EXPERIMENTAL PERFORMANCE OF A PV-POWERED CENTER-PIVOT IRRIGATION SYSTEM

Juan I. Herraiz[1,2,*], Rita H. Almeida[1], Manuel Castillo-Cagigal[2], Luis Narvarte[1]
[1]Instituto de Energía Solar – Universidad Politécnica de Madrid, 28031 Madrid, España.
[2]Qualifying PhotoVoltaics. Centro de Empresas la Arboleda. Calle Alan Turing 1, 28031 Madrid, España.
[*]E-mail: ji.herraiz@upm.es

ABSTRACT: High-power diesel-based or grid-connected irrigation systems are giving way to high-power photovoltaic irrigation systems (PVIS) without batteries that reduce the energy costs by up to 80%. The operation of PVIS is affected by factors other than their quality, and there are no experimental data available about their performance. The traditional performance ratio (*PR*) needs to be factorized to better understand the losses strictly related with the PV system itself, the ones that vary with the crop and its irrigation period, what is intrinsic to the PVIS design, and what happens as a consequence of the behavior of the end-user. This article provides the PV community experimental performance data of a battery-free 160 kWp PV-powered constant pressure center-pivot irrigation system. The system has been analyzed over one year of real operation in which the performance ratio was 48.1%.
Keywords: Performance, PV irrigation system, Water pumping, Stand-alone PV system

1 INTRODUCTION

High-power photovoltaic irrigation systems (PVIS) are increasing worldwide [1][2][3][4], taking the place traditionally held by high-power diesel-based or grid-connected irrigation systems [5]. Rising energy costs in modernized agriculture [6][7][8] is being decisive in accelerating this process.

Until recently, PVIS consisted of a PV generator, a frequency converter (FC) and an alternating current centrifugal motor pump [9][10][11]. The maximum power of the systems was 40 kWp due to fluctuations in PV power that caused instabilities and sudden stops of the FC, producing water hammer in the hydraulic system and overvoltages between the FC output and pump motor [12][13][14]. This problem was solved by integrating batteries [15][16][17], but their high cost prevented the power of the systems from being increased.

In the last decade, the development of new control algorithms [18] solved control instabilities and the use of horizontal north-south axis trackers led on to quasi-constant daily PV power profiles that better adjust to irrigation needs [19][20][21]. New communication protocols and irrigation controllers improved the control of irrigation systems. "Delta" support structures (fixed structures with an east-west orientation) were also proposed for the PV generator to produce constant power profiles [22].

Regarding performance, as the operation of high-power PVIS is affected by external factors other than their quality, the *PR* calculation needs to be reconsidered. In 2018, Almeida et al. [1] proposed to factorize the traditional *PR* into various utilization ratios to quantify and better understand the impact of these external factors on the system performance. The new indices considered different types of losses: losses strictly related with the PV system itself (PR_{PV}); losses that vary with the crop and the irrigation period (UR_{IP}); those intrinsic to the design of the PV generator and the hydraulic infrastructure (UR_{PVIS}); and losses that happen as a consequence of the behavior of the irrigator (UR_{EF}) [1]. These indices where applied to hybrid PV-diesel and PV-grid systems to irrigate olive trees through drip systems (at constant pressure) [1] and, lately, to PVIS pumping to water pools (at variable pressure and water flow)[23]. Anyway, there is still a lack of information available in the literature on experimental performance data that allows us to know what the expected performance is in this type of systems.

This paper provides the PV community experimental performance data of a PV-powered center-pivot irrigation system and opens the door to the knowledge of the expected performance in this kind of systems.

The paper is structured including a methodology section that describes the PVIS under study and the performance indices to be calculated, a results section that presents the results of the performance evaluation and the discussion of these results and a conclusions section that summarizes the main conclusions of the work.

2 METHODOLOGY

2.1 Description of the PVIS

The system is located in Alejos, Spain (41º16'23.4''N, 5º16'48.8''E) and belongs to the cooperative "Estrella de San Juan", irrigating a total area of 150 ha.

The pre-existing system consisted of a diesel generator that fed two frequency converters which in turn fed two pumps: a 92 kW submersible pump (Caprari – E10S50S/6C+MAC10125DS-8V), pumping water from a 140m-deep borehole to an elevated water tank of 1000m^3, and a 30 kW surface centrifugal pump (Caprari – MEC-AS2/80A+FELM 30KW 2P), in charge of pumping water from the tank to the irrigation network at a constant pressure required by an accurate performance of the pivot sprinkles.

The PV system consists of a 160 kWp PV generator, divided into 8 North-South horizontal trackers, and three additional FCs: a 110 kW FC that feeds the 92 kW submersible pump, a 37 kW FC that feeds the 30 kW pump and another 37 kW FC used to feed the motors for the movement of the pivots and working at a constant frequency of 50 Hz to simulate an electrical grid. Figure 1 shows the configuration of the system.

By definition, the system is considered a stand-alone PV pumping system. However, since the pre-existing system was kept, the whole system can operate in three operation modes that the user can manually choose:

- PV mode: the entire irrigation system is fed by the PV generator.
- PV/Diesel mode: pivots and the irrigation pump

are fed by the PV generator while the borehole pump is fed by the diesel generator.
- Diesel mode: the only power supply is the diesel generator.

The PV system is being used in PV mode to pump the maximum volume of water during the day, punctually using the diesel generator when the PV system does not provide enough energy to keep irrigation working during low availability of radiation or at nights.

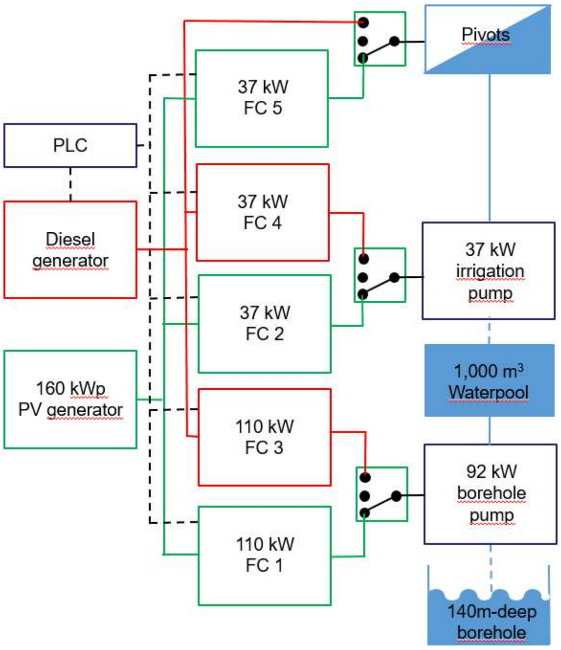

Figure 1. PVIS configuration: A PV generator, three FCs (all in green), and a PLC have been added to the pre-existing configuration (diesel generator and two FCs in red and two motor-pumps).

The system includes an external PLC that depending on the end-user irrigation needs, the selected operation mode, the estimated available PV power and the borehole and tank water levels, controls the start and stop of the FCs. The irrigation FC has priority over the borehole FC in case there is not enough PV power to make both pumps work. Otherwise, the PLC controls the start and stop of the FCs based on a set of thresholds: one start threshold and one stop threshold to operate each FC. When the estimated available power is higher than the first start threshold (35 kW), the PLC sends a start signal to the irrigation FC and the irrigation pump starts operating. Another start signal is sent to the borehole FC when the estimated PV power is greater than a second start threshold (110 kW). If the estimated PV power falls below any stop threshold (51 kW for the second FC and 30 kW for the first one) during a 60 second time interval, a signal is sent to the corresponding FC to stop. In order to avoid start/stop cycles due to tank water levels a hysteresis control based on four thresholds is used. When the tank water level is below a minimum threshold (L1), typically a 5% of the tank capacity, the tank is considered to be empty and the irrigation FC is stopped. It will only be started by the PLC when the tank water level reaches a second threshold (L2), typically a 10% of the tank capacity. Similarly, when the tank water level reaches a maximum threshold (L4), typically 100% of the tank capacity, the borehole FC is stopped and it is only restarted when the water level drops below L3 (usually 90% of the tank capacity).

Besides the PLC operating logic, all FCs have their own control programmes. The FC that feeds the borehole pump is controlled by a Maximum Power Point Tracking (MPPT) routine that maximizes the efficiency of the PV production. The irrigation FC runs a pressure control routine, to keep pressure at the irrigation network constant (there are three different pressure setpoints, 3, 4 and 5 bar, according to the field sector that is being irrigated). And the pivots FC is parameterized to work continuously at 50 Hz, simulating the grid. All FCs have passing cloud routines that allow the system not to be destabilized by fast irradiance fluctuations.

The system is monitored by means of one-minute records of: output frequency, V_{DC}, I_{DC}, P_{DC}, V_{AC}, and I_{AC} of irrigation and borehole FCs, pressure and pressure setpoint for the irrigation network, G and T_c.

2.2 Indicators used to assess the PVIS in real operating conditions

The performance ratio (*PR*) [24] has been traditionally used to analyse the performance of PV grid-connected plants. It is defined as $PR = E_{PV}/((P^*/G^*)\int Gdt)$, where P^* is the peak power of the PV generator, G^* is the irradiance at standard test conditions (1000W/m^2), G is the irradiance on the plane of PV generator, and E_{PV} is the energy produced by the PV system,.

Due to their specificities, High-power PVIS include *PR* losses not only related to the quality of the PV system itself, but also to the crop and its irrigation period, the intrinsic characteristics of the PV irrigation system design and external circumstances that may affect the *PR* like the irrigation community decisions. Considering them, the *PR* can be expressed as [1]:

$$PR = \frac{E_{PV}}{P^*/G^*} \cdot \frac{1}{\int Gdt} \cdot \frac{\int_{IP} Gdt}{\int_{IP} Gdt} \cdot \frac{\int G_{useful}dt}{\int G_{useful}dt} \cdot \frac{\int G_{used}dt}{\int G_{used}dt}$$

where:

IP is the irrigation period determined by the water needs of the crop and, in case of pumping to a water pool, by the relation between water needs, pumping capacity and pumped water storage capacity.

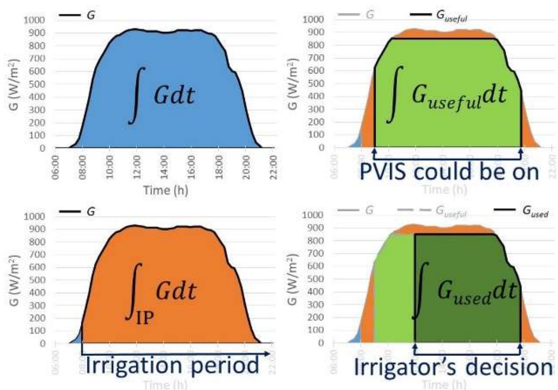

Figure 2. Graphical representation of $\int Gdt$, $\int_{IP} Gdt$, $\int G_{useful}dt$ and $\int G_{used}dt$.

G_{useful} (Figure 2) is the irradiance required to deliver the power needed to pump water, when available, during the IP. It is determined by the relationship between the PV generator nominal power (P^*), the PV generator supporting structure, and the characteristics of the irrigation system. When the available irradiance is below a minimum threshold, the system cannot pump because there is not enough power. When the available irradiance is above G_{useful}, part of the irradiance is wasted because the PV generator cannot supply more power than that consumed by the pump working at its nominal power.

G_{used} (Figure 2) is the irradiance effectively used by the system and depends on external circumstances like the availability of water or the irrigator's decisions about whether to activate the system or not.

The previous equation can be rewritten as

$$PR = PR_{\mathrm{PV}} \times UR_{\mathrm{IP}} \times UR_{\mathrm{PVIS}} \times UR_{\mathrm{EF}} \; [1],$$

where:

$$PR_{\mathrm{PV}} = \frac{E_{\mathrm{PV}}}{P^*/G^*} \cdot \frac{1}{\int G_{\mathrm{used}} dt}; \; UR_{\mathrm{IP}} = \frac{\int_{\mathrm{IP}} G dt}{\int G dt}$$

$$UR_{\mathrm{PVIS}} = \frac{\int G_{\mathrm{useful}} dt}{\int_{\mathrm{IP}} G dt}; \; UR_{\mathrm{EF}} = \frac{\int G_{\mathrm{used}} dt}{\int G_{\mathrm{useful}} dt}$$

PR_{PV} is the *PR* considering losses strictly related to the PV system itself; UR_{IP} is the utilization ratio considering losses related to the irrigation period; UR_{PVIS} is the utilization ratio considering losses related to the PVIS design (type of irrigation system, the ratio PV peak power - PV power required for irrigation, the tracking geometry and the accuracy of the PLC control algorithms setup); and UR_{EF} is the utilization ratio considering losses related to the irrigator's decisions.

In addition to the *PR*, Herraiz et al. [23] describe the importance of two other indices to assess the correct functioning of PVIS: the number of abrupt stops and the passing-cloud resistance ratio. In order to calculate these indices, the PVIS requires to be monitored by means of one-second records. Since the monitoring system of the PVIS under study only collects data every minute, it has not been possible to obtain these indices in the present work.

3 RESULTS

Monthly performance indices for 2021 are shown in Table I.

Table I. Monthly real performance indices (%)

Month	PR_{PV}	UR_{IP}	UR_{PVIS}	UR_{EF}	*PR*
Jan	90.0	9.2	86.3	100	7.1
Feb	-	0.0	-	-	0.0
Mar	82.5	59.4	76.9	87.4	32.9
Apr	80.8	100	73.5	96.4	57.3
May	79.3	100	74.4	95.7	56.4
Jun	78.1	100	76.4	90.9	54.3
Jul	78.0	100	81.9	98.0	62.6
Aug	75.7	100	87.6	97.6	64.7
Sep	77.9	100	62.0	93.2	45.0
Oct	76.3	100	74.7	97.0	55.3
Nov	78.8	56.7	62.1	43.5	12.1
Dec	79.5	1.3	66.9	93.4	0.6
Total	78.2	85.7	76.4	93.9	48.1

PR_{PV} values (78.2% for the whole year) are similar to *PR* values expected for grid-connected PV systems.

UR_{IP} is 85.7% because the irrigation period starts on March the 17th and ends on November the 15th. For this reason UR_{IP} is 100% from April to October, close to 50% in March and November, and close to 0 in January, February and December. Values greater than cero in January and December are due to the occasional start-up of the system to fill the water tank.

UR_{PVIS} value is 76.4%. Compared to those reported by [23] for PVIS pumping to a water pool, the obtained value is similar to the 75.6 reported for Aldeanueva PVIS but lower than the 85.2 of Villena PVIS. It is reasonable to expect a lower UR_{PVIS} for a constant flow and constant pressure PVIS than that expected for a PVIS pumping to a water pool, in which the flow of pumped water can be adjusted to the available power. Similar UR_{PVIS} values for both types of systems must be explained based on the design decisions for each system (for example, an oversizing of the PV generator of the PVIS pumping to a water pool would explain the lower UR_{PVIS}).

The design factors that most affected the UR_{PVIS} value of the PVIS under study during 2021 are:

- The ratio PV peak power - PV power required for irrigation. At the beginning of the day, or whenever the irradiance is low enough, the PV generator does not generate enough power to start the motor-pumps (depending on the irradiance and the PV peak power). The PLC estimates the available power and starts the FCs when possible according to the stablished thresholds. On the other hand, when the irradiance is high the PV generator can provide more power than the maximum that can be consumed by the system. The difference between the available irradiance and the maximum irradiance needed to make the whole system work is wasted. UR_{PVIS} can be improved by adjusting the PV peak power and the start and stop thresholds for all the FCs, but there is always a part of the irradiation that is wasted.
- The time the PLC waits to start a FC after it has been stopped. To protect the pumps from continuous stops and starts, the PLC waits a certain time (8 minutes for the borehole FC) after a stop until it commands a new start. On days with many passing clouds, in which the irradiance can vary abruptly and drop below the minimum thresholds required to operate the system, the FCs remain stopped, at 8-minute intervals, part of the irrigation time.
- The water tank capacity. The tank has been empty or completely full at some points of the irrigation period. A full tank prevents de PLC to start the borehole FC, while an empty tank stops the irrigation FC. A larger tank capacity would have mitigated this effect.

UR_{EF} value (93.9%) is smaller than expected (close to 100%). The possibility of operating the system in diesel mode and the water needs of the crop have led the irrigator to activate the system in diesel mode at night and in times of low irradiance. The delay in switching to PV mode when the irradiance allowed it has caused the UR_{EF} to worsen. This effect has been increased by long stops of the system when the irrigator changed the irrigation program.

PR is below 50% (48.1%) due to the combined effect of all the indices, but specially UR_{IP} (highly dependent on the crop) and UR_{EF} (which is lower than expected). If UR_{EF} had been closer to 100%, assuming the same values for the rest of factors, the *PR* would have reached 51.2%

Data show that UR_{IP} is very dependent on the crop and that it is reasonable to expect PR_{PV} values close to or even above 80.0%, UR_{PVIS} values above 75.0%, and UR_{EF} values very close to 100% when the irrigator uses properly the PVIS (PV irrigation centred at midday, planning of maintenance tasks in cloudy days or during the night, management of water consumption,…).

PR_{PV}, UR_{IP}, UR_{PVIS} and UR_{EF} determine PR values. Their expected values make us suggest that it is reasonable to expect PR values above 50% in high-power constant pressure PVIS. But this statement must be confirmed with future measurements in other similar systems

4 CONCLUSIONS

Stand-alone high-power PV irrigation systems without batteries is a recent innovation and there are not enough experimental data about the performance of this kind of systems available. This paper is a contribution to the knowledge of the experimental performance data of a constant pressure center-pivot PV irrigation system and, thus, to the expected values for other similar systems.

To assess the systems performance, the traditional PR has been factorized into four factors: PR_{PV} (evaluates the performance quality of the PV system itself), UR_{IP} (measures the effect of the crop irrigation period), UR_{PVIS} (measures the effect of the hydraulic irrigation system) and UR_{EF} (considers losses due to the user behavior).

Relevant conclusions can be drawn from the results about the performance that can be expected from this type of system: The expected PR in good quality constant pressure PV irrigation systems is over 50%. The expected values for the different factors are: PR_{PV}>=80%, similar to what is expected in grid-connected PV systems; UR_{IP}>=85% if the needs of the crop are extended for most of the year; UR_{PVIS}>75% and UR_{EF}≈100% if the end user makes appropriate use of the PV irrigation system.

Nevertheless, it is necessary to confirm these expected values with experimental measurements in other high-power constant pressure PV irrigation systems.

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