Performance study of a standalone direct pumping photovoltaic system used for drip irrigation

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Abstract: Photovoltaic (PV) energy attracts more people to pump water as a friendly environment technology and provide autonomy in many remote areas. Morocco characterized by its important solar potential, promote use of this alternative energy in agriculture. Photovoltaic water pumping systems (PVWPS) coupled directly to drip irrigation network represents an affordable technique that can be promoted without use of any capacitive device for electric or hydraulic energy storage. This paper aims to study performances of a standalone photovoltaic pumping system confronted to actual behaviour of incident irradiance. The system is based on a photovoltaic generator, a maximum power point tracking (MPPT) and direct curent (DC) converter, and a DC diaphragm pump connected to calibrated (Flow versus Pressure) orifices to simulate small drip irrigation network, mounted in parallel scheme to vary the pump operating point according to timely varied irradiance. The result showedthat daily trend of solar irradiance influence considerably operating behaviour of the pump, consequently the performance of the standalone PV system is affected as there is inadequation between charges of the PV generator and the DC pump. The hydraulic efficiency trends showed a dispersion and varying performances according to irradiance change and to hydraulic system unstability. A method of governing hydraulic performance is proposed to improve the system efficiency and pressure stability as requirements for water distribution uniformity in drip irrigation network supplied by a standalone PV pumping system.

Keywords: standalone, photovoltaic pumping system, performances, irradiance, efficiency, MPPT, DC pump

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1 Introduction

In many parts around the world and in developing countries, agriculture production is mainly based on rainfall for crop production and something on small pumping systems based on groundwater for irrigation. In Morocco, small scale farming is dominant and needs significant technological solutions for improving it's subsistence.

In the last decades, agricultural production systems are most vulnerable to energy prices rising (fuel and electricity) and consequently final costs of agricultural products are influenced.

According to subsequent fuel price rising, farmers transformed their diesel based irrigation pumping systems to butane, meanwhile butane is considered as a low cost energy that is subsidized. Approximately more than 100000 ha that are irrigated in this way, with a consumption of 3349.10^{10} KJ year^{-1} (Moumen, 2014). As alternative, the promotion of using alternative energy is becoming important according to existing average irradiance in Morocco (about 2.253 kW hm^{-2} year^{-1}) (Giz, 2011). Moroccan government initiated a national program on photovoltaic pumping in 2013 to promote irrigation pumping for small scale farming representing a workforce of 90% and an area of 44% (Missaoui, 2014). Odeh et al. (2006) compared PV water pumping system to diesel based system, and showed better technical and economical performances for equivalent hydraulic energy

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capacities up to 8000 m^4/d, 4100 m^4/d and 2600 $m^{4/}$d for interest rate values of 0% (subsidized project), 10% (average market rate developing countries) and 20% (high market rate), respectively.

Photovoltaic water pumping systems **(**PVWPS) are mainly used for drip irrigation to save energy and water and promote sustainability of farming systems (Reca et al., 2016). Performance of PV pumping systems for irrigation depends mainly on its design. Sizing is considered as the important step that could lead to system reliability and cost effectiveness (Renu et al., 2016). However, knowledge on crop, soil and irrigation systems adaptation are required (Firatoglu and Yesilata, 2004; Glasnovic and Margeta, 2007; Gad and Safya, 2011). Adaptation of PV panels to pump requirement cannot be fullfiled without integration of a robust energy conversion of Direct Current to Alternating Current (DC-AC) or Direct Current to Direct Current (DC-DC) for a pumping systems performances. Several studies were done on PVWPS performance and use maximum power point tracking (MPPT technologies) (Sefriti and Boumhidi, 2015). Akihiro et al. (2009) simulated PVWPS performance using MPPT algorithms of Incremental Conductance (IncCond) and Perturb and Observe (P&O) on Matlab/Simulink. They found that low efficiency of PVWPS can be improved by 35% using MPPT technology and the system valorized more than 99% of the PV panel's energy to satisfy more than 87% of water requirement. Khan et al. (2012) studied performance of standalone PVWPS based on DC-DC converter coupled to a DC pump. The system efficiency has been improved by integrating close loop control with DC-DC buck converter to increase its daily pumping output. Essam et al. (2017) developed a standalone PVWPS based on batteries energy storage to drive brushless direct current (BLDC) motor-pump. They proposed an integrated control strategy based on use of MPPT, speed control and hysteresis current of the BLDC motor and batteries charging/discharging optimization to improve an overall system efficiency.

In last decades, use of DC pumps has been promoted to improve performance of PV based irrigation systems. In fact, technologies emergence of BLDC motors and positive displacement pumps improved cost effectiveness by decreasing maintenance rate and efficient use of DC pumps in PV agricultural irrigation. Compared to centrifugal pumps, positive displacement pumps are characterized to efficiently work at high pressure (more than 100 m) and low flow rate requirements. But, it cannot be appropriate to be associated directly with PV panels without adequate linking between photovoltaic energy input and irrigation network charge. Positive displacement pumps are only used for DC low-voltage applications (24 to 48 V) to deliver small daily flows (up to 5 m^3 day^{-1}). Hamidat et al. (2003) studied performance of PVWPS using both centrifugal and positive displacement pumps. They used a multistage centrifugal pump coupled to alternating current (AC) motor and three-phase inverter. The second pump is coupled to DC-DC converter actuating a BLDC motor. They showed that the positive displacement pump was an efficiency of 45% compared to centrifugal pump efficiency reached only 14%. In other study, Hamidat and Benyoucef (2008) compared PVWPS performances of centrifugal and positive displacement pumps simulation for different sites characterized by atmospheric conditions (Saharan climate and raining in summer). A comparison between electrical and hydraulic performances of both centrifugal and positive displacement pumps showed better efficiency, less energy losses and high water volume pumped by the positive displacement pump. Protogeropoulos and Pearce (2000) and Kashyap et al. (2013) stated that more improvements are needed for standalone PVWPS to satisfy water demand in small drip irrigation systems with control of surrounded pressure change due to influence of daily insolation variation.

This paper aims to study performance of a standalone PVWPS based on a DC positive displacement pump faced to actual problem of overcoming hydraulic instability of connected drip irrigation network due to varying solar irradiance. Studying a standalone PVWPS based on a DC pump is of importance to find better adequation between pressure potential of a positive displacement pump to deserve a hydraulic network (mounted of parallel nozzles to simulate drip irrigation lines). The parallel scheme simulates operating behavior of a small drip irrigation system that requires a constant operating pressure and better distribution uniformity.

2 Materials and methods

To evaluate performances of the standalone PVWPS, a test bench (Figure 1) based on a PV panel (Monocrystal Silicon Module, Sharp^{TM} 175W$_p$), an MPPT controller (Victron Blue Solar 48/24/12V), a DC diaphragm Pump (FLOJET, 12 VDC, 144W) and a hydraulic ramification of seven identical calibrated orifices (Albuz, 11004, 1.3 L.min^{-1} at 3 bar) mounted in parallel scheme to simulate outputs of a connected irrigation network and to evaluate flow rate withreference to pressure potential created by the pump using orifices hydraulic models (Q vs P).

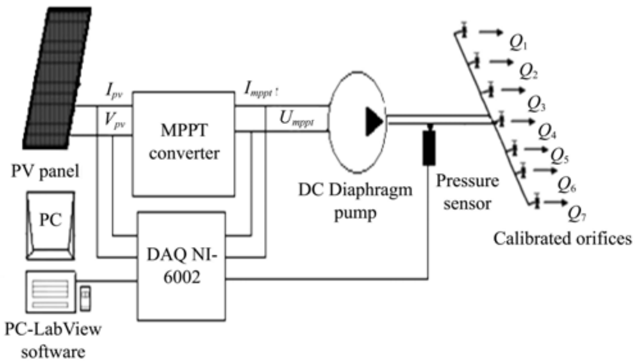


Figure 1 Test bench of a photovoltaic DC pumping system without capacitance

The PV panel current (I_{pv}) and voltage (V_{pv}), the MPPT converter current (I_{mppt}) and voltage (U_{mppt}) and the pump downstream pressure are acquired during one day from 8:00 am to 6:00 pm (sampling frequency of 100 Hz, sampling interval of 5 min hr^{-1}).

The acquired data were treated to select systematically five values per second for evaluating electrical and hydraulic efficiencies according to pump operating point behaviors influenced by variation of the solar irradiance and number of the orifices switched on (from one to seven).

Voltage and current sensors (ACS712) were installed at upstream and downstream points of the MPPT converter to evaluate electrical power at the both levels using Equations (1) and (2):

$$P_{pv} = V_{pv} \times I_{pv};$$
$$P_{mppt} = V_{mppt} \times I_{mppt} \quad (1)$$
$$I_{pv} = (a_1 \times V_{s1}) + b_1;$$
$$I_{mppt} = (a_2 \times V_{s2}) + b_2 \quad (2)$$

where, P_{pv}, P_{mppt}, a_1, b_1, a_2, b_2, V_{s1} and V_{s2} arepower of PV panel, power of MPPT converter, intercepts and constants ofcurrent calibration curves and Voltages sensors outputs, respectively. The operating pressure was measured using an analogue sensor (Wika Tronic Line, P_{max} = 10 bar) mounted between the pump and the seven orifices to evaluate its flow rate according to the hydraulic models (Equation (3)):

$$Q = K \times P^X \text{ (bar)} \quad (3)$$

where, Q, P, K and X are flow rate (L min^{-1}), pressure (bar), discharge coefficient and exponent of the hydraulic orifice model, respectively. The parameters K and X were taken experimentally by calibration of the seven orifices (Table 1).

Table 1 Hydraulic parameters of the seven orifices

Orifices number	*K*	*X*
Orifice 1	1.1557	0.5006
Orifice 2	1.1718	0.5186
Orifice 3	0.5778	0.5384
Orifice 4	0.968	0.5745
Orifice 5	1.1576	0.5053
Orifice 6	1.1369	0.5042
Orifice 7	0.7663	0.4759

The current sensors were calibrated using an acid lead battery source supplying a circuit of parallel mounted automotive lamps (12 VDC, 55 W) (Figure 2(a)). The calibration model is presented in Figure 2(b). All data were acquired as voltage analogue input using Labview^{TM} software and DAQ NI-6009data acquisition system. The actual data were taken using the calibration curves (Figure 2(b)) and Excel software.

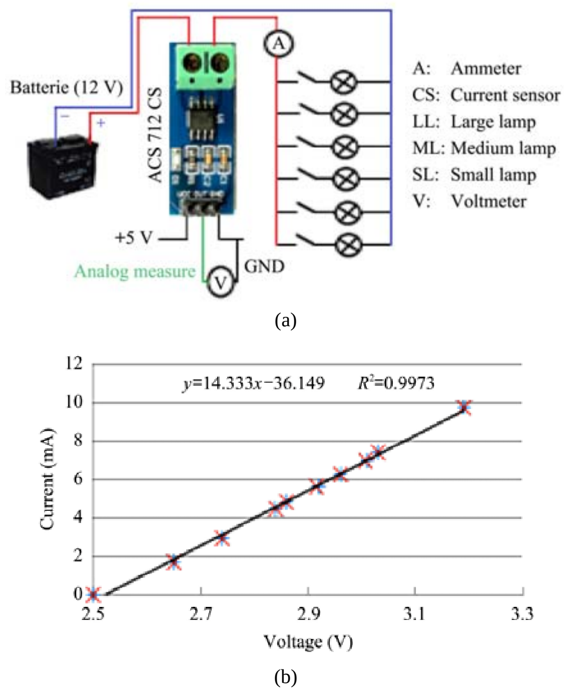
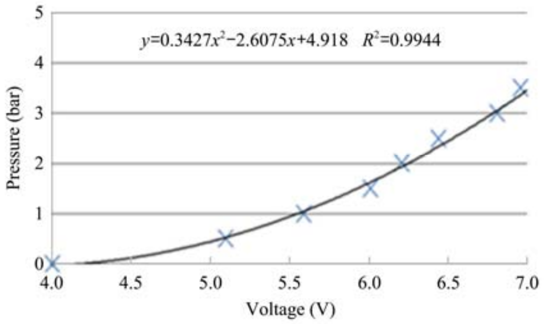
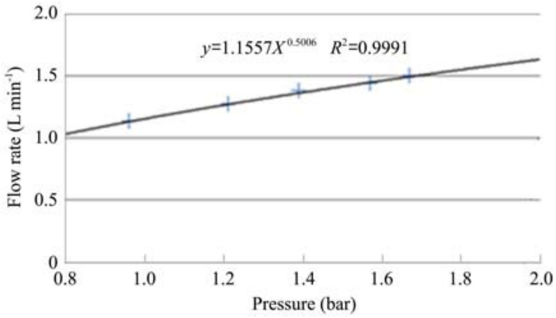


Figure 2 (a) Setup calibration of the current sensors; (b) the calibration curve (Amperage amperage versus Voltagevoltage)

The orifices calibration curves (Figure 3) were taken experimentally by varying pressure level according to engaged number of orifices (from one to seven) to take thirty five points of pressure vs flow rate. Figure 3(b) shows the calibration curve due to one engaged orifice.



(a) Pressure versus voltage



(b) Flow rate versus pressure

Figure 3 Orifice calibration curves

The pump flow rate was computed according to the orifice calibration curves obtained for each orifice. The parameters of each orifice are represented in the Table 1. The calibration curve of the pump was taken using 12 VDC acid lead battery and pulse width modulation (PWM) to set the pump rotational speed (rotation per minute or rpm) using two voltage supply of 6 and 12 VDC. Two pump calibration curves (referenced to both voltages) were served as references curves (Figure 4) to evaluate operating points of the pump and relatives performances taken experimentally during the study day.

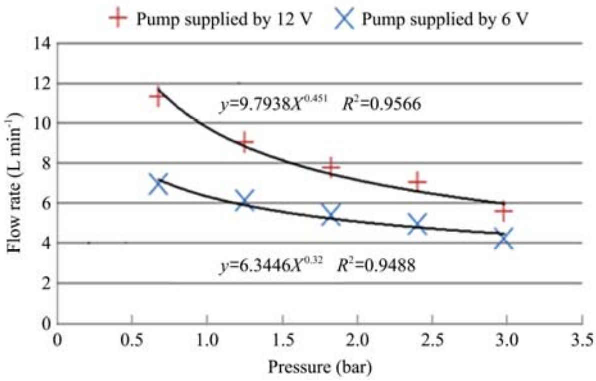


Figure 4 Pump calibration curves for 6 VDC and 12 VDC

Irradiance datas were taken using meteorological station located at the research center (X: –7.624233, Y: 32.953487). The daily irradiance data occurred in May 25th, 2017 was taken as reference (Figure 5).

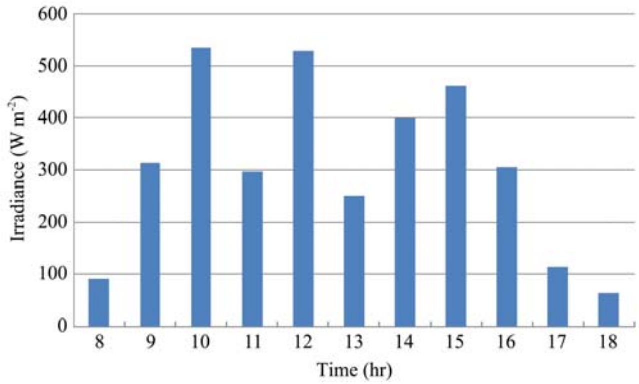


Figure 5 Daily solar irradiance of May 25th, 2017

3 Results and discussions

Performance of the PVWPS studied by monitoring the pump behavior (From 8:00 am to 6:00 pm) showedchanges of the pump efficiencyaccording to daily solar irradiance.

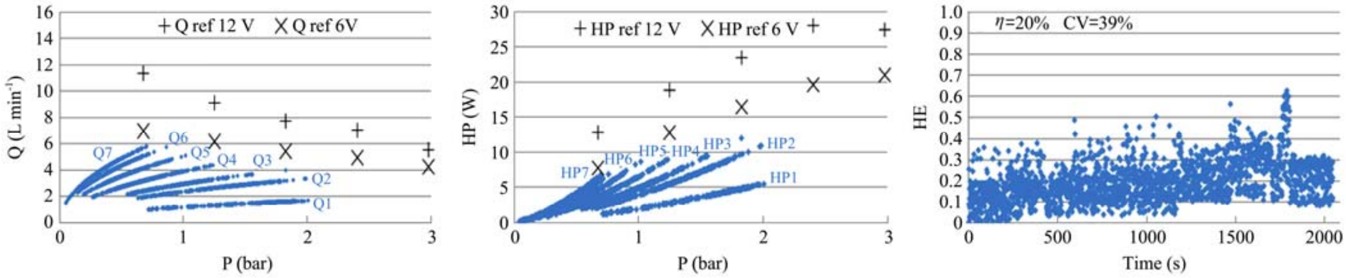
Figure 6(a) shows the pump response relative to low irradiance of 90 W m^{-2} (8:00 am). Seven flow behaviors are presented with reference to the number of engaged orifices to displace the pump operating point as flow rate decreasing causes pressure increasing. This displacement show that is possible to operate pump not only to satisfy requirement of operating the orifice around a stable and predefined operating pressure (network requirement of a drip irrigation system) but also to satisfy condition of better performance. In fact, adaptation between the number of engaged orifices and actual irradiance is needed to actuate the pump around its better performance. As the pressure is satisfied, a better performance is correlated with an engaged part of the hydraulic network (number of engaged orifices).

The characteristic curves, flow vs pressure [$Q = f(P)$] and hydraulic power vs pressure [$P_h = f(P)$] don't converge with reference curves of the pump (Figure4) as solar irradiance is lacking in the morning for the best performance convergence.

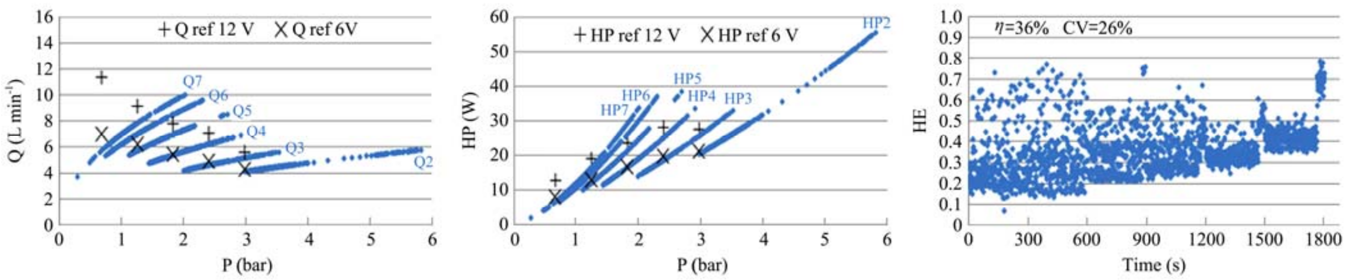
Graph two (Figure 6(a) /8:00 am) illustrates varying behavior of hydraulic powers due to the variation of flow and pressure induced by variation of the number of orifices switched on. This make possible control of the pump operating point and prediction of its convergence for best efficiency and/or for satisfying operating pressure required for best uniformity distribution of connected drip irrigation system.

Graph three **(**Figure 6(a)/ 8:00 am**)** shows the overall system efficiency varying from 1% to 63% (average of 20%). This shown dispersion in efficiency is due to the standalone system behavior as any capacitance is set to regulate and stabilize instantaneous behavior of flow vs pressure influenced by solar irradiance change.

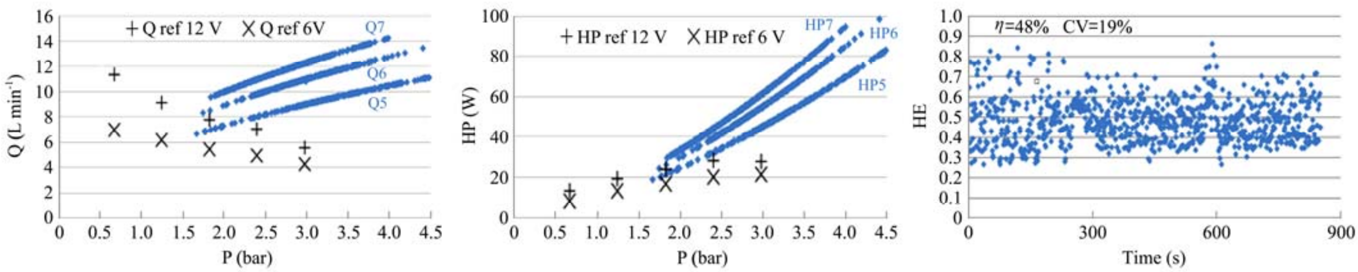
Similarly, the system behavior (Figure 6(d)) at 11am is influenced by low incident irradiance (385 W m^{-2}). Consequently, the pump efficiencies are affected. All characteristic curves are kept below the reference curves of the pump calibration using 6 and 12 VDC supplies (Figure 4).



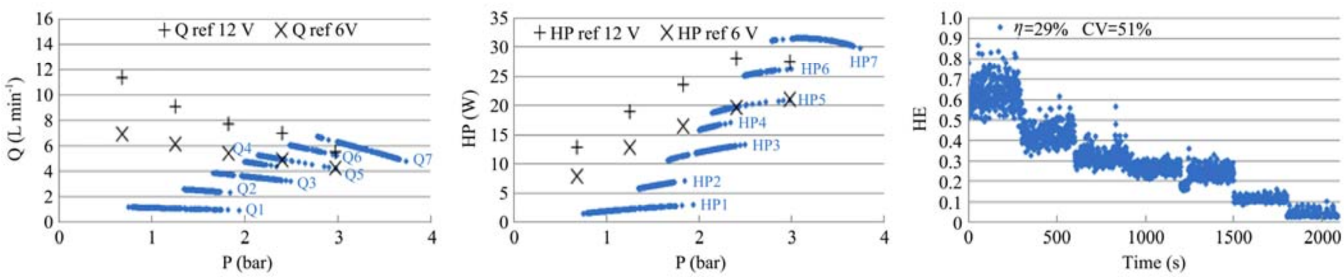
(a)



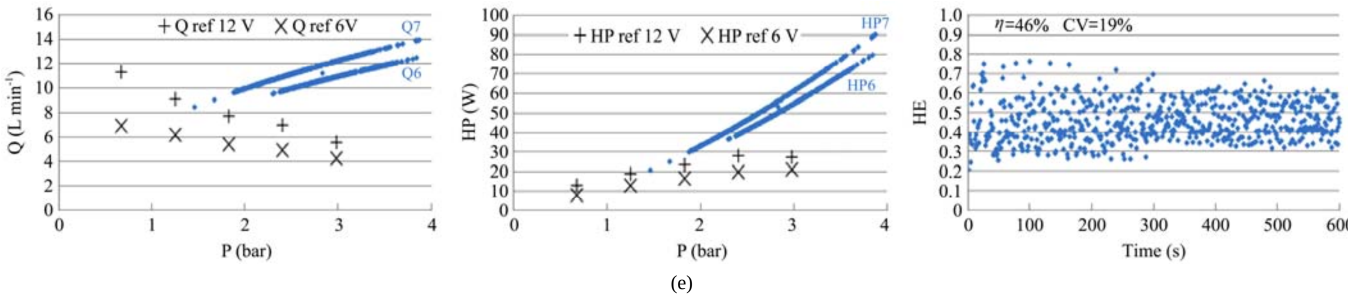
(b)



(c)



(d)



(e)

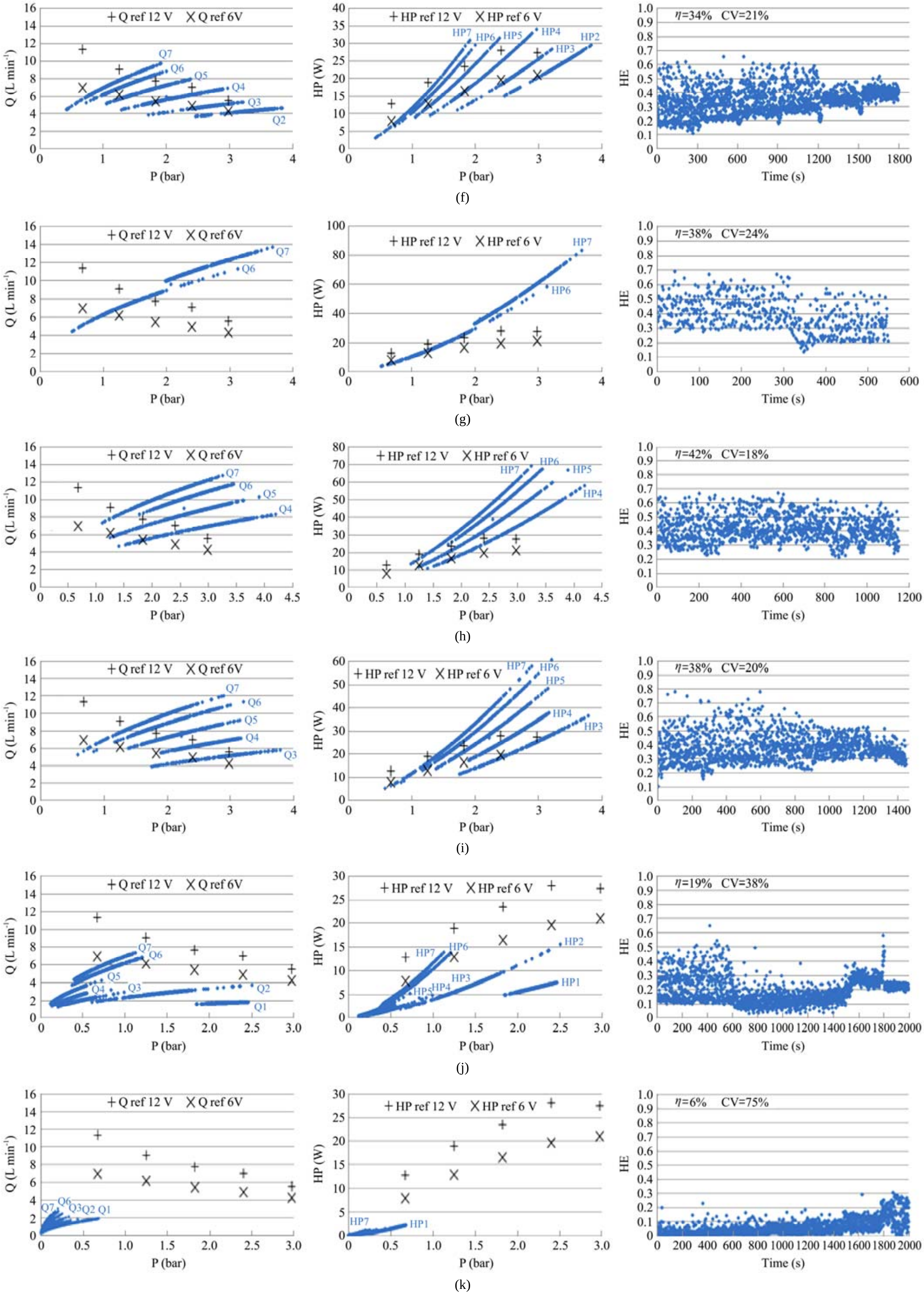


Figure 6 Performance of PVWPS from 8 am to 1 pm and from 2. pm to 6. pm

The system performance at 6:00 pm (Figure 6(k)) showed a behavior similar to of 8:00 am. This is practically due to lack of incident irradiance (63 W m^{-2}). The third graph (Figure 6(k)) shows an efficiency varying from 3% and 65% with an average of 20%. This difference in flow/pressure behavior was induced mainly by sunlight/shadow alternance occurred. As the pump not performed at low level of sunshine, the flow/pressure adequacy was required to optimize pump efficiency according to adaptation of hydraulic equivalence model of the connected orifices (effect of the orifices number switched on). However, at 9:00 am, convergence of the performance curves is observed (Figures 6(b), 6(c), 6(e), 6(f) and 6(g)) as irradiance at 9:00 am, 10:00 am, 12:00 am, 1:00 pm and 2:00 pm were important to operate the pump without decreasing the number of operating orifices. The superposition of the actual curves with the references makes it possible to locate the optimal operating point of the pump for each behavior (number of switched orifices). The solar irradiance increase influenced positively the pump efficiency to be more than 35%. The results obtained at 10:00 am (Figure 6(c)) showed three hydraulic [flow vs pressure; power vs pressure] behaviors. In fact, the incident irradiance (533 W m^{-2}) impacted the pump to operate with three orifices that converge the operating point to increase efficiency to be 49%. The system has shown good hydraulic performance, since the pump holds the maximum pressure (4.5 bar). According to mid-day (12:00 am) irradiance (528 W m^{-2}), the system showed interesting performance (around 40%) as the hydraulic characteristic curves are situated above the reference curves and the number of switched on orifices is maximal. In fact, the excessive irradiance (528 W m^{-2}) made possible to operate the pump with the maximum number of orifices without inducing any decrease in the pump efficiency as showed before in the morning incident irradiance. At the midday, the system showed better hydraulic performance as the pump reached the maximum flow rate vs pressure characteristics (16 L min^{-1} vs 4.6 bar).

According to the pumping system response for each configuration of the number of switched on orifices, a significant dispersion in terms of efficiency is shown Table 2. Table 2 summarizes the standalone system behavior during a day, for low irradiance, the system operates in normal mode (all orifices switched on) with low yields, while switching on orifices make the pump operating point move to the optimal point which make the system forced to perform (high yield). For high irradiation the system performs in normal mode. There is a negative influence of change in irradiance on the pump performance for a standalone PVWPS if the pump operating point kept static. In fact, the pump operating point needs adjustment to maintain highly hydraulic performance and pressure stability. The adaptation of the pump operating point done using orifices switching on/off is of importance to efficiently valorize actual irradiance at upstream level to adequately fit it with a portion of a connected drip irrigation network (number of switched on orifices).

Table 2 Daily performance of PVWPS according to irradiance change and portion of switched on orifices (experimental test results)

Daily time	Irradiance (Wm^{-2})	Engagedorifices	Mean hydraulic yield % (CV %)	Mean pressure bar (CV %)	Mean flow rate (L min^{-1}) (CV %)
08 am	90	7	13 (47)	00.33 (34)	03.84 (19)
	90	6	16 (35)	00.42 (23)	03.91 (12)
	91	5	18 (16)	00.52 (24)	03.55 (13)
	91	4	19 (35)	00.66 (24)	03.07 (13)
	91	3	22 (30)	00.93 (21)	02.78 (11)
	91	2	29 (29)	01.26 (21)	02.60 (11)
	85	1	22 (28)	01.45 (21)	01.38 (11)
09 am	280	7	30 (33)	01.10 (22)	07.20 (11)
	280	6	33 (35)	01.31 (23)	07.03(12)
	281	5	35 (24)	01.56 (16)	06.33 (09)
	281	4	36 (23)	01.92(15)	05.45 (08)
	278	3	36 (14)	02.47(10)	04.62(05)
	485	2	45 (15)	03.69(12)	04.51(06)

Daily time	Irradiance (Wm⁻²)	Engagedorifices	Mean hydraulic yield % (CV %)	Mean pressure bar (CV %)	Mean flow rate (L min^{-1}) (CV %)
10 am	540	7	49 (22)	02.78(15)	11.70(08)
	538	6	49 (16)	02.99(15)	10.88(06)
	520	5	47 (17)	03.27 (15)	09.32(08)
11 am	610	7	63 (09)	03.30(06)	05.70(07)
	529	6	43 (08)	02.58(02)	05.89(01)
	275	5	32 (09)	02.27(02)	05.07(01)
	235	4	26 (07)	02.10(02)	04.62(01)
	150	3	23 (12)	02.08(06)	03.50(03)
	88	2	11 (08)	01.53(04)	02.44(02)
	59	1	04 (28)	01.09(19)	01.06(04)
12 am	520	7	44 (22)	02.66(15)	11.46(08)
	535	6	47 (15)	02.99(10)	10.90(05)
01 pm	280	7	30 (31)	01.12(22)	07.27(12)
	278	6	31 (25)	01.30(17)	07.04(09)
	280	5	34 (24)	01.61(16)	06.44 (08)
	281	4	36 (22)	02.08(15)	05.68(08)
	275	3	35 (09)	02.60(06)	04.75 (03)
	110	2	39 (08)	03.33(06)	04.29(03)
02 pm	520	7	44 (19)	02.67(12)	11.47(06)
	279	6	32 (25)	01.35(23)	07.14(12)
03 pm	514	7	41 (21)	02.20(16)	10.36(08)
	530	6	44 (17)	02.66(11)	10.24(06)
	510	5	42 (17)	02.57 (17)	08.21(09)
	289	4	40 (15)	02.89(18)	06.75 10)
04 pm	370	7	36 (26)	01.70(20)	09.04(11)
	298	6	39 (26)	01.95(18)	08.70(09)
	289	5	39 (19)	02.18(13)	07.55(07)
	287	4	39 (14)	02.58(10)	06.40(05)
	278	3	36 (11)	02.83(12)	04.95(06)
05 pm	130	7	23 (37)	00.69(25)	05.68(13)
	130	6	23 (40)	00.72(28)	05.14(15)
	130	5	12 (36)	00.30(25)	02.64(13)
	130	4	13 (28)	00.35(19)	02.19(10)
	130	3	14 (24)	00.47(19)	01.95(10)
	130	2	27 (14)	01.40(16)	02.75(08)
	130	1	22 (06)	02.21(04)	01.72(02)
06 pm	68	7	02 (76)	00.05(56)	01.36(31)
	64	6	03 (72)	00.06(54)	01.33(29)
	61	5	03 (63)	00.08(48)	01.31(26)
	61	4	04 (52)	00.12(41)	01.23(22)
	57	3	05 (52)	00.16(44)	01.09(23)
	51	2	09 (41)	00.26(35)	01.15(19)
	79	1	16 (43)	00.36(41)	01.33(23)

4 Conclusion

The performance of a standalone PVWPS is monitored under varying solar irradiance and varying hydraulic operating point of the pump/orifices connection. The portion of hydraulic network (number of switched on orifices) can be simulated by an equivalent hydraulic model of a defined number of a calibrated orifices. The equivalent model of a given hydraulic circuit can be taken experimentally as done in this work for establishing a governing diagram of the performance pump with reference to incident irradiance and to pressure setting atdownstream level.

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Nomenclature

Symbol	:	Meaning
AC	:	Alternating current.
BLDC	:	Brushless Direct Current.
DC	:	Direct Current.
HP(W)	:	Hydraulic Power
HE	:	Hydraulic Efficiency
I_{mppt}	:	Output Current of MPPT.
IncCond	:	Incremental Conductance.
I_{pv}	:	Photovoltaïc Panel Current.
K	:	Discharge coefficient of nozzle
Ktep/ Koe	:	kiloton d'équivalent pétrole; kilotonne of oïl equivalent
MPPT	:	Maximum Power Point Tracking.
P (bar)	:	Pressure
P&O	:	Perturb and Observe.
PV	:	Photovoltaïc
PVWPS	:	Photovoltaic Water Pumping System
PWM	:	Pulse Width Modulation
Q (L min^{-1})	:	Flow rate
Rpm	:	Rotation per minute
U_{mppt}	:	Output Voltage of MPPT
V_{pv}	:	Photovoltaic Panel Voltage
vs	:	Versus
x	:	Exponent of hydraulic nozzle model