x 8.57%). Nogueira *et al*. (2015) compared a system with three 50 Wp polycrystalline modules, model KS50 of the brand Solartec, with a system with a monocrystalline panel of 135 Wp, model HG135 of the mark Solarterra. A metal structure was built 2.5 meters high, with a water tank with a capacity of 100 liters at the top of the structure and another tank of the same capacity on the floor of the structure. The water was continuously pumped from the lower tank into the upper tank via a Shurflo suction diaphragm pump. The polycrystalline system had better performances than the monocrystalline system in results such as water pumping (average of 4182 liters/day x 3536 liters/day), pump efficiency (76.07% x 45.38%) and overall system efficiency (5% x 4.27%).

Tiwari and Kalamkar (2018) verified the performance of a direct coupled photovoltaic pumping system at 4 different gauge pressures, 4 bar, 6 bar, 8 bar and 10 bar. Each pressure was tested for five sunny days. The photovoltaic arrangement had 1.6 kWp of power, with 8 modules of 200 W_p, being 2 lines in parallel with 4 modules in series. The pump used was a Grundfos submersible (model SQF 2.5-2) and the motor was an MSF 3 model with MPPT. The highest average daily flow was found with the pressure of 4 bar, 27.09 m^3/day. The daily flow had a drop between 3.5 and 4.5% for each addition of 1 bar in the pressure. With an irradiance of 800 W/m², the water flow per hour was very similar in the four pressures studied. However, at 400 W/m² the system had 2.34 m^3/h of flow with 4 bar of pressure against 1.32 m^3 / h with a pressure of 10 bar. The system with 10 bar presented the best average efficiency, with a value of 7.68%.

MATERIALS AND METHODS

The experiment was carried out at the State University of Ceará (UECE) - Brazil, located in the geographical coordinates 3º 79' of Latitude South (S) and 38º 55' West Longitude (W). The study evaluated the performance of two photovoltaic water pumping systems with direct coupling. The three photovoltaic modules used in the experiment (Fig. 1) are of the brand Komaes, model KM50, with nominal power of 50 W_p each. The first system consists of two Komaes photovoltaic modules connected in parallel, with a nominal power of 100 W_p that supply a Shurflo pump. The second system has only one module of the Komaes connected to the other Shurflo pump of the same model used in the first system. The fixation of the solar modules was carried out in an iron structure, which was grounded. The modules were tilted 10° from the horizontal, oriented at 0° azimuth. The module presents in standard test conditions (STD) maximum power voltage of 17.74 V, maximum power current of 2.84 A, and short circuit current of 3.04 A (MINHA CASA SOLAR, 2020). The water pressure was performed with two Shurflo pumps, model 8000-443-136. It is a surface pump with positive pumping systems through diaphragm chambers. It has 12 VDC rated voltage and operates at open pressure, has a flow rate of 396 liters/hour and works with 3.1 A of electrical current (NEOSOLAR, 2020), which is a current value close to the short circuit current.

Fig. 1. Picture of three photovoltaic modules installed

The hydraulic part of the system (Fig. 2) was mounted on a pre-existing masonry structure with 2 meters in height. It has a solid cube-shaped base with a hollow cylinder at the top. Inside the cylinder were the pipes, the pumps, the hydrometers and the electrical measuring equipment.

Fig. 2. Hydraulic structure

Above the cylindrical structure, a glass cube with edges of 30 cm was fixed. Next to the masonry structure, a 150-liter Fortlev water tank was installed at ground level. Between the water surface level inside the water tank and the water outlet in the glass cube there is a height difference of 1.91 meters. All the water pumped into the upper reservoir returned immediately to the lower reservoir, generating a permanent cycle. The water pumped from the water tank through the pumps, then through the two hydrometers and reaches the glass cube in two separate pipes. The glass cube is not airtight, it allows the passage of external air from openings at the top. The equipment of measurement of the volume of water pumped was the Unijato hydrometer of the brand Saga, model US-3.0, nominal flow of 1,5 m³/h, maximum flow of 3 m³/h. This vertical hydrometer is Class A, with a minimum flow rate of 40 liters/hour and a transition flow rate of 150 liters/hour (SAGA MEDIÇÃO, 2020). The device that measures the electric energy generated by the solar modules is the DC wattmeter model PZEM-031, of the brand Peacefair. It works with measuring ranges between 6.5 V and 100 V voltage, 0 to 20 A current, 0 to 9999 Wh of energy, with an accuracy of ± 1% (PEACEFAIR, 2020). The schematic diagram of the experiment is shown in Fig. 3.

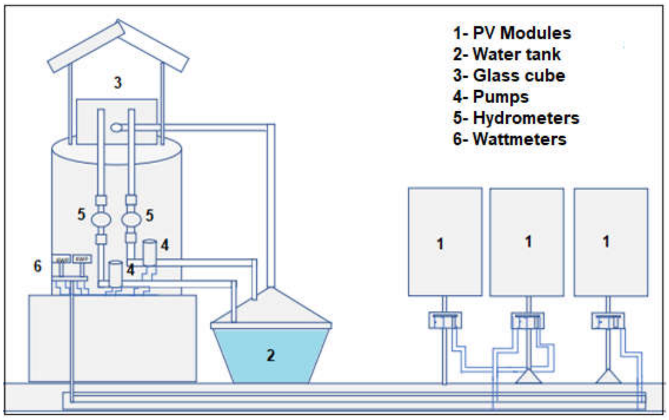


Fig. 3. Schematic diagram of the experiment

The pyranometer that measured the solar radiation is of the brand Kipp & Zonen, model CMP3, being in a station PCD to 85 meters of distance of the installed photovoltaic modules. The pyranometer CMP3 (ISO 9060: 1990 Second Class) provides measurement of global short-wave solar radiation in the 300 to 2800 nm spectral range (KIPP&ZONEN, 2020). The data in the station is integrated in periods less than 60 minutes. Between the photovoltaic modules and the pumps there is a DC wattmeter to measure the generated electric energy. The flow data of the water and the energy generated were collected weekly from the direct reading of the hydrometers and wattmeters respectively. The experiment was carried out during April/2018, in the period from April 2 to April 28, and the months of August/2018 and September/2018, from Auguster 6 to September 2, representing 56 days of collect. At the end, seven indicators were obtained.

Pumped flow: The flow refers to the volume of water pumped divided by the operating time of the system, which can be in hours, days or months. In equation 1 are the flow (Q) in liters / day, i.e., the volume of water (v) in liters and the time (t) in day:

$$Q = \frac{v}{t} \tag{1}$$

Electric power: The daily electrical energy (E_{ed}) in Wh is achieved by integrating the instantaneous electric power (Pot) in watts, over time (t) in seconds. The integration quoted in equation 2 is done by the PZEM-031 wattmeter itself. The resulting value in joules is then converted to Wh:

$$E_{ed} = \int_{day} Pot_e \, .dt \tag{2}$$

The daily radiant energy received by the PV generator (E_{dgf}) in Wh is achieved by integrating the instantaneous irradiance (G) in W/m² incident on the horizontal plane of the photovoltaic arrangement, over time (t) in seconds, multiplied by the area of the photovoltaic (A_g) generator in m², thus:

$$E_{dgf} = A_g \int_{day} G \, .dt \tag{3}$$

The area of the photovoltaic modules is obtained by multiplying two dimensional data (750 mm x 510 mm). The integration contained in equation 3 is provided by the pyranometer of the PCD station.

Photovoltaic conversion efficiency: The daily efficiency of the photovoltaic conversion is obtained through the quotient between the daily electric energy generated and the radiant energy received by the photovoltaic generator (STEIGLEDER, 2006, p.109). Thus we can calculate the daily efficiency of the photovoltaic conversion (η_{pv}) from the equation 4:

$$\eta_{pv\ daily} = \frac{E_{ed}}{E_{dgf}} \tag{4}$$

Performance ratio (PR): Another parameter evaluated is the performance ratio (PR) that consists of the relation between the real and theoretical energy outputs of a photovoltaic installation (MORAIS, 2017, p.66). It shows the proportion of electric power that is available to the pump after the operation losses, such as losses due to the heating of the photovoltaic modules. It is expressed in percentage and can be calculated by the following formula (DE LIMA *et al.*, 2017, p.81):

$$PR = \frac{Y_F}{Y_R} \ x\ 100\% \tag{5}$$

The final productivity (Y_F) of equation 5 can be defined as the total electric energy generated by the photovoltaic array and delivered to the motor pump during a defined period of time (day, in the case) divided by the nominal output power of the PV system. It represents the amount of hours per day that the photovoltaic system must operate at its nominal power to generate the amount of energy produced.

$$Y_F = \frac{E_{ed}}{P_{FV,nom}} \left(\frac{kWh}{kW_P}\right) \tag{6}$$

The reference productivity (Y_R) is the global horizontal irradiation (H_T) in the plane divided by the reference irradiance (H_R). The (H_R) value is of the order of 1 kW/m². The reference productivity is a measure of the theoretical energy available in a location over a defined period of time.

$$Y_H = \frac{H_T}{H_R} \left(\frac{kWh}{kW_P}\right) \tag{7}$$

Manometric height: The determination of the manometric height uses as reference the study of Moreira (2009, p.55). It is measured in meters from the geometric height (H_g) and the friction losses occurring in the suction and settling pipes, converted to an equivalent length (H), starting from the formula:

$$H_M = H_G + H_P \tag{8}$$

The friction losses in the pipes had their results obtained through tables constructed using the Flamant Equation (FRANKLIN ELECTRIC, 2016, p.66), which is applied to load loss calculations in small diameter pipes.

Efficiency of the pump: The daily efficiency of the pump is achieved with the quotient between the daily hydraulic energy (E_H) and the generated daily electrical energy (E_{ed}). The electric energy (E_{ed}) was found in equation 2. And the hydraulic energy (E_H), in Wh/day, is obtained from the total manometric height (AMT) in meters and the daily flow pumped (Q_d), in the case converted from liters/day to m³/day.

$$E_H = 2{,}725 \, . \, Q_d \, . \, AMT \tag{9}$$

Thus, the calculation of the daily efficiency of the pump (η_{ehd}) (STEIGLEDER, 2006, p.112) is performed as follows:

$$\eta_{ehd} = \frac{E_H}{E_{ed}} \tag{10}$$

RESULTS AND DISCUSSIONS

In this section, we analyzed all data collected from solar irradiation, and from the wattmeter and hydrometer of each pumping system, with weekly frequency, during the month of April/2018, in the period from April 2 to April 28, and the months of August 2018 and September 2018, from August 6 to September 2. The total was eight weeks with results, representing 56 days of collection, being 28 days in each period.

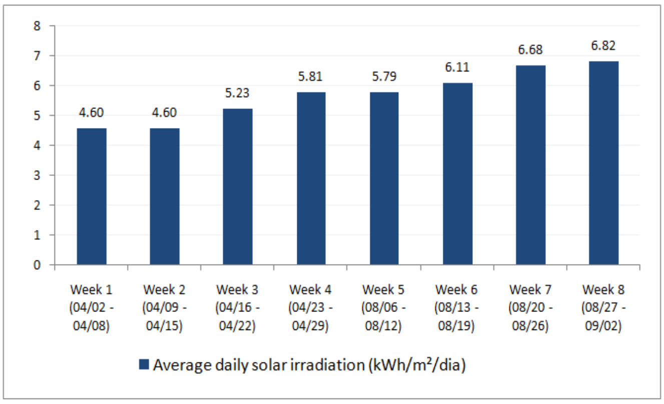


Fig. 4. Average daily solar irradiation per week

The mean daily irradiation of the two periods of 28 days each, show that period 1 was a good reference of low solar irradiation while period 2 was a good reference of high solar irradiation. Period 1 with average daily irradiation of 5.05 kWh/m² had values close to the average of the month of

April/2018, which with irradiation of 5.02 kWh/m², presented the third lowest monthly average of the year 2018. The period 2, with average daily irradiation of 6.35 kWh/m², had values close to the average of August/2018, which with irradiation of 6.23 kWh/m², presented the third highest monthly average of the year 2018. Fig.4 brings the values of average daily solar irradiation in each of the eight weeks of the experiment. In most cases, the weeks of period 2 had irradiations higher than the weeks of period 1. Week 1 and 2 had the worst average daily solar irradiation between the eight weeks, with averages of 4.6 kWh/m², values that are only higher than the values of the month of February/2018, only 3.8% more irradiation compared with the worst month of the year. Week 8 presented an average daily irradiation of 6.82 kWh/m², higher than the value of the month of September/2018, 1.3% more irradiation compared to the best month of the year. These data show that within the eight-week universe of the experiment, weeks 1, 2, and 8 are good references of extreme solar irradiance values, compared to the monthly values for 2018. The daily radiant energy received by the photovoltaic generator (E_{dgf}) in kWh was obtained through solar irradiation by the area of the photovoltaic (A_g) generator in m². The area of the Komaes KM50 module is 0.38 m², so the area of the 50 W_p system was the same area of the module and the area of the 100 W_p system was twice, because the larger system has 2 modules. The lowest daily solar irradiance in the 50 Wp system occurred at weeks 1 and 2, with a mean of 1.76 kWh, while the highest value occurred at week 8, with a mean of 2.61 kWh. The average daily flow rate of the two photovoltaic water pumping systems, in liters per day, in each 28-day period is shown in Fig. 5. The mean volume of water pumped in period 1 was 1,089.75 liters per day in the 50 W_p system, representing only 41.03% of the average flow pumped by the 100 W_p system, which in turn was of the order of 2,655.5 liters per day. As the incident radiation on the 50 W_p system represented 50% of the incident radiation in the 100 W_p system, it can be stated that the volume pumped by radiation incident in period 1 was higher in the 100 W_p system. The average volume of water pumped in period 2 was 2,248.5 liters per day in the 50 W_p system, equivalent to 59.31% of the average flow pumped by the 100 W_p system, which in the case pumped 3,790.5 liters per day. Thus, the volume pumped by incident radiation in period 2 was higher in the 50 W_p system.

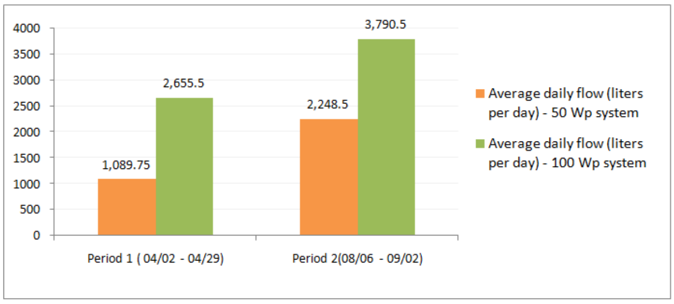


Fig. 5. Average daily flow (liters / day) per period in each system

The results of the pumped water flow show that the system with lower power (50 W_p) was more impacted by the variations of solar irradiation. In the set of 56 days of the experiment, the average flow rate of the 50 W_p system was 1,669 liters per day, and the flow rate of the 100 W_p system was 3,223 liters per day. The result of the smaller system flow represented 51.79% of the largest system flow. For the purpose of comparison, Chilundo (2014) developed an experiment with a photovoltaic pumping system applied to the irrigation of an agricultural unit in the city of Fortaleza with the Shurflo pump 8000-443-136 in 2014, the same city and the same pump used in this study. The photovoltaic module used was the CSUN 135-36P model, of the brand Exxa Solar, with a nominal power of 135 W_p, with power higher than the larger system of the present study. The system applied to irrigation achieved a daily average flow of 5.84% greater, compared to the daily average of the system of 100 W_p in the 56 days. The average daily solar irradiation level in the comparison had a difference of less than 1%. The 100 W_p system had higher flow per installed power, but the irrigation system operated with a higher total head, of the order of 10.5 meters. The 50 W_p system had great difficulty working on days of low radiation, a fact that happened on rainy and cloudy days. At week 1 there was precipitation in five of the seven days. Despite representing 50% of the nominal power of the 100 W_p system, at week 1 the 50 W_p system only pumped the equivalent of 34.34% of the water pumped through the bigger system, just in the week with the lowest daily average solar irradiation of the order of 4.6 kWh/m². This shows that it is difficult for a low power system to ensure supply in isolated systems of the public power grid, where there is no possibility of a grid connected auxiliary system compensating for insufficient water pumping. On the other hand, at week 8, where there was the highest average daily solar irradiation at 6.82 kWh/m², the 50 W_p system pumped 61.83% of the water pumped by the bigger system. The months of August and September have historical radiation higher than the month of April in the city of Fortaleza, and in the week 8 the days had many hours of full sun. The 100 W_p system presented lower volume variation pumped between the 8 weeks of the experiment, demonstrating greater reliability in the water supply, which can be vital in applications that require this characteristic. However the differences between the worst week and the best week were relevant, at week 1 only 55.6% of what was pumped at week 8 was pumped. The average daily electrical energy (E_{ed}) generated in each 28-day period by the two pumping systems, one with 100 W_p and the other with 50 W_p, is available in Fig. 6. The daily average electrical energy (E_{ed}) generated by the lowest power system in period 1 was 90 Wh/ day, which meant only 30.31% of the average of the bigger power system, which reached 296.9 Wh/day. In period 2, the average (E_{ed}) of the 50 W_p system had 182.53 Wh/day as a result, 45.92% of the value of 397.53 Wh/day of the 100 W_p system. Therefore the ratio of generated energy/incident radiation was always lower in the 50 Wp system.

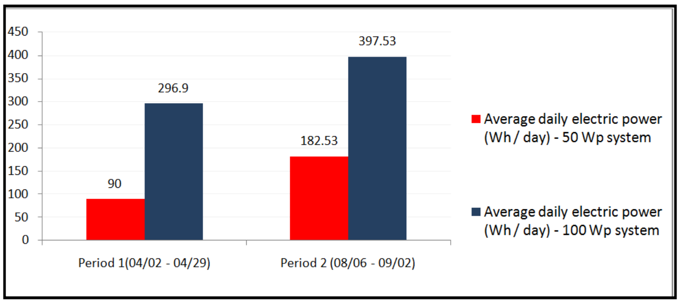


Fig. 6. Average daily electrical energy (Wh/day) per period in each system

As for the average daily electrical energy (E_{ed}) in each week, the 50 W_p system presents 50% of the nominal power of the 100 W_p system, but in every week generated less than 50% of the energy generated by the bigger system. In week 1, it only generated 25.22% of the largest system. The 100 W_p system on the other hand had the energy generated with a more proportional behavior in relation to the flow, since as the water pumped increased in each of the 8 weeks, the generated energy also increased in all the 8 weeks. In the routine observations of the wattmeter it was found that the 50 W_p system operated with the voltage at levels much lower than the values of the rated voltage of the pump, except for hours closer to noon. This significantly impacted on the low energy generated. The greatest impact factor in the power generation of the 100 W_p system was the presence or absence of cloudiness, since even between 8:00 am and 9:00 am the system worked with good power whenever the sky was cloudless. In 56 days, the daily electricity generated averaged 136.27 Wh/day in the smallest system and 347.22 Wh/day in the biggest system. One point to note is that with a clean sky, in the early hours of the day, the pumps of the two systems started operating with a voltage between 7 V and 7.5 V, thus above the minimum operating voltage of the wattmeter, and a current value between 1.7 A and 1.8 A. The working point inside the IV curve of the solar module of the experiment, with the voltage and current levels mentioned, is far from the point of maximum power (PMP) of the module, because the maximum power voltage (VMP) of the Komaes KM50 module is 17.74 V, under standard test conditions (STC). A far-left working point voltage of the (VMP) means a current close to the current short-circuit on curve IV.

A current of 1.8 A from start-up of the pump, considering the short-circuit current of 3.04 A of the Komaes KM50 module in STC, means a radiation incident on the module of approximately 60% of the radiation incident on STC, or 600 W/m^2. Thus we have an operating input of the pump with an approximate incident irradiance of 600 W/m^2 in the system of 50 W_p and with an approximate irradiance of 300 W/m^2 in the system of 100 W_p. The 100 W_p system with 1000 W/m^2 of incident irradiance would operate with approximately 5.68 A of electric current if it were connected to an inverter or controller with MPPT, since the nominal current of the 2 photovoltaic modules in parallel are added, with minimum differences caused by the increase in temperature. However, as the electric current in the wattmeter reached a maximum of 3.5 A at high-radiation times at noon, the system's working point moved to the right of the IV curve, distancing itself from the maximum power point (PMP) and impacting negatively on the generation of electric energy. The daily efficiency of the photovoltaic conversion (η_{pv}daily) in each 28-day period was obtained by dividing the values of average daily electrical energy (E_{ed}) by the daily radiant energy received by the photovoltaic generator (E_{dgf}). The data of the daily (η_{pv}) per period are shown in Fig. 7.

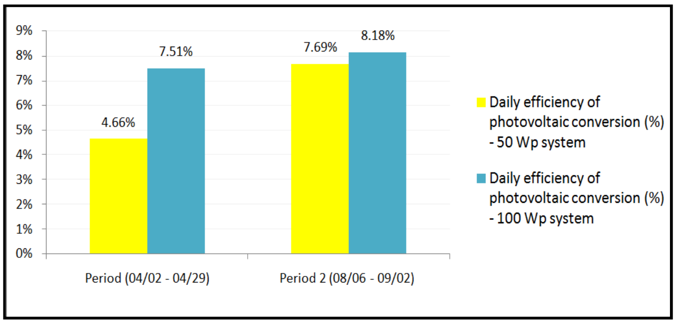


Fig. 7. Daily efficiency of photovoltaic conversion by period

The daily efficiency of photovoltaic conversion reached 4.66% in period 1 and 7.69% in period 2, in the case of the 50 W_p, in the system of 100 W_p the efficiency was 7.51% in period 1 and 8.18% in period 2. The very low result of the efficiency of the system of 50 W_p in period 1, compared with the other three results, can be explained by the difficulty of the smaller set working with radiations below 600 W/m^2. And since period 1 had significantly lower irradiations, this minimum value of irradiation had more difficulty to be achieved. The Shurflo 8000-443-136 pump showed an interesting operation, only starting with a minimum level of current and voltage sufficient to perform water pumping. Therefore, the irradiations below the minimum input level of the Shurflo 8000-443-136 pump did not generate electrical energy measured by the wattmeter. The efficiency of the photovoltaic conversion had an average value during the experiment of 7.84% in the 100 W_p system, and in 50 W_p system it reached only 6.18% of efficiency. Nogueira *et al.* (2015) compared a pumping photovoltaic system with three 50 W_p polycrystalline modules, model KS50 of the brand Solartec, with a system with a monocrystalline panel of 135 W_p, model HG135 of the brand Solarterra, in the city of Cascavel, Brazil. The efficiency of the photovoltaic conversion was 9.4% in the monocrystalline set and 6.57% in the polycrystalline set. Thus the result of the 50 W_p system was lower than the two sets of the Cascavel and the result of the system of 100 W_p was superior to that of the polycrystalline system and inferior to the monocrystalline system.

The lowest values of the reference productivity (Y_R) and final productivity (Y_F) in the 50 W_p set were found at week 1, with 4.6 kWh/kWp.day and 1.33 kWh/kWp.day, respectively. The highest values of (Y_R) and (Y_F) were at week 8, with 6.82 kWh/kWp.day and 4.07 kWh/kWp.day. The reference productivity values (Y_R) in the 100 W_p set were the same as the 50 W_p system for weeks and periods. The lowest value of final productivity (Y_F) in the bigger system occurred at week 2, with 2.49 kWh/kWp.day. Meanwhile the highest value of (Y_F) occurred at weeks 7 and 8 with 4.22 kWh/ Wp.day. During the 56 days, the (Y_R) score reached 5.7 kWh/kWp.day and the (Y_F) at 2.73 kWh/kWp.day in the 50 W_p system, and in the 100 W_p system the (Y_F) score reached 3,47 kWh/kWp.day. With the values of the final productivity and the reference productivity, an important result was obtained, the performance ratio (PR). It shows the proportion of electrical energy that is available to the water pumping system after system losses, such as those caused by the heating of photovoltaic modules and by the non-operation of the photovoltaic system near the maximum power point (PMP) of the curve IV. The results of the performance ratio of the two systems per week are shown in Fig. 8. The performance ratio in the 50 W_p system varied greatly at 8 weeks, from vexative value such as 28.9% at week 1, the worst result, up to acceptable results for a direct coupling pumping photovoltaic system, such as 59.7% at week 8, the best result. The performance ratio in the 100 W_p system ranged from 54.1% at week 2, the worst result, and 63.2% at weeks 6 and 7, the best result. In period 1, in period 2 and total time of 56 days, the performance of the smaller system was 35.6%, 57.5% and 47.9%, respectively. During every week the largest system obtained acceptable results for a system that does not work with inverter or load controller with MPPT function. In period 1, in period 2 and in total time of 56 days, the system performance ratio of 100 W_p was 58.8%, 62.7% and 60.9%, respectively.

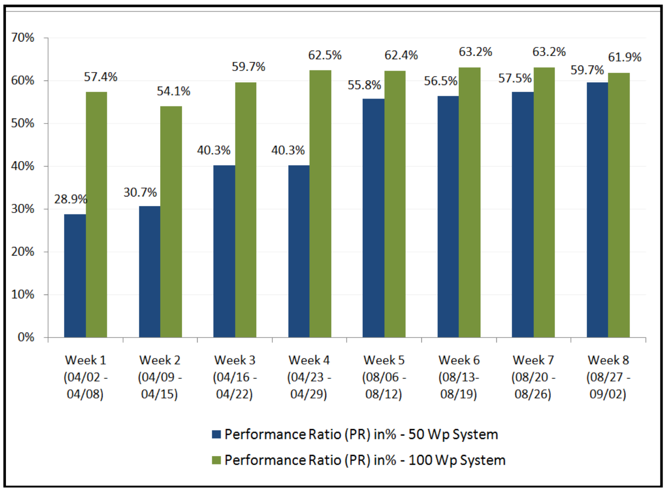


Fig. 8. Values of the weekly performance ratio (PR) per system

Morais (2017) evaluated the performance ratio of a 5.2 kWp photovoltaic system connected to the public electricity grid through an MPPT inverter. The system is located at a distance of 40 meters from the two pumping systems of this study, in Fortaleza, Ceará. The study was conducted between October/2016 and September/2017. The performance ratio (PR) over the 12 months was 75.6%. The relevant difference for the two pumping systems is justified by the absence of equipment that makes the PV pump system with direct coupling work at the point of maximum power of the I-V curve. The identification of the total manometric height (AMT) allowed to obtain the results of the hydraulic energy (E_h) of the systems and the daily efficiency of the pump (η_{ehd}). The manometric height is the sum of the geometric height (H_g), whose value is 1.91 meters, with friction losses in the pipes calculated in equivalent meters (H_p). The values of the losses were based on the addition of the length of the suction pipe, the length of the settling pipe and the equivalent length of two 90° knees, two 45° curves and a check valve, existing in each pumping. At the end, with the addition of all the values, a result of 15.7 meters of extension was obtained, adding pipes and connections. In order to calculate the (H_p) result, the value 15.7 meters was multiplied by 1.2%, loss of load found for 3/4" PVC pipes with 0.5 m^3/ hour flow (FRANKLIN ELECTRIC, 2016, p.66). The result of the (H_p) friction losses found was 0.19 meters. The value of the total manometric height (AMT) was 2.1 meters, from the addition of 1,91 meter (H_g) with 0.19 meter (H_p). The average daily hydraulic energy (E_h) in Wh/day of the two systems required to pump the water had the result based on the daily flow multiplication, in the case converted to m^3/ day, by the (AMT) and the value 2.725. In period 1, in period 2 and in the total time of 56 days, the mean values of the daily hydraulics of the smaller system had results of 6.23 Wh/day, 12.86 Wh/day and 9.55 Wh/day, in this order. In period 1, in period 2 and in the total time of 56 days, the average values of the daily hydraulics of the bigger system reached 15.19 Wh/day, 21.68 Wh/day and 18.44 Wh/day, respectively. The daily efficiency of the pump (η_{ehd}) was found by simply dividing the average hydraulic energy by the average electric energy generated. The efficiency data of the pump per week are shown in Fig. 9. The efficiency levels of the pump system of the 50 W_p system were significantly higher than the levels of the 100 W_p system, ranging from 6.5% to 7.3% in weekly values, against values between 4.8% and 5.5% of the bigger system. The efficiency of the pump in 56 days averaged 7% in the 50 W_p system and 5.31% in the 100 W_p system. The efficiency of the pump in both systems had a weak result. However, these results were expected because the range of operation with the manometric height of the experiment is very far from the operating range where the Shurflo 8000-443-136 pump has a higher level of efficiency.

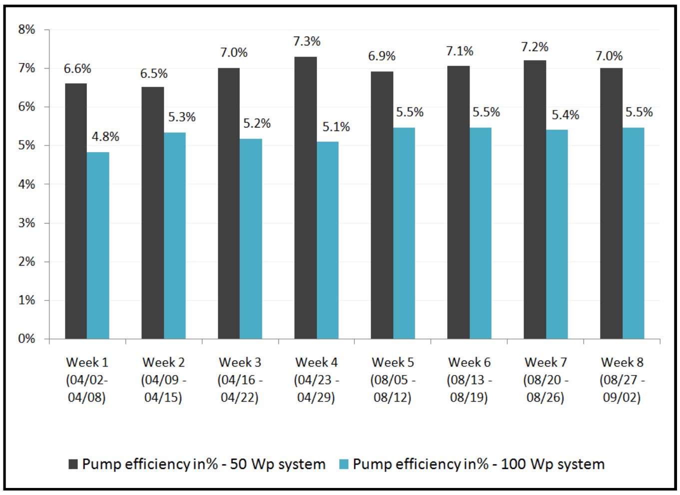


Fig. 9. Efficiency of the motor pump assembly per week in each system

Conclusions

The comparison between the photovoltaic system of water pumping of 50 W_p and the system of 100 W_p presented a proportional evaluation in indicators like flow of water and electric energy generated, having as reference that the power of one system is twice the power of the other. In indicators such as photovoltaic conversion efficiency the comparison was made through the absolute values found. The comparison was balanced, the 50 W_p system won three of the six indicators. The average water flow of the 50 W_p set achieved the best proportional result with 1,669 liters per day against the system flow of 100 Wp of 3,223 liters per day, the lowest system had 51.79% of the largest system flow, having only 50% of the rated power. As the hydraulic power depends directly on the flow value, there was a new proportional win of the 50 W_p set, with the same 51.79% of the absolute value of the 100 W_p set. During the period of the experiment, the average daily hydraulic energy of the smaller system was 9.55 Wh/day, while the average daily hydraulic energy of the larger system reached 18.44 Wh/day. Finally, the system of 50 W_p obtained the best level of efficiency of the pump, with an average of 7% against 5.31% of the system of 100 W_p. The 100 W_p system won the comparative in three indicators. The daily electrical energy (E_{ed}) generated by the largest system had an overall average of 347.22 Wh/day, the highest proportional value, against only 136.27 Wh/day in the lowest system. The 50 W_p system obtained only 39.24% of the largest result, having 50% of the nominal power. The efficiency of the photovoltaic conversion had an average value during the experiment of 7.84% in the set of 100 W_p, the best result, while the set of 50 W_p reached only 6.18% of efficiency of the photovoltaic conversion. The performance ratio (PR) in the 100 W_p system achieved the highest value, with 60.9%, against only 47.9% in the smaller system. The result of the system of 100 W_p regarding the pumped flow had a more satisfactory result in relation to the level of stability of the average weekly flows. The worst week in terms of average flow, with 2,242 liters/day, reached 69.56% of the average flow of the eight weeks, in the system of 50 W_p the worst week had only 46.13% of the average average flow. The result of the average flow rate of the 50 W_p system was surprising because no photovoltaic pumping kits with such low rated power are sold in the Brazilian market with the value of the electric current of the photovoltaic system in STC similar to the nominal electric current of the pump in the range of smaller manometric height required. The100 W_p system presented better performance in period 1, with lower solar irradiations, and the 50 W_p system presented better performance in period 2, with higher levels of solar irradiation. At the end it can be concluded that the results of the two photovoltaic pumping systems were satisfactory. For comparison purposes, the average pumping of 3,223 liters per day in the 100 W_p system is equivalent to 8.14 uninterrupted hours of operation of the Shurflo 8000-443-136 pump with its nominal flow of 396 liters/hour, in the smaller manometric height possible. Thus, the photovoltaic system of water pumping proved to be a good alternative to pump water in the rural area of Ceará, with the possibility of avoiding expenses with the electricity bill and alleviating poverty.

Acknowledgments

Authors are also indebted to FUNCEME – Ceará State Foundation for Meteorology and Water Resources for providing meteorological data.

REFERENCES

ANEEL. *Banco de Informações de Geração:*Capacidade de Geração do Brasil. 2020. Available in: <http://www2.aneel.gov.br/aplicacoes/capacidadebrasil/capacidadebrasil.cfm>.

CHILUNDO, Rosa Jacob. *Sistema fotovoltaico aplicado à irrigação de uma unidade agrícola de produção familiar.* 2014. 97 f. Dissertação (Mestrado) - Curso de Pós-graduação em Engenharia Elétrica, Departamento de Engenharia Elétrica, Universidade Federal do Ceará, Fortaleza, 2014.

DE LIMA, Lutero Carmo *et al*. Performance analysis of a grid connected photovoltaic system in northeastern Brazil. *Energy for Sustainable Development*,[s.l.], v. 37, p.79-85, 2017.Elsevier BV. https://doi.org/10.1016/j.esd.2017.01.004.

FEDRIZZI, Maria Cristina.*Sistemas fotovoltaicos de abastecimento de água para uso comunitário:* lições apreendidas e procedimentos para potencializar sua difusão. 2003. 174 f. Tese (Doutorado) - Programa de Pós-graduação em Energia, Universidade de São Paulo, São Paulo, 2003. Available in: < http://lsf.iee.usp.br/sites/default/files/Doutorado_Cristina_Fedrizzi.pdf>.

FRANKLIN ELECTRIC. *Tabela para seleção de bombas e motobombas.*2016. Available in::< https://www.agrolinkirriga.com.br/pdf/motobombas/SCHNEIDER-Bombas.pdf>.

IBGE. *Características gerais dos domicílios e dos moradores 2017*. 2017. Available in: <ftp://ftp.ibge.gov.br/Trabalho_e_Rendimento/Pesquisa_Nacional_por_Amostra_de_Domicilios_continua/Anual/Caracteristicas_Gerais_dos_Domicilios_e_dos_Moradores_2017/PNAD_Continua_2016_2017_Caracteristicas_Gerais_dos_Domicilios.xls>.

IEA (INTERNATIONAL ENERGY AGENCY). *WEO-2017 Special Report:* Energy Access Outlook. 2017. Available in: < https://webstore.iea.org/weo-2017-special-report-energy-access-outlook>.

IPECE (Instituto De Pesquisa e Estratégia Econômica do Ceará). *Indicadores Sociais do Ceará - 2015.*2017. Available in: <https://www.ipece.ce.gov.br/wp-content/uploads/sites/45/2014/05/Indicadores_sociais_ceara_2015.pdf>.

IRENA.*Renewable Power Generation Costs in 2017.*2017. Available in:< https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_2017_Power_Costs_2018.pdf>.

IRENA.*Solar pumping for irrigation:*Improving livelihoods and sustainability. 2016. Available in: <www.irena.org/DocumentDownloads/Publications/IRENA_Solar_Pumping_for_Irrigation_2016.pdf>.

KIPP&ZONEN.*CMP3 Pyranometer.*Available in: <http://www.kippzonen.com/Product/11/CMP3-Pyranometer#.WQjrGtrytPY>.

MICHELS, Roger Nabeyama. *Avaliação de um sistema de bombeamento de água alimentado por painéis fotovoltaicos.*2007. 57 f. Dissertação (Mestrado) - Programa de Pós-graduação em Engenharia Agrícola, Universidade Estadual do Oeste do Paraná, Cascavel, 2007. Available in: <http://repositorio.utfpr.edu.br:8080/jspui/bitstream/1/429/3/UNIOESTE_%20PGEAGRI_M_Michels%2c%20Roger%20Nabeyama_2007.PDF>.

MINHA CASA SOLAR. *Painel Solar de 50WKomaes Solar.*Available in:< https://www.minhacasasolar.com.br/produto/painel-solar-de-50w-komaes-solar-%E2%80%93-km-p-50-78871>.

MNRE (Ministry of New and Renewable Energy). *National Solar Mission:* Anual Report 2017-2018. 2018. Available in: <https://mnre.gov.in/file-manager/annual-report/2017-2018/EN/pdf/chapter-4.pdf>.

MORAIS, Francisco Hedler Barreto de Lima. *Análise de desempenho de um sistema fotovoltaico de 5,2 kW_pconectado à rede instalado na UECE.*2017. 95 f. Dissertação (Mestrado) - Curso de Mestrado Acadêmico em Ciências Físicas Aplicadas, Centro de Ciência e Tecnologia, Universidade Estadual do Ceará, Fortaleza, 2017. Available in: <https://www.researchgate.net/profile/Francisco_Hedler_Morais/publication/321862717_ANALISE_DE_DESEMPENHO_DE_UM_SISTEMA_FOTOVOLTAICO_DE_52_kWp_CONECTADO_A_REDE_INSTALADO_NA_UECE/links/5a35c995aca27247ede9cf3/ANALISE-DE-DESEMPENHO-DE-UM-SISTEMA-FOTOVOLTAICO-DE-5-2-kWp-CONECTADO-A-REDE-INSTALADO-NA-UECE.pdf?origin=publication_detail>.

MORALES, Luis Roberto Valer. *A utilização de sistemas fotovoltaicos de bombeamento para irrigação em pequenas propriedades rurais.* 2011. 170 f. Dissertação (Mestrado) - Programa de Pós-graduação em Energia, Universidade de São Paulo, São Paulo, 2011. Available in: <http://www.teses.usp.br/teses/disponiveis/86/86131/tde-10112011-105243/publico/DissertValerMorales.pdf>.

MUHSEN, Dhiaa Halboot; KHATIB, Tamer; ABDULABBAS, Tawfeeq Enad. Sizing of a standalone photovoltaic water pumping system using hybrid multi-criteria decision making methods. *Solar Energy*, [s.l.], v. 159, p.1003-1015, 2018. Elsevier BV. http://dx.doi.org/10.1016/ j.solener.2017.11.044.

NEOSOLAR. *Ficha Técnica do Produto, Modelo: 8000-443-136*. Available in: <https://www.neosolar.com.br/

loja/fileuploader/download/download/?d=1& file=custom %2Fupload%2FFile-1366224807.pdf>.

NOGUEIRA, Carlos Eduardo Camargo *et al*. Performance of monocrystalline and polycrystalline solar panels in a water pumping system in Brazil. *Renewable And Sustainable Energy Reviews*, [s.l.], v. 51, p.1610-1616, 2015. Elsevier BV. http://dx.doi.org/10.1016/j.rser.2015.07.082.

PEACEFAIR.*Pzem-031 DC*. Available in: < https://peacefair.en.made-in-china.com/productimage/ojuEIiVbHLhJ-2f1j00mUyYodVPEIcz/China-Pzem-031-DC-6-5-100V-20A-4in1-LCD-Voltage-Power-Ammeter-Electric-Energy-Meter.html>.

PINHO, João Tavares; GALDINO, Marco Antonio (Org.). *Manual de Engenharia para Sistemas Fotovoltaicos.*2014. Available in: <http://www.cresesb.cepel.br/publicacoes/download/Manual_de_Engenharia_FV_2014.pdf>.

SAGA MEDIÇÃO. *Saga Medição:*Catálogo de Produtos. Available in: < http://www.sagamedicao.com.br/download/1008/>.

STEIGLEDER, Marco Antonio. *Comparação do desempenho de duas bombas acopladas diretamente a geradores fotovoltaicos.*2006. 129 f. Dissertação (Mestrado) - Curso de Pós-graduação em Engenharia Mecânica, Universidade Federal do Rio Grande do Sul, Porto Alegre, 2006. Available in: <https://www.lume.ufrgs.br/bitstream/handle/10183/7736/000554930.pdf>.

TIWARI, Arunendra K.; KALAMKAR, Vilas R.. Effects of total head and solar radiation on the performance of solar water pumping system.*Renewable Energy,* [s.l.], v. 118, p.919-927, 2018. Elsevier BV. http://dx.doi.org/10.1016/j.renene.2017.11.004.

WHO (World Health Organization); UNICEF (United Nations Children's Fund) (Org.).*Progress on drinking water, sanitation and hygiene: 2017 update and SDG baselines*. 2017. Available in: <https://washdata.org/report/jmp-2017-report-final>.

****