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Effectiveness of Solar Pumping System in the Wadi Agriculture in Northern East Africa

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Abstract: Authors installed a small solar pumping system in a farm which ran Wadi agriculture in the northeastern African Republic of Djibouti 2008 and carried out experiments to confirm its effectiveness. The average annual precipitation in this area and the maximum amounts of solar radiation, are 130 mm year^{-1} and 25 MJ m^{-2} day^{-1} each (Ismael *et al*., 2003). The farm area is 1.5 ha and the cultivated crops are melon, onion, pepper, tomato, eggplant etc. as food and pastures as livestock's feed. The livestock are mainly goats and serve as dairy and meat and its excrement is use as compost. The quantity of solar radiation, PV-module output and water level of the water tank were measured in March 2011 and August 2012 to estimate the quantity of water required as well as the appropriate scale of the system. As a result, it was found out that, a system of about 1 kW is reasonable for either season having a water tank of 75 m^3 lifted 15 m head from well (Tajima *et al*., 2012). And last time one of the PV-module had been damaged by stone, so a new PV-module was installed in 2012.

Key Words: Agro-pastral, Djibouti, Solar pumping system, Wadi agriculture

1. Introduction

Authors installed a small solar pumping system in a farm which ran Wadi agriculture in the northeastern African Republic of Djibouti 2008. The farm is one of a practical farmer having three farms in the Dikhil city suburbs, and melon and onion are cultivated mainly there with grass or cover crops to breed the domestic animal for the making of compost. And the farm is located to midstream of Arouo Wadi, 42°33'E, 11°7'N, and 679 m above sea level.

In March, 2011 when three years passed after installing, we carried out an investigation into operation state of the solar pumping system. Because the system was operating although one of the PV-module included damage by the stone-throwing, we estimated the loss by the damage. As the result, as for the average quantity of discharge of pumping was 39 m^3 day^{-1}, and the estimated loss by damage was 9.24% (Tajima *et al*., 2012).

In August, 2013, we changed the damaged PV-module and investigated the operation situation of the system in the complete state. And we compared and considered about different in irrigation water quantity between March, 2011 and August, 2012. In addition, the PV-module that we changed assumed it a single crystal silicon type one of the same size, because it was hard to obtain a same type PV-module in Japan. **Figure 1** shows a ground plan of the farm and **Figure 2** shows the whole view of solar pumping system (Tajima *et al*., 2012) (GRUNDFOS:CU-200, SQF5A-6 with BP-SOLAR BP380J : 80 W×5 + NET SM55 : 95 W×1 + PHOTOWAT TPWX500 : 50 W×4, Total 695 W, Water Tank with 5×10×1.5 m＝75 m^3). In addition, the PV module array was set up 0° to the south and

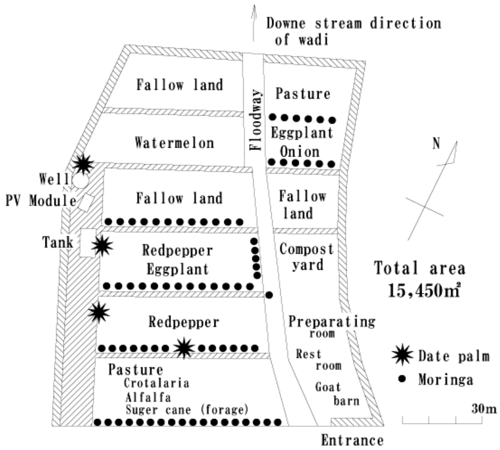

Fig. 1. Ground plan of the farm (Aug.2012).

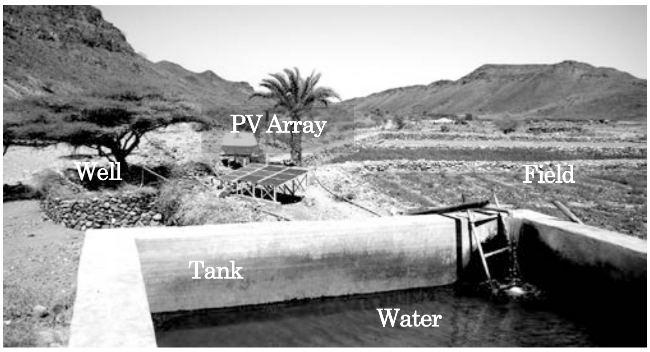

Fig. 2. Whole view of solar pumping system (Tajima *et al*., 2012).

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the tilt angle was 10° to horizontal level, and total array area was 5.82 m^2.

2. Objective

Identifying the appropriate scale of the system by investigating the operation situation of the solar pumping system for well which installed temporarily in Wadi agriculture of Republic of Djibouti. And we aimed to establish the investigation technique by using these data and to grasp the water income and expenditure when seasons are different.

3. Methodology

We measured the output voltage and output current of the PV system, sunlight strength, a change of the water level of the water tank and the well every five minutes. And we demanded a correlation of sunlight strength and quantity of pumping of the solar pumping system and, from provided data, estimated the operation situation of the irrigation system. But there was the intake, the discharge that we could not predict because an engine pump was used together for pumping, and the intake to a water tank and the discharge by the use were performed appropriately in any time. Thus, we found intake by the solar pumping from sunlight strength, and it was necessary to calculate irrigation quantity of water used for farming and the quantity of the intake by the engine pumping.

The measure which used a pyrheliometer (EIKO: ML-020VM), ammeter (SANWA: CL-22AD), a voltage measurement and data logger (SI-ELECTRONICS: TH3a), water level sensor (HOBO: U20 Water Level Logger 4 m), temperature-humidity meter (T&D: TR72U, TR71Ui). We carried out the measurement in 4.5 days until 12:00 of August 30 since August 25, 2012 and the interval of each measurement was five minutes.

4. Results

4.1. Global horizontal irradiance, temperature, PV-module temperature, and relative humidity

Figure 3 shows the 3-days results of a measurement until 25-27 days in August. Although it was a fine day as for the weather and was relatively stable, a change of the sunlight by the passage of the cloud was accepted. As for the global irradiance of 26th that was fine weather, up to 1.00 kW m^{-2}, the quantity of global horizontal irradiance were 26.0 MJ m^{-2} day^{-1}.

As for the highest temperature, the module temperature quite reached approximately 40°C, the minimum temperature with temperature +20°C with 62.6°C at approximately 25°C. It became lowest and, about the relative humidity, cut 10% at

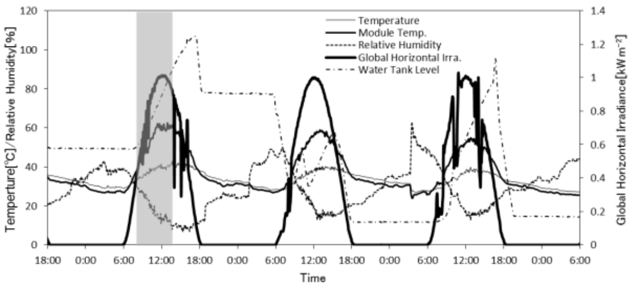

Fig. 3. Global horizontal irradiance, temperature, relative humidity and water tank level.

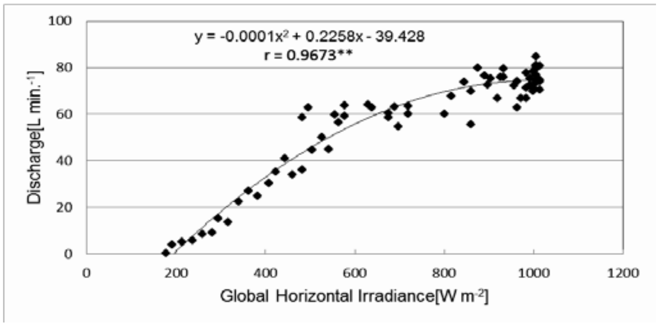

Fig. 4. Relationship between Global Horizontal Irradiance and Discharge of Pump.

about 2:00 p.m. when I showed the highest temperature. It was approximately 60% at about 6:00 of the daybreak to have shown the highest humidity. It was with the value that August that was the end of the wet season than March that was the end of the dry season was low about the humidity.

4.2. Global solar radiation and water level of the water tank

Figure 3 also shows the measurement results of the global solar irradiance and the water level of the water tank. Sunlight was stable and performed identification (approximately three hours of August 25 7:04 a.m.-12:59 p.m.) of time considered that there were not the intake from an engine pump and not use of the water in this result. Thus we demanded global solar irradiance relations of the pumping quantity of the solar pump. **Figure 4** shows the result. In addition, the number of the data was 72.

As a result of having recurred with a second curve, the coefficient of correlation was 0.9673, and the significant difference by the statistical significant test was meaningful with 1% of levels of significance.

4.3. Output of the PV-module array

Figure 5 shows the result of measurement of the output voltage and current of the PV-module array. The output current became shape that was approximately similar to a change of the solar irradiance. In addition, the output power wave pattern became approximately similar to solar irradiance because the output voltage was flat. And the output voltage

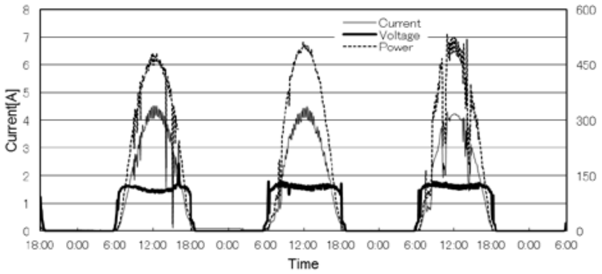

Fig. 5. Output of PV-module array.

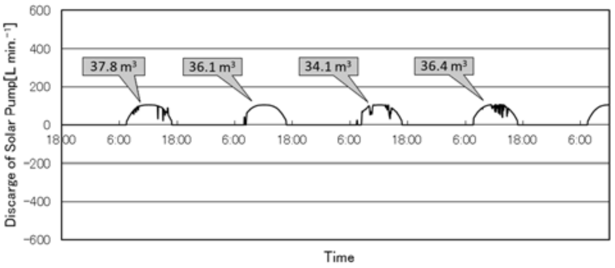

Fig. 6. Evaluated discharge of solar pump.

was approximately 130 V, the output current was up to 4.5 A, the output power was up to 530 W each.

Using the equation of regression that we found in section 4.2, we estimated the discharge of pumping from the global solar irradiance data during all measurement period. **Figure 6** shows the result of the estimation. Because relations of the global solar irradiance and the discharge of pumping was provided with a quadratic function curve, the pumping discharge was provided as a semicircular curve of the convex on the top. During the 4 days (August 25 6:00 a.m.-August 29 6:00 a.m.), the maximum pumping discharge was 109 L min.$^{-1}$ and the maximum pumping quantity per day was 34.1-37.8 m^3, the total pumping quantity was 144 m^3 and the average pumping quantity was 36.1 m^3 day^{-1}.

4.4. Intake and discharge of the water tank

We found the intake to the water tank and the discharge from the water tank by multiplying the horizontal cross section of the water tank by the result that differentiated the water level change wave pattern of the water tank. **Figure 7** shows the result. In addition, because the differential calculus wave pattern was unstable and vibrational, the data was smoothed with the moving average method with 6 data (5 minutes × 6 = 30 minutes). In Figure 7, the + side shows intake to water tank and the - side shows the discharge from the water tank which is mean the water use. Both of intake and discharge wave patterns were spike shape, and these wave patterns were clearly different from the intake rate wave pattern with the solar pump.

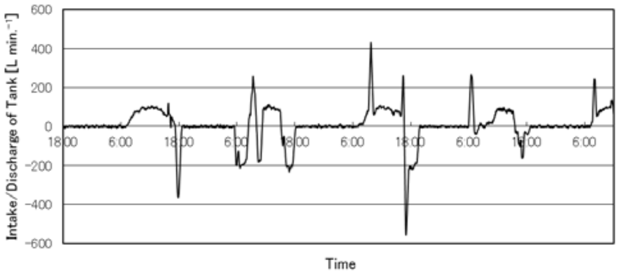

Fig. 7. Intake and discharge of the tank (1).

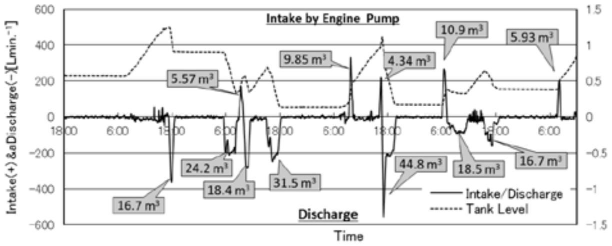

Fig. 8. Intake and discharge of the tank (2).

4.5. Estimate of the intake with the engine pumping and the discharge of the water usage

We estimated the water consumption and quantity of the water pumping with the engine pump, by deducting the discharge of the solar pump which calculated in section 4.2 (Fig. 6) from the discharge that we calculated from the water level of the water tank (Fig. 7). We show the result that was matched with the water level of the tank in **Figure 8**. In this, the + side of the figure showed the intake to a tank and the - side showed the discharge from a tank. In addition, the separation of the part that driving and the irrigation of the pump were carried out at the same time was difficult, but as a result of having demanded the quantity of water every each event by integral calculus, showed it in addition.

During the 4 days (August 25 6:00a.m.-August 29 6:00a.m.), the total quantity of pumping with the engine pump was 30.6 m^3, the use quantity of water was 167 m^3, and the day average was 7.66 m^3 day^{-1}, 41.7 m^3 day^{-1} each.

5. Considerations

5.1. Output power of the PV-module array

We changed one of the modules that glass part was damaged by stone-throwing three years ago and measured the output. We estimated that there was 9.24% of loss in comparison with the data just after the setting by the previous announcement in 2008. But we were not able to confirm the truth by the following reasons.

There was a difference to the ① solar irradiance and ② module temperature, because of the season when we measured. ① It was 62.9°C in March, 2012 whereas August, 2011 was up to 54.8°C in the daytime, and ② it was 25.0 MJ m^{-2} day^{-1} August, in 2012 whereas March, in 2011 was 27 MJ m^{-2} day^{-1} with the maximum. Generally, the output power would be dropped by the temperature of the PV-module in crystal silicon type with 0.41% °C^{-1} (Itagaki *et al*., 2013). Therefore in 2012, 0.41 × (62.9 - 54.8) = 3.32 % might be lower than data of 2011. In addition, because the output under 25°C in the standard of the performance notation of the module, it was expected 19-38 points of output dropped. When we watched a measurement result of 2012, the measured maximum output 547 W was equivalent to 82.6% of notation output 695 W, thus it was considered that the main reason of the output drop would be the temperature rise. Furthermore, the PV-module which we changed in 2012 was a mono-crystal silicon type. A research is pointing out that there is possibility of the degradation of performance in the mixture use of such a heterologous PV-module, although it is higher-performance than a poly-crystal silicon type before the exchange is accomplished (Nishikawa, 2008).

5.2. About quantity of pumping of the solar pump

The quantity of pumping of August, 2012 was 36.1 m^3 day^{-1} whereas the pumping quantity as of March, 2011 was 39.0 m^3 day^{-1}. It is thought that the latter was 25.0 MJ m^{-2} day^{-1} other than a difference of the temperature of the module whereas quantity of former sunlight was 27.0 MJ m^{-2} day^{-1}. However, it is necessary to convert it into the direct solar radiation on the inclined surface I_D to obtain the array input because these values are the direct global solar radiation H_D. Therefore we try to get the ratio T of these radiations by the following equations.

The first measurement was carried out at 4th March 2011, therefore n = 63, δ = -7.12°, $\omega_s = \omega_t$ = 91.5° were determined. And in the second measurement at 26th August 2012, n = 238, δ = 10.69°, $\omega_s = \omega_t$ = 87.8° could be determined.

$$T = \frac{I_D}{H_D} = \frac{\omega_t \sin(\varphi-\theta)\sin\delta + \cos(\varphi-\theta)\cos\delta\sin\omega_t}{\omega_s\sin\varphi\sin\delta + \cos\varphi\cos\delta\sin\omega_s} \quad (1)$$

$$\omega_s = \cos^{-1}(\tan\varphi\tan\delta) \quad (2)$$

$$H_0 = \frac{24}{\pi} \times I_{SC} \times \left(1 + 0.033\cos\left\{\frac{2\pi(n-2)}{365}\right\}\right) \times (\cos\varphi\cos\delta\sin\omega_s + \omega_s\sin\varphi\sin\delta) \quad (3)$$

$$K_T = H / H_0 \quad (4)$$

$$K = 0.9166 + 0.0866K_T - 2.8445K_T^2 + 1.8582K_T^3 \quad (5)$$

$$H_d = H \times K \quad (6)$$

$$H_D = H - H_d \quad (7)$$

$$I_D = T \times H_D \quad (8)$$

$$Id = (1 + \cos\theta) \times K \times H / 2 \quad (9)$$

$$I_r = (1 - \cos\theta) \times \rho/100 \times H / 2 \quad (10)$$

$$I_t = I_D + I_d + I_r \quad (11)$$

Here,

T: The ratio of I_D for H_D
I_D: Direct normal irradiance [W m^{-2}]
H_D: Direct global horizontal irradiance [W m^{-2}]
ω_t: Sunset - hour angle for array direction [degrees]
ω_s: Sunset - hour angle for horizontal surface [degrees]
θ: Array tilt angle [degrees]
δ: Solar declination [degrees]
φ: Latitude [degrees]
H: Global horizontal irradiance [W m^{-2}]
H_0: Extraterrestrial horizontal irradiance [W m^{-2}]
I_{sc}: Solar constant = 1.382 [kW m^{-2}] = 4.97 [MJ m^{-2} hr^{-1}]
n: Day number in the day [No.]
I_t: Normal irradiance [W m^{-2}]
I_d: Diffuse normal irradiance [W m^{-2}]
I_r: Reflected normal irradiance [W m^{-2}]
H_d: Diffuse horizontal irradiance [W m^{-2}]
ρ: Reflectance of the ground = 20%

Here, we got the solar radiation on inclined surface (I t) values, 28.3 MJ m^{-2} day^{-1} and 24.5 MJ m^{-2} day^{-1} by the upper expression (1)-(11) (Watanabe *et al*., 2013, Liew *et al*., 1960). Therefore we could calculate the conversion efficiency of the system, about 2011, 39.0 × 10^3 × 9.8 × 15 ÷ 5.82 / (28.3 × 10^6) × 100 = 3.48%, and about 2012, 36.1 × 10^3 × 9.8 × 15 ÷ 5.82 / (24.5 × 10^6) × 100 = 3.73 %.

In addition, the maximum discharge quantity was high with 108 L $min.^{-1}$ for 2012 whereas it was 88.0 L $min.^{-1}$ for 2011. We think that we cannot identify the cause that this difference produced when we do not analyze a change of the water level of the well which we did not measure in 2011 and relations with the solar irradiance. In addition, the change of the ground water level in the well in measurement period 2012, was 0.8 m at 14.4-15.2 m in lift, therefore we considered that it would be little influence in this simulation.

5.3. About use quantity of water

The use quantity of water of 2012 was fewer approximately 30% than 60.2 m^3 day^{-1} of 2011 in 41.7 m^3 day^{-1}. This was not only caused by difference of the solar irradiation, but by the difference of the planting crops. Anyway, we think that to perform correct analysis, data sampling period was too short.

In addition, there was little quantity of pumping with the engine pump with 7.66 m^3 day^{-1} for 2012 whereas it was 21.5 m^3 day^{-1} for 2011. It became 695 / 36.1 × (36.1 + 7.66) = 842W when we predicted necessary PV-module capacity based on a result of 2012 and was less than a prediction in 2011 saying that 957 W was necessary.

5.4. General consideration

We tried to confirm an output drop by the damage of the PV-module by comparing the measurement of August, 2012 with the measurement of March, 2011, but a difference of the PV-module temperature was big and was not able to confirm it. And if seasons were different, not only climatic condition but also the crops cultivated were different. Therefore we understood that the use quantity of water (irrigation water + domestic animal water to drink + compost fermentation water) was changed significantly.

Because we established technique in pursuit of the water use situation by measuring water level and the quantity of the water tank and the global solar irradiance, we want to connect it with establishment of the technique to chase not only the evaluation of the solar pumping system but also the water income and expenditure by a long-term measurement exactly in future in Wadi agriculture. In addition, about not only the traditional furrow irrigation but also the saving water effect by sprinkling irrigation or the drip irrigation (Amu-mensah *et al*., 2000; Takahashi *et al*., 2010), we would like to investigate these technology effects in Wadi agriculture with a local farmers.

6. Conclusions

We identified the appropriate scale of the system by investigating the operation situation of the solar pumping system in the Djiboutian Wadi agriculture. In addition, we established the investigation technique. Furthermore, we grasped the water income and expenditure when seasons are different. As a result of the executed field measurements for the purpose of identifying the appropriate scale of the system in March, 2011 and August, 2012, we got the following conclusions.

(1) There was a difference of around 8°C in PV-module temperature in two seasons and influenced the array output. By the driving of August, it was around 78.7% of driving output of the indication output.

(2) The quantity of pumping was 39.0 m^3 day^{-1} in lift of approximately 15 m in 36.1 m^3 day^{-1} (695 W), March, 2011 in August, 2012 (680 W one of the PV-module was damaged).

(3) The conversion efficiency of the system which I calculated from quantity of whole sky sunlight and quantity of pumping was 3.69 % with both years.

(4) The use quantity of water in the integrate Wadi agriculture (using grass production and a goat, product a melon and onions mainly while making soil) of 1.5 ha was 60.2 $m^3 day^{-1}$ in 41.7 $m^3 day^{-1}$, March, 2011 in August, 2012.

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