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LABORATORY EVALUATION AND SYSTEM SIZING CHARTS FOR A 'SECOND GENERATION' DIRECT PV-POWERED, LOW COST SUBMERSIBLE SOLAR PUMP

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Abstract—A 'new generation' solar operated low-power and low capital cost submersible diaphragm pump designed for medium head applications is evaluated in this paper. The pump is designed and made by SHURflo Ltd. and is the 9325 type. The primary use of this pump is in providing water for remote homes and clinics, for human consumption and for agricultural use. In all tests, the pump was connected to a dedicated controller that allows either 12 V or 24 V operation. The experiments were undertaken by using the pumping test rig at CRES, and the evaluation methodology was 'simulated field conditions'. The instantaneous water flow versus head characteristics were functions of the global irradiance on the array plane. The PV array power varied between 55 Wp and 220 Wp and both voltage modes were examined. The hydraulic efficiency was also calculated with respect to equivalent head. The daily operation charts were obtained by using the instantaneous pump performance in combination with typical daily irradiation profiles and the pump starting and stopping characteristics. These charts are useful for system sizing, taking into account the solar resource at the site of application, the required daily water delivery at a particular head and the available PV array. The results show that with this 'new generation' of direct solar-powered pumping systems, the PV array has been minimised, and so has been the capital investment cost, the need for battery storage has been eliminated and adequate water is delivered at an affordable price.

1. INTRODUCTION

A few years ago, the solar pumping market was dominated by the so-called 'first generation' PV pumping systems, i.e. centrifugal pumps, usually driven by variable frequency AC motors, with proven long-term reliability and hydraulic efficiency in the order of 25 to 35%. The so-called 'second generation' PV pumping systems refer to positive displacement pumps, progressing cavity pumps or diaphragm pumps, generally characterised by the low PV input power requirements (between 100 Wp and 400 Wp), low capital cost and high hydraulic efficiencies of even 70%. A comparison assessment of the performance of different types of PV pumps available in the market is found in the AVICENNE Programme (1995), EC Contract No. AVI-CT94-0004. An overview of the solar pump types tested and the main experimental results obtained for these pumps are presented in Appendix A.

The performance of a typical representative of the 'second generation' pumping systems is presented in this paper. The main aim of the work is to analyse the potential of a small pumping system in terms of water delivery capability at a low investment cost. The solar pump tested is made by SHURflo, type 9325. The 'simulated field testing' procedure was adopted, i.e. head is maintained by artificial means, as defined in detail in the AVICENNE Programme (1995). The experiments were carried out at CRES using the existing test rig and instrumentation. The tests distinguished between instantaneous performance evaluation and daily operation of the pump. Both 12 V and 24 V operation modes were examined. In all tests, the SHURflo 9325 pump was connected to a dedicated controller, type LCB-G. The instantaneous flow vs. head characteristics are presented as a function of the global irradiance on the array plane and the PV array power. The hydraulic efficiency is calculated with respect to the equivalent head.

Compared to the technical analysis undertaken in previous works, the pump daily operation charts presented here provide a concise methodology for PV pumping system sizing. The determining parameters are the nominal PV

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power, the head and the daily irradiation available at the site of application. A solar pumping system lifetime economic analysis in terms of cost of hydraulic energy yield and quantity of water delivered is also presented.

2. DESCRIPTION OF THE PUMPING TEST RIG AND SET-UP AT CRES

The experimental solar water pumping facility at CRES is designed for evaluating submersible PV water pumping systems. The non-conductive DN25 piping is made of PVC. The fittings such as, elbows, tees, socket unions, double sockets, reducers, socket flanges, support clips etc., are threaded. The geometrical design of the piping is in accordance to international standards for pump testing, especially the sections before and after the pressure transducer and the flowmeter. Indicative references for the design of closed water conduits for laboratory pump testing are given below,

- ISO Standards Handbook 28 (1986) ‘Pipes, Fittings and Valves’
- ISO/DIS 6817 (1990) ‘Measurement of Conductive Liquid Flow in Closed Conduits; Method using Electromagnetic Flow-meters’
- BS 5200 (1986) ‘Specification for Dimensions of Hydraulic Connectors and Adapters’
- BS 5728 (1988) ‘Specification for Installation Requirements for Single Meters’
- ISO 2186 (1973) ‘Fluid Flow in Closed Conduits; Connections for Pressure Signal Transmissions between Primary and Secondary Elements’
- ISO 2785 (1986) ‘Guidelines for the Construction of Water Pipelines; Code of Practice’.

A general layout of the pumping test rig at CRES is shown in Fig. 1.

In Fig. 1, numbers 6, 7, 8 and 9 refer to voltage, current, pressure and flow measurements, respectively; 10 is a pressure control valve and 12 to 15 is a PC-based measuring system.

2.1. Solar modules

Two types of photovoltaic modules were used in the experimental procedures with the SHURflo type 9325 pump. The modules are made by BP Solar, types BP255F and BP585F, rated 55 Wp and 85 Wp, respectively. Both solar modules comprise 36 cells in series and their response under different global irradiance levels is presented in Appendix B, Table B.1.

2.2. Measuring equipment and devices

2.2.1. Electromagnetic flowmeter. A Danfoss DN25 electromagnetic flowmeter was used for the water flow measurement. This instrument incorporates a MAG 3100 type sensor and a MAG 3000 signal converter and is an IP67 version. Potential equalisation is achieved by using a special earthing flange placed between the flowmeter and pipe flanges. The electrodes are surrounded by a standard neoprene liner. The signal converter

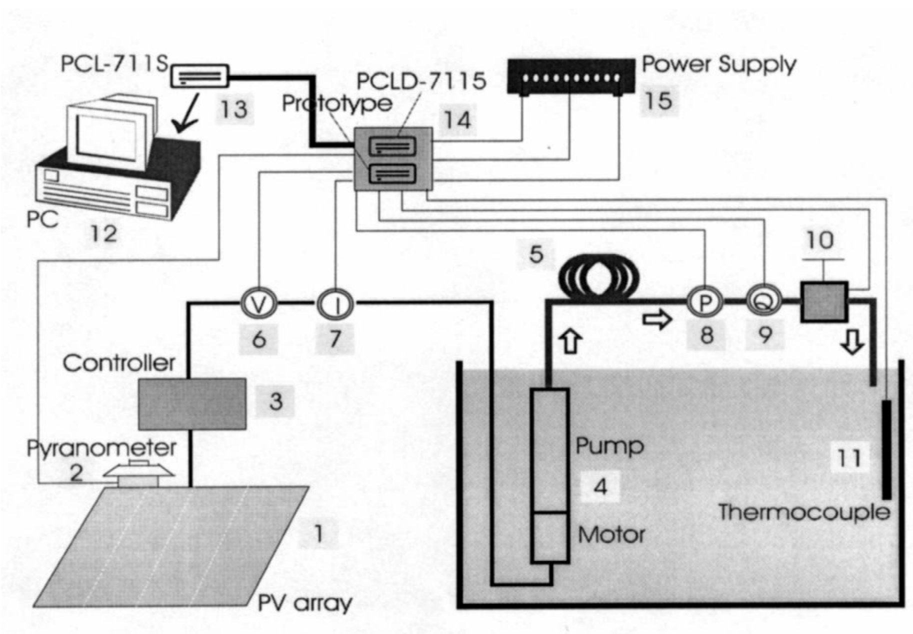

Fig. 1. Layout of the PV pumping test facility at CRES.

gives an output signal proportional to flow, in the range 0 mA to 20 mA.

The measuring range of this flowmeter with nominal accuracy $\pm 0.25\%$ of the actual flow is between 0.1 l s^{-1} and 5.0 l s^{-1}. For lower than 0.1 l s^{-1} flow rate, the accuracy of the flowmeter decreases. For example, the minimum flow rate measured with the SHURflo 9325 solar pump was around 0.014 l s^{-1} (50 l h^{-1}). According to a graph supplied by the manufacturer, the measuring error at 50 l h^{-1} for DN25 is $\pm 1.5\%$ of the actual flow.

2.2.2. Pressure transducer. The Danfoss pressure transmitter, type AKS 33, features a piezoresistive sensor whose specific resistance changes when pressure is applied on a silicon membrane. Resistance variation is in linear proportion to the pressure applied. This instrument requires an external power supply of 10 V DC. The output signal is 4 mA to 20 mA, corresponding to -1 bar to $+7$ bar pressure, respectively. The manufacturer claims linearity of better than 0.2% over the full measuring range.

2.2.3. Control valve. A manually operated control valve was used to obtain variable system pressure, and thus simulate water head.

2.2.4. Solar sensor. An ESTI silicon sensor was used for global irradiance measurements during the experiments with the SHURflo 9325 pump. It was serial no. ES1390, and was calibrated at JRC-ISPRA in September 1994. The calibration factor at 25°C, 1000 W m^{-2} global irradiance and AM = 1.5 is 32.80 ± 0.02 mV. The temperature correction coefficient is 0.007 ± 0.001 mV $°C^{-1}$.

2.2.5. Voltage and current measurements. Voltage values from the pump DC motor were converted to recordable signals by means of a voltage divider constructed by high precision resistors. Motor current was calculated by measuring voltage across a high precision shunt.

3. SHURflo 9325 SUBMERSIBLE SOLAR PUMP INFORMATION AND CHARACTERISTICS

The SHURflo 9325 pumping system consists of a diaphragm pump, powered by a DC motor, while control is achieved by a DC/DC dedicated converter. Details of the components are given below.

3.1. Pump

The pump is a positive displacement type and features a three-chamber piston/diaphragm arrangement driven by the motor through an eccentric thrust system.

3.1.1. Construction. The pump is constructed from materials selected specifically for the application to resist corrosion, salt water and chemical attack. Internal parts are of Food Grade plastics, elastomer and stainless steel. External parts are of high impact plastics with stainless steel fasteners.

3.1.2. Reliability. Servicing is recommended once per year under normal PV operating conditions. This is a straightforward task carried out using simple tools.

The main annual service items are,

- Motor Endbell Assembly (including new carbon brushes)
- Diaphragm/drive module.

The regular replacement of these items returns the pump to near-new condition, since the main bearing surfaces are also replaced under the above procedure.

3.1.3. Likely pump life. The model 9325 pump can be simply and economically refurbished, and in theory can be kept in service for as long as the spare parts are available from the manufacturer.

3.2. Motor

The DC motor is of ‘conventional’ permanent magnet carbon-brush design, incorporating proprietary materials and processes. This design was chosen in preference to the more modern alternatives (brushless DC) for reasons of economy, motor performance and service compatibility.

3.3. Controller

A DC/DC converter, type LCB-G, is used as an interface between the SHURflo 9325 pump and the PV array (or other DC power source). The main function of this controller is to maximise the daily water output while providing protection for the pump. The controller can be used in 12 V DC and 24 V DC systems and features current boosting for matching the load of the pump motor.

The manufacturer’s general information concerning the pumping system under evaluation is presented in Table 1.

A cross-section of the pump and motor and the parts in exploded view are presented in Fig. 2.

In Fig. 2, letters correspond to:

Table 1. Technical specifications summary of the SHURflo pumping system

Pump	Series:	9300
	Type:	Three-chamber diaphragm positive displacement
	Model no. tested:	9325-043-101
	Cam:	3 degree
	Serial no. tested:	014689
	Manufactured:	August 1996
	Design Q and P:	0.063 l s^{-1} at 6.9×10^{5} Pa (1 gpm at 100 psi)
	Maximum head:	70.1 m (230 ft)
	Maximum submersion:	30 m
	Output port:	1/2 inch (12.7 mm)
	Materials:	High strength engineered plastics and stainless steel fasteners and metal parts
	Weight:	2.72 kg
	Dimensions:	305 mm×95 mm
Motor	Type:	DC, permanent magnet, brushed, thermally protected
	Nominal voltage:	24 V DC
	Maximum amperage:	4.0 A
	Nominal power:	120 W
Controller	Type:	LCB-G
	Max. input voltage:	45 V DC (open circuit)
	Start-up voltage, 12 V:	12.5 V±2% (one module)
	Start-up voltage, 24 V:	25.0 V±2% (two modules in series)
	Shut-down voltage:	28.0 V
	Maximum power:	150 W (PV/pump system)
	Max. output current:	7 A
	Fuse:	10 A
	Self-consumption:	25 mA
	Operation temperature:	−10°C to +45°C
	Over-temp. shut-down:	+80°C

Item	Description	Quantity
A	Cable	1
B	Inner cable boot	1
C	Outer cable boot	1
D	Nut	1
E	Screw (lift plate)	6
F	Lift plate	1
G	Outlet fitting	1
H	O-ring (outlet fitting)	1
I	O-ring (lift plate)	3
J	Receptacle (cable adapter)	1
K	Set screw (receptacle)	2
L	Screw (motor)	3
M	Filter screen	1
N	Upper housing	1
O	O-ring (upper housing)	2
P	Spring (bypass)	3
Q	Poppet (bypass)	3
R	Valve housing assembly	1
S	Lower housing assembly	1
T	Motor	1
U	Canister	1
V	Screw (canister)	3
W	Lock washer (motor screw)	3

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A general view of an assembled SHURflo 9325 solar pump is shown in Fig. 3.

Additional information on the pump hourly flow rate as a function of the vertical lift is provided in the owner's manual. These data are presented in Fig. 4 for both 12 V and 24 V operational voltage modes.

The curves shown in Fig. 4 are indicative only of the pump performance and refer to fixed voltage operation. In Fig. 4, the reference voltage for 12 V DC and 24 V DC modes is 18.6 V and 37.6 V, respectively. In system operation, where the pump is coupled to a PV array, the solar generator power is not constant, strongly depending on the instantaneous variability of global irradiance, thus affecting the operation point of the pump. In practice, voltage will vary with head. The motor voltage change as a function of head and global irradiance is presented in Section 4.5.

4. SHURflo 9325 INSTANTANEOUS PERFORMANCE EVALUATION

4.1. Method of testing

In the instantaneous performance pump evaluation, the experimental measurements refer to water flow, equivalent head, DC motor voltage and current, and global irradiance on the array plane. At 12 V configuration, using one, two and three BP255F solar modules, the nominal PV

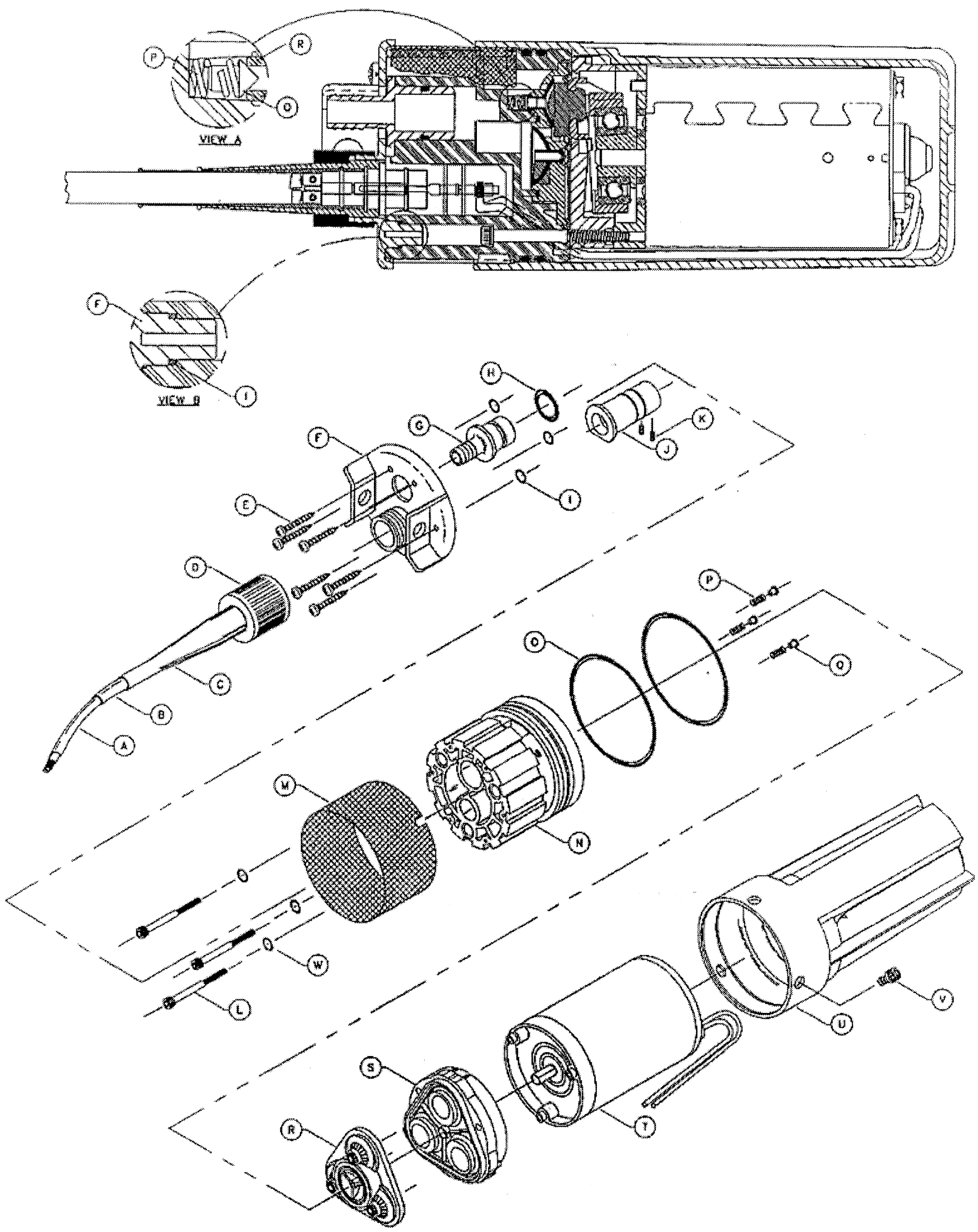

Fig. 2. Engineering and design details of a SHURflo, type 9325 solar pump.

power was 55 W, 110 W and 165 W, respectively. For 24 V mode, the 110 W and 220 W tests were carried out with two and four BP255F modules, while two BP585F modules were used for the 170 W experiment. The tests were carried out at CRES, outdoors, during clear blue-sky summer days, at three representative global irradiance levels, 1000 W m^{-2}, 700 W m^{-2} and 400 W m^{-2}. These values were selected in order to characterise the pumping system in a representative range of solar power input. The 1000 W m^{-2} global irradiance level was achieved at 12:00 h, with the PV array surface tilt adjusted to be vertical to the sun. The other two global irradiance levels were obtained in afternoon and late afternoon hours.

In all cases, the measuring period for a head versus water flow characteristic was around 2 min. In this time, change in global irradiance was negligible. After setting the array power and voltage mode, measurements started at atmospheric pressure, corresponding to almost 0 m head, towards higher values. Measurements were

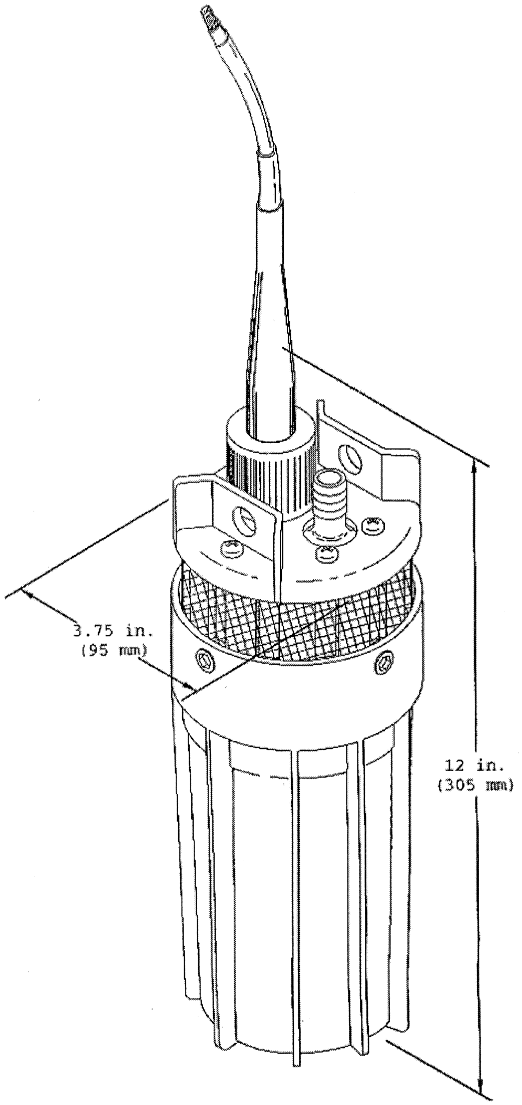

Fig. 3. View of a SHURflo 9325 solar pump with basic dimensions.

taken in the whole range of equivalent head, up to 70 m. In case that a h vs. Q curve was not satisfactory, the measurements were repeated. The accuracy of the measurements depends on the accuracy of the individual measuring equipment (see Section 2.2), and is $\pm 1.2\%$ in normal measuring conditions.

Note that for the water flow Q, although the SI unit is ($m^3\ s^{-1}$), in the figures presented in this paper, the unit ($l\ h^{-1}$) is used. Due to the relatively small Q values of this pumping system compared to other general use pumps, the use of the original SI unit would lead to confusion at low water flow rates.

4.2. Calculations

The instantaneous hydraulic power is given by

$$P_{\mathrm{hyd}} = \rho g h Q. \tag{1}$$

As it is seen in Fig. 1, the voltage and current measurements were taken in points 6 and 7, respectively, between the SHURflo dedicated controller and the pump DC motor. Thus, controller losses are not included in the calculations.

The DC motor input power is the product

$$P_{\mathrm{M}} = I_{\mathrm{M}} V_{\mathrm{M}}. \tag{2}$$

Hydraulic efficiency is the ratio between hydraulic output and controller output and is calculated, in %, by

$$\eta_{\mathrm{hyd}} = (P_{\mathrm{hyd}}/P_{\mathrm{M}}) \times 100. \tag{3}$$

4.3. SHURflo 9325 instantaneous performance at 12 V mode

The SHURflo model 9325 pump operates on a nominal supply voltage of 24 V DC. However, the motor used to power the pump will run with a wide range of voltage with no resulting damage. It is this feature of the pump that is used to characterise the LCB-G controller.

Unlike an MPP tracker, the LCB-G controller is designed to maximise current supplied to the pump motor under varying PV input power. Under high radiation, the pump and module impedance is matched 100%, provided that PV output current is higher than pump motor demand. Under lower input power, the LCB-G acts as an impedance converter, providing lower voltage but higher current to the pump motor.

The SHURflo pump instantaneous head versus water flow characteristics at 12 V are presented in Figs. 5–7, while the hydraulic efficiency versus head characteristics are shown in Figs. 8–10.

As it is seen in Figs. 5–7, the maximum instantaneous water flow at 12 V mode is ~370 $l\ h^{-1}$ at 5 m head, irrespective of the input power. Since the pump is a positive displacement type, pump output is proportional to motor speed. At low heads, the pump performance is limited by the maximum output voltage of the LCB-G controller to prevent motor overload in peak sun conditions.

Comparing the characteristics of Figs. 6 and 7, it is noticed that for 700 $W\ m^{-2}$ global irradiance and higher, water flow is almost constant for 110 Wp or 165 Wp solar array power. Therefore, the three-module configuration should be selected if

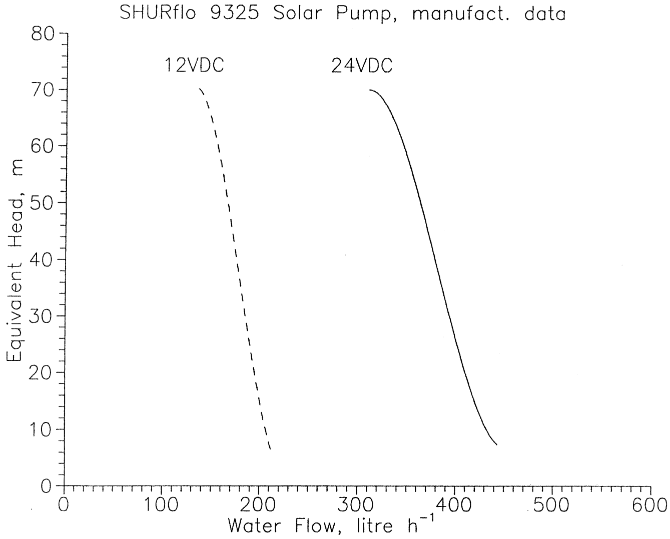

Fig. 4. Manufacturer’s data on the performance of a SHURflo 9325 pump.

only high water flow is needed even at relatively low irradiance, e.g. 400 W m^{-2}.

The hydraulic efficiency (controller output to water), of the SHURflo solar water pumping 9325 system at 12 V mode reached 60%, irrespective of the input power. This is seen in Figs. 8–10; the optimum efficiency was obtained between 20 m and 40 m water lift. The maximum hydraulic efficiency of a ‘first generation’ 1.5 kWp centrifugal solar water pumping system tested under the same conditions at CRES (see Protogeropoulos and Tselikis, 1997) was around 28%. Similar results for a ‘first generation’ pump were obtained in AVICENNE, see Appendix A, Fig. A.2. This comparison shows a substantial technological improvement in low-power ‘second generation’ water pumping systems as hydraulic efficiency has been doubled.

4.4. SHURflo 9325 instantaneous performance at 24 V mode

The SHURflo pump instantaneous head versus water flow characteristics at 24 V mode are presented in Figs. 11–13, while the hydraulic

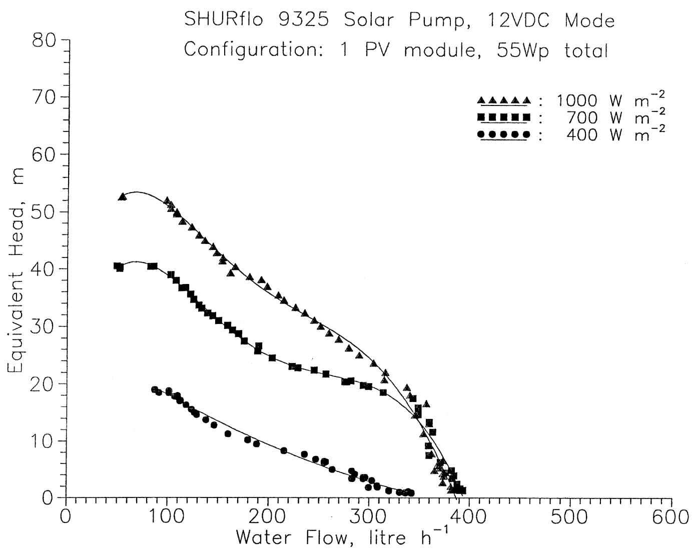

Fig. 5. SHURflo 9325 h vs. Q characteristics at 12 V mode and 55 Wp array power.

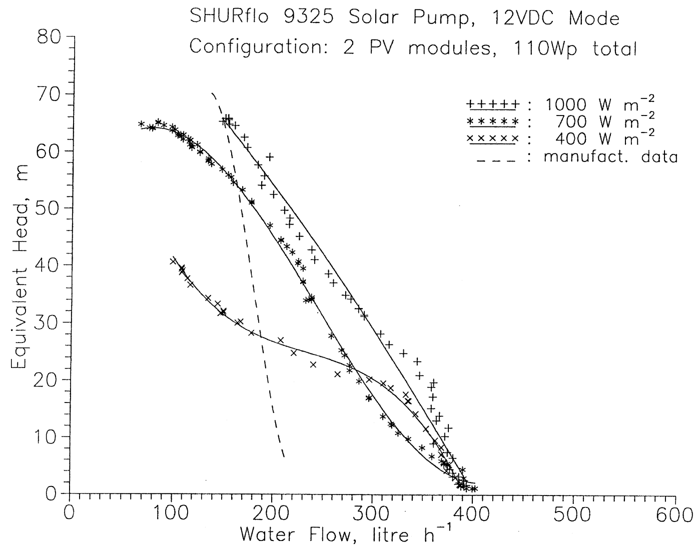

Fig. 6. SHURflo 9325 h vs. Q characteristics at 12 V mode and 110 Wp array power.

efficiency versus head curves are shown in Figs. 14–16.

At 24 V operation and 5 m head, the instantaneous water flow is around 500 l h^{-1} for all PV module configurations as is noticed in Figs. 11–13. That is 130 l h^{-1} more compared to the 12 V mode, i.e. 35.1% increase of water delivery at shallow conditions. At 24 V mode and almost 0 m head, higher controller voltage results in higher DC motor speed compared to the 12 V mode. The manufacturer's characteristics (dashed lines), shown in Figs. 12 and 15 refer to fixed voltage operation.

The use of two PV modules connected in series of total 110 Wp would result in moderate water delivery as shown by the characteristics in Fig. 11. For a 170 Wp PV array, Fig. 12, the water supply improves, although a distinctive 'knee' on the curve at 700 W m^{-2} irradiance occurs at ~30 m head. The situation improves for 220 Wp array, Fig. 13, where the combination of 2p/2s module connection shows the benefits of parallel connection at 24 V mode.

As of the hydraulic efficiency at 24 V, the maximum value calculated was 50% between 40 m and 50 m head as is seen in Figs. 14–16 for 110

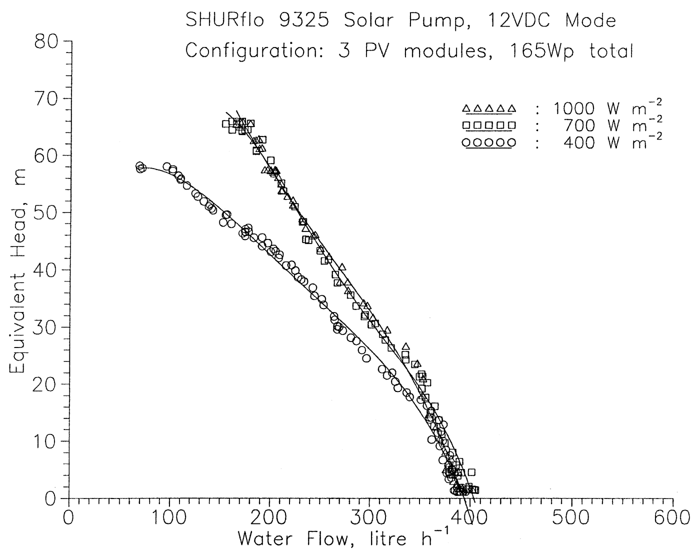

Fig. 7. SHURflo 9325 h vs. Q characteristics at 12 V mode and 165 Wp array power.

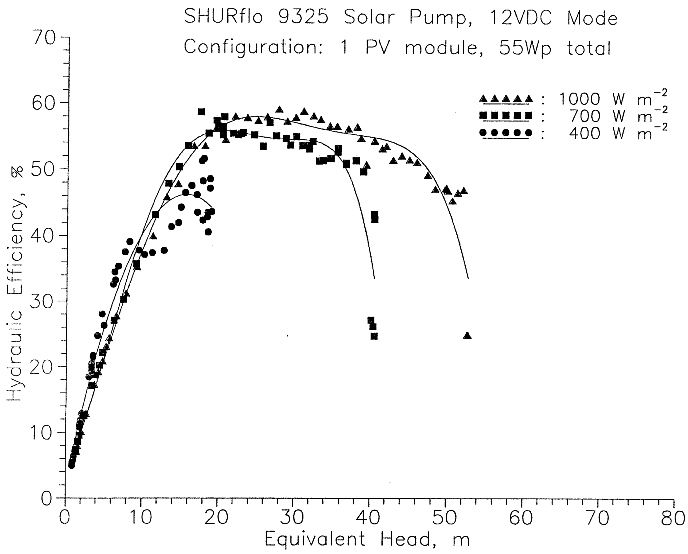

Fig. 8. SHURflo 9325 η_{hyd} vs. h characteristics at 12 V mode and 55 Wp array power.

Wp, 170 Wp and 220 Wp PV array power, respectively.

4.5. Motor voltage variation with head during instantaneous testing

As was mentioned in a previous section, practically motor voltage changes with head. In Figs. 17 and 18, motor voltage values are presented as a function of head with varying parameters PV array power and global irradiance for 12 V and 24 V modes, respectively.

As it is seen in Fig. 17, the measured DC motor voltage at shallow head for 12 V mode is between 17 V and 18 V in almost all cases. This voltage range is virtually identical to the manufacturer’s value at very low heads and equal to the array

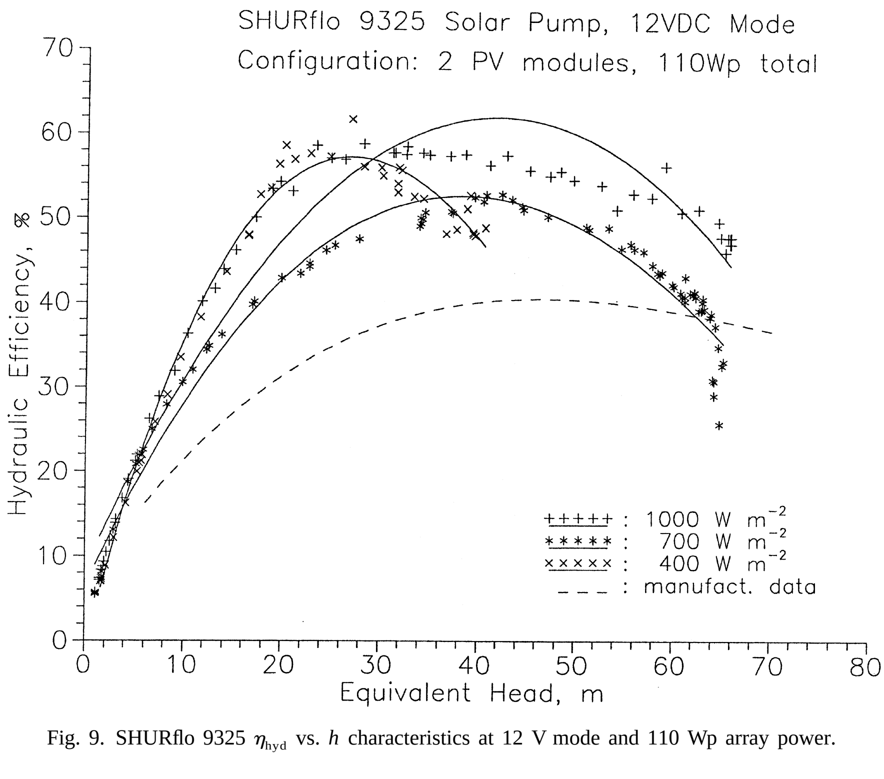

Fig. 9. SHURflo 9325 η_{hyd} vs. h characteristics at 12 V mode and 110 Wp array power.

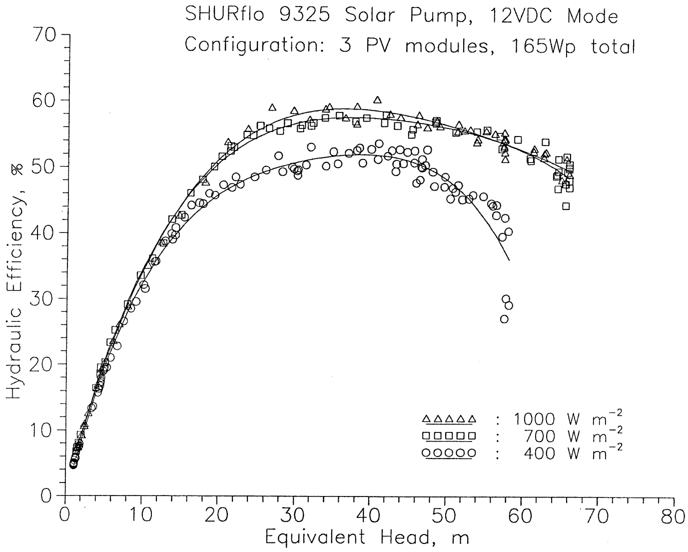

Fig. 10. SHURflo 9325 η_{hyd} vs. h characteristics at 12 V mode and 165 Wp array power.

voltage at MMP conditions. For 24 V operation, Fig. 18, the starting motor voltage is limited by the LCB-G controller maximum operating voltage, see Table 1, and is measured around 29 V. This value is 7 V lower than the PV array optimum voltage at MPP and 10 V lower compared to the nominal voltage claimed by the manufacturer.

In both modes, the trend for motor voltage is to decrease as head increases. At 24 V, in high power and high irradiance levels combinations, motor voltage is not affected substantially by load, even at 60 m head. This is seen in Fig. 18 for array power 220 Wp at 1000 W m^{-2} and 700 W m^{-2} irradiance levels and for 170 Wp power at 950 W m^{-2}. In low global irradiance levels and head close to the maximum achievable by the pumping system, motor voltage drops below 8 V at 12 V mode, Fig. 17, and below 12 V at 24 V mode, Fig. 18.

4.6. Comparison between 12 V and 24 V operation

In terms of hydraulic efficiency, the maximum value calculated at 24 V mode was 10% lower compared to 12 V operation. This could be

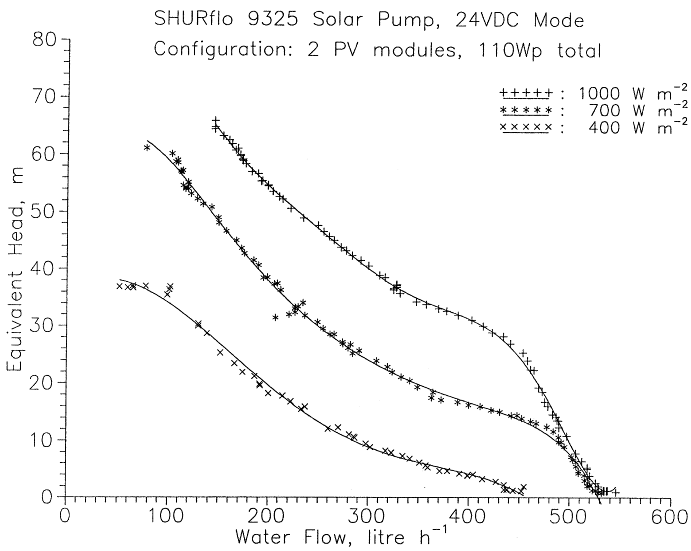

Fig. 11. SHURflo 9325 h vs. Q characteristics at 24 V mode and 110 Wp array power.

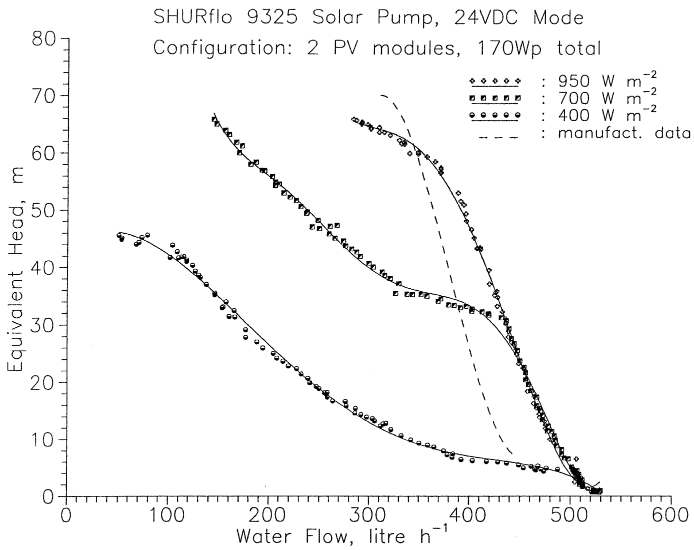

Fig. 12. SHURflo 9325 h vs. Q characteristics at 24 V mode and 170 Wp array power.

explained by the fact that motor voltage at 24 V mode is limited by the shut-down voltage of 28 V, see technical specifications in Table 1. Thus, at 24 V mode, the controller output voltage does not much to an array MPP operation, i.e. a voltage value of around 36 V. It is thus concluded that an improvement on controller regulation is needed at 24 V operation. However, at 24 V, the maximum efficiency of 50% is reached between 45 m and 55 m water head, i.e. 15 m higher compared to the 12 V mode.

The instantaneous SHURflo pump performance evaluation shows that 12 V operation is preferable when the available array power is in the range 50 Wp and 130 Wp and head is between 30 m and 40 m in order to obtain maximum system efficiency. Parallel module connection offers quicker start-up at low global irradiance values and average water flow characteristics even at heads close to 60 m.

If the input PV power supply can be increased, e.g. four PV modules of around 200 Wp, the SHURflo system dedicated controller should then be set at 24 V in order to maximise water delivery. For example, at 65 m head and 1000 W m^{-2} irradiance, the instantaneous water flow with a

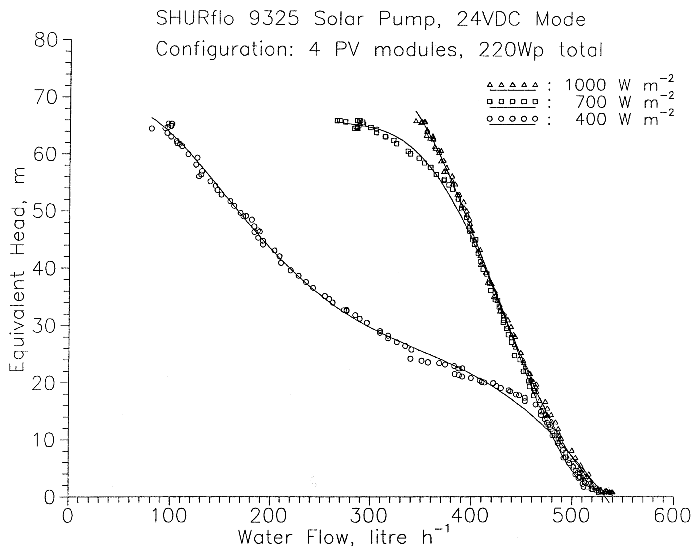

Fig. 13. SHURflo 9325 h vs. Q characteristics at 24 V mode and 220 Wp array power.

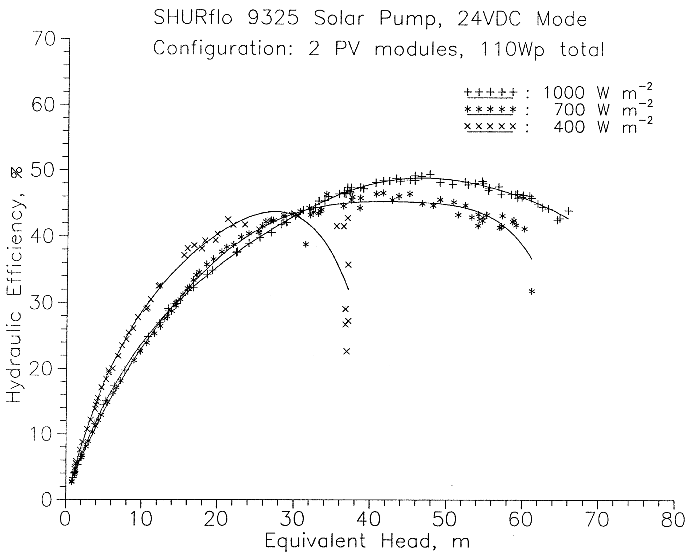

Fig. 14. SHURflo 9325 η_{hyd} vs. h characteristics at 24 V mode and 110 Wp array power.

170 Wp/24 V system (Fig. 12), is approximately twice as much compared to a 165 Wp/12 V configuration (Fig. 7).

5. SHURflo 9325 DAILY PERFORMANCE AND SYSTEM SIZING CHARTS

5.1. Method of calculation

In order to calculate the water delivery of a SHURflo 9325 pumping system on a daily basis, the instantaneous performance characteristics presented in the previous sections were used in combination with the PV module response at different irradiance levels (Appendix B, Table B.1), a set of typical daily global irradiation profiles (Appendix C, Fig. C.1), and the starting and stopping pump characteristics (Appendix D, Fig. D.1).

It must be stressed that the results presented herein were obtained by using monocrystalline PV modules of 36 cells in series. A quantitative analysis and the results for the effect of 33-cell

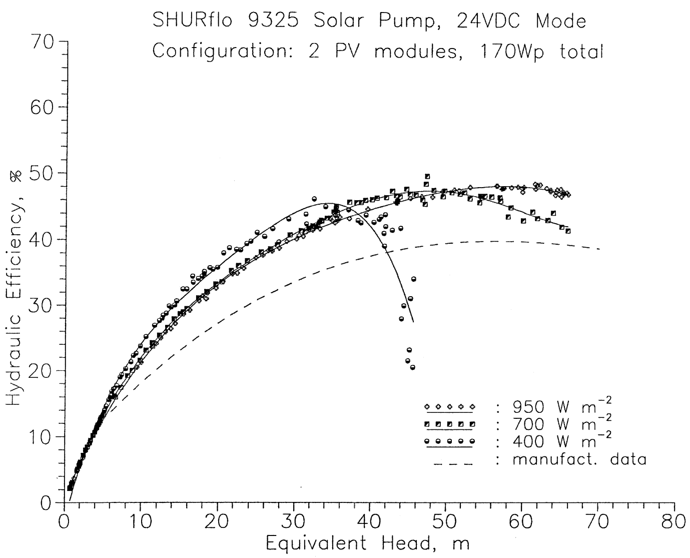

Fig. 15. SHURflo 9325 η_{hyd} vs. h characteristics at 24 V mode and 170 Wp array power.

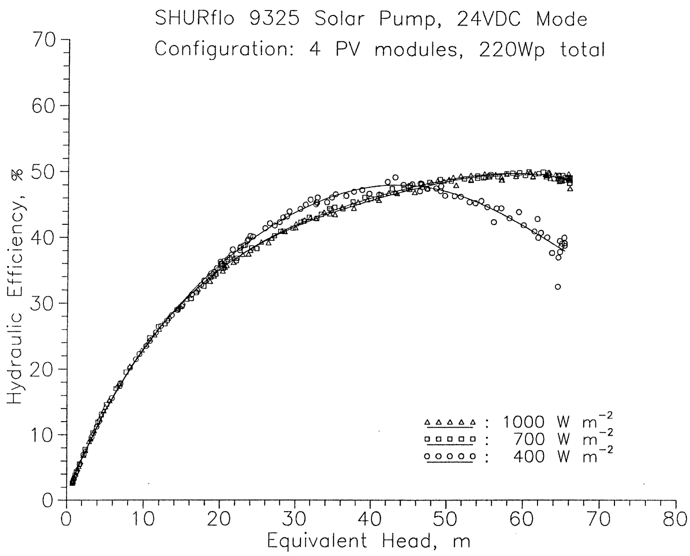

Fig. 16. SHURflo 9325 η_{hyd} vs. h characteristics at 24 V mode and 220 Wp array power.

and 36-cell type crystalline PV modules connected in series and in parallel on the operation of the SHURflo pumping system was presented by Alonso-Abella *et al.* (1995).

5.2. SHURflo 9325 daily water delivery

The characteristics presented in Figs. 19–26 refer to PV nominal power of 55 Wp, 110 Wp and 165 Wp at 12 V configuration and 110 Wp, 170 Wp and 220 Wp at 24 V operation. Each figure refers to a particular total daily global irradiation at the site of application. In steps of 3.6 MJ m^{-2} (1 kWh m^{-2}), the global irradiation values vary between 7.2 MJ m^{-2} (2 kWh m^{-2}) and 32.4 MJ m^{-2} (9 kWh m^{-2}). A 2nd degree polynomial interpolation between the calculated points was made.

5.3. Discussion of the results

As it is seen in Fig. 19, very little water will be delivered from a SHURflo 9325 system at sites or time periods of extremely low irradiation, espe-

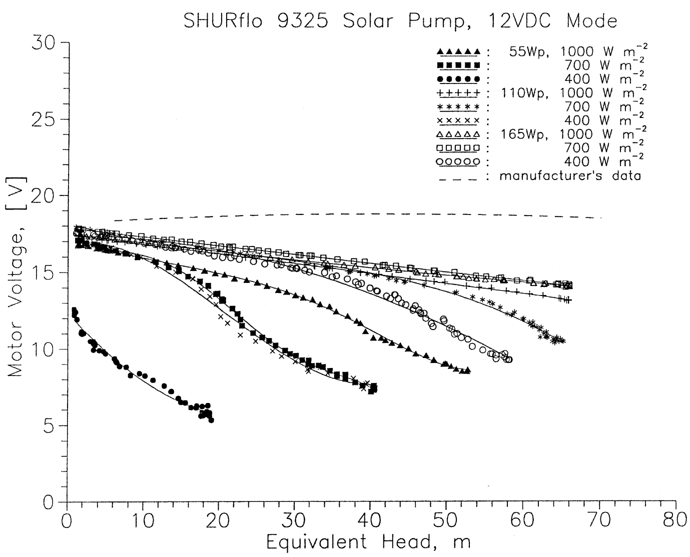

Fig. 17. SHURflo 9325 motor voltage at 12 V mode.

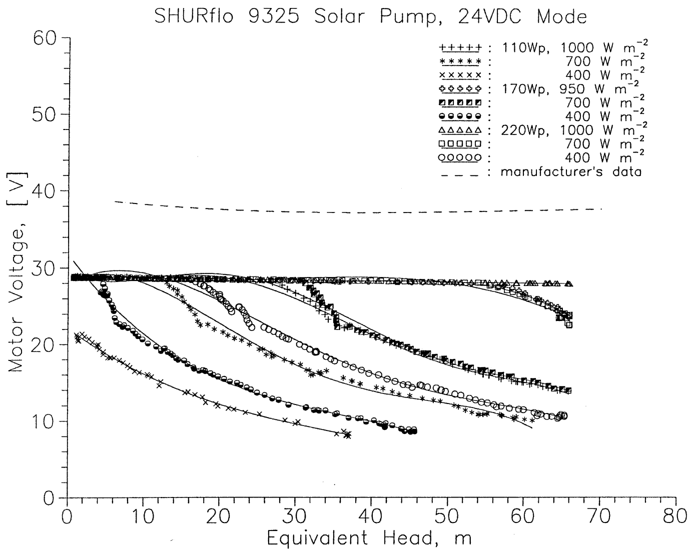

Fig. 18. SHURflo 9325 motor voltage at 24 V mode.

cially for heads around 30 m and higher. The performance of the pump is satisfactory for daily global irradiation of more than 14.4 MJ m^{-2} (4 kWh m^{-2}), even with only 80 Wp array power, see Fig. 21.

From the results, the general conclusion is that 12 V system operation is preferable when low PV array power is available. The daily performance calculations have shown that, at ~160 Wp solar PV power, the characteristics level out, i.e. the daily water delivery remains almost constant. At the same wattage, the system operation at 24 V would increase the water delivery, for the same head and daily irradiation values.

The charts presented in Figs. 19–26 are valuable for sizing a SHURflo 9325 solar-powered pumping system. The varying parameters are

- daily solar energy resource on the array plane
- nominal PV input power
- operational voltage

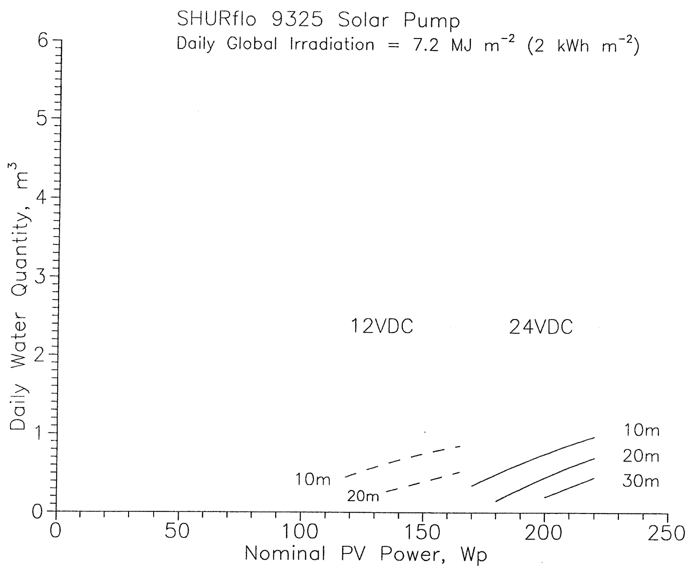

Fig. 19. SHURflo daily water delivery, $H = 7.2$ MJ m^{-2}.

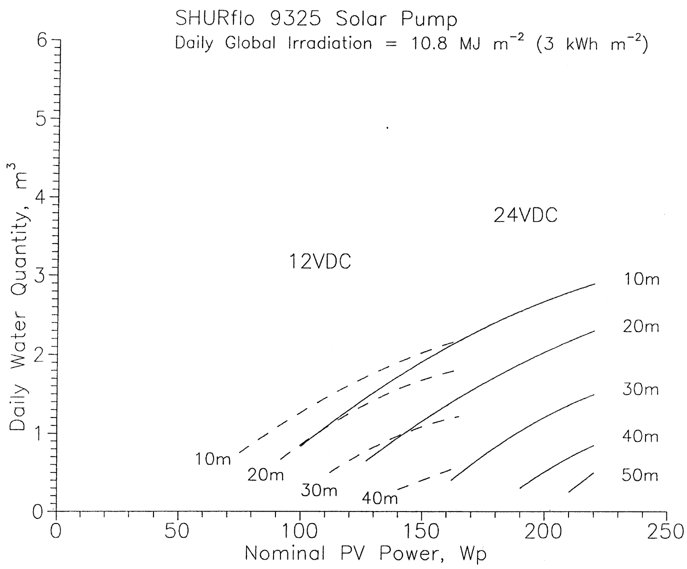

Fig. 20. SHURflo daily water delivery, $H = 10.8$ MJ m^{-2} daily.

- well head
- required water delivery.

As an example, a 9325 SHURflo pumping system installed at a Mediterranean site and powered by a 100 Wp PV array at 12 V, would deliver 1.5 m^3 water from a 50-m well in a summer day of 28.8 MJ m^{-2} (8 kWh m^{-2}) irradiation on the array plane, see Fig. 25. Under the same conditions, for 3.0 m^3 water requirement on a daily basis, the PV array should be around 190 Wp and the system voltage should be set at 24 V mode.

6. ECONOMIC ANALYSIS

The ‘end user’ product cost for a 200 Wp SHURflo 9325 pumping system is presented in Table 2.

The PV module cost in Table 2 was assumed \$US 6.0/Wp. The calculated total cost of

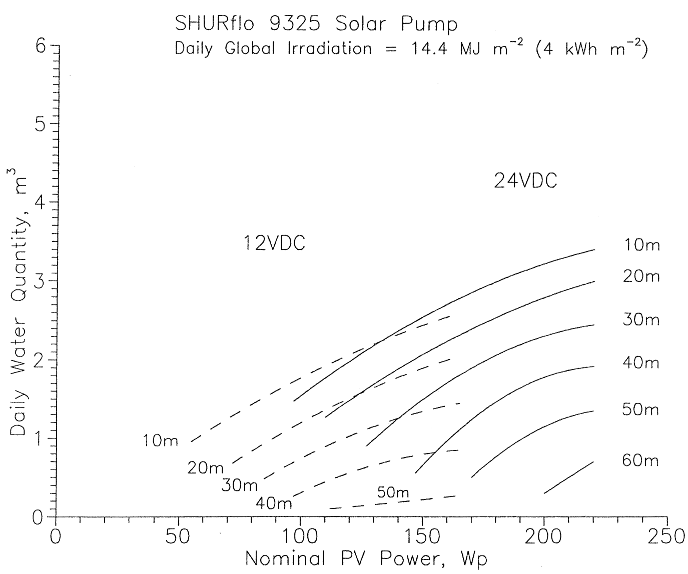

Fig. 21. SHURflo daily water delivery, $H = 14.4$ MJ m^{-2} daily.

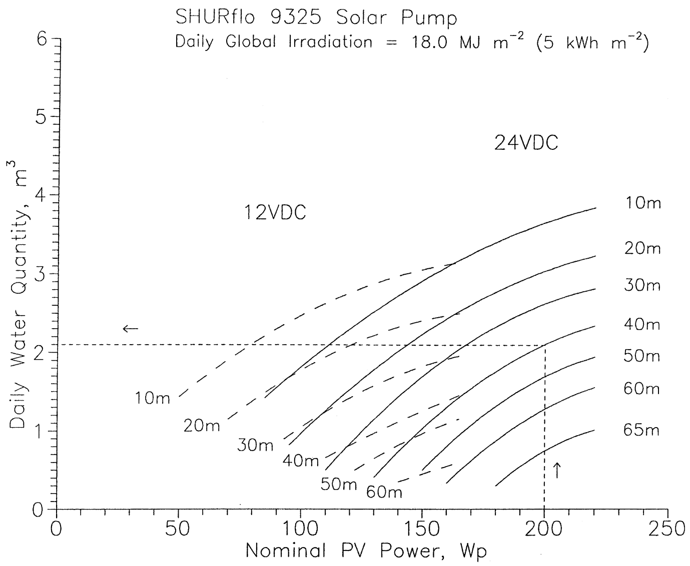

Fig. 22. SHURflo daily water delivery, $H = 18.0$ MJ m^{-2} daily.

$US 2085 indicates that a 'second generation' low-power water pumping system offers an economically attractive solution to the end user in terms of capital investment. It must be stressed however, that a significant part of the system cost is due to the PV array. In this particular pumping system, the 200 Wp PV array accounts for about 60% of the capital cost.

Typical maintenance activities for the pumping system refer to replacement of the motor carbon brushes ($US 56) and the main pump diaphragm drive ($US 30). Considering that maintenance is necessary every year, the annual maintenance cost for the pumping system is calculated to be $US 86.

The hydraulic energy yield over the lifetime period is a general criterion for the economic assessment of pumping systems. In this way, confusion between pumping systems of different technologies, designs and input power requirements is avoided. The hydraulic energy is the product

$$E_{\text{hyd}} = P_{\text{hyd}} ta = \rho g h Q t a. \quad (4)$$

For long-term calculations, the availability of

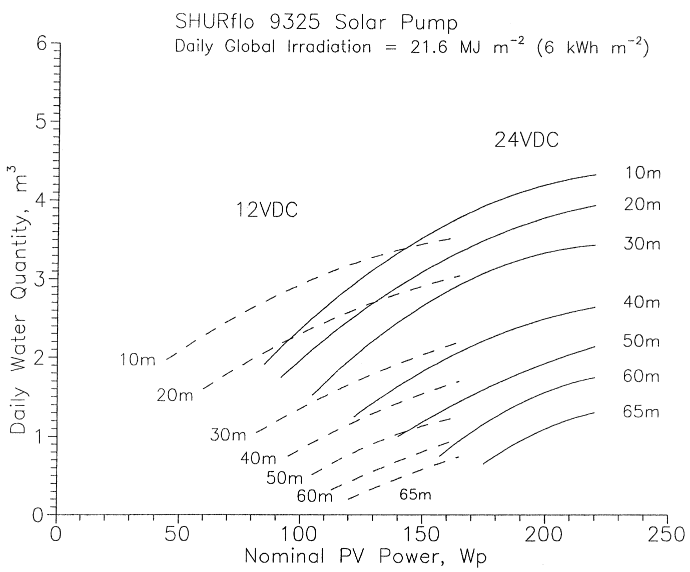

Fig. 23. SHURflo daily water delivery, $H = 21.6$ MJ m^{-2} daily.

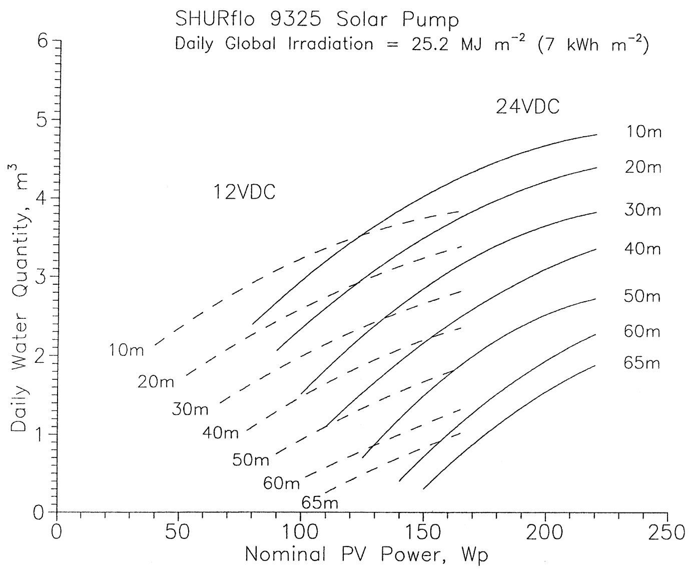

Fig. 24. SHURflo daily water delivery, $H = 25.2$ MJ m^{-2} daily.

the pumping system should also be considered. A typical value for availability is $a = 95\%$. From Fig. 22, the water delivery on a daily basis for a 200 Wp system at 40 m head and global irradiation 5 kWh m^{-2} is calculated at 2.1 m^3. Substituting in Eq. (4), the total energy delivered in 20 years is

$$E_{\mathrm{hyd}}$$
$$= 1000\ \mathrm{kg\ m^{-3}} \times 9.81\ \mathrm{m\ s^{-2}} \times 40\ \mathrm{m} \times 2.1\ \mathrm{m^3\ day^{-1}} \times (365 \times 20)\ \mathrm{days} \times 0.95 =$$
$$= 5{,}714{,}717{,}400\ \mathrm{J} = 5{,}714.7\ \mathrm{MJ}$$

Additionally, the total volume of pumped water is calculated

$$U_{\mathrm{tot}} = 2.1\ \mathrm{m^3\ day^{-1}} \times (365 \times 20)\ \mathrm{days} \times 0.95 = 14{,}563.5\ \mathrm{m^3}.$$

System lifetime cost is the summation of capital costs and total operation and maintenance cost

$$C_{\mathrm{tot}} = C_{\mathrm{c}} + [(\$\mathrm{US}\ 86\ \mathrm{year^{-1}}) \times 20\ \mathrm{years}] = \$\mathrm{US}\ 2085 + \$\mathrm{US}\ 1720 = \$\mathrm{US}\ 3805$$

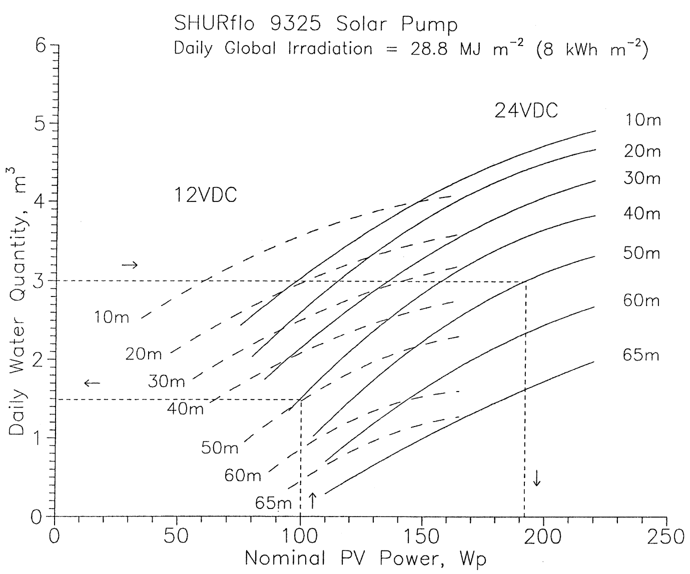

Fig. 25. SHURflo daily water delivery, $H = 28.8$ MJ m^{-2} daily.

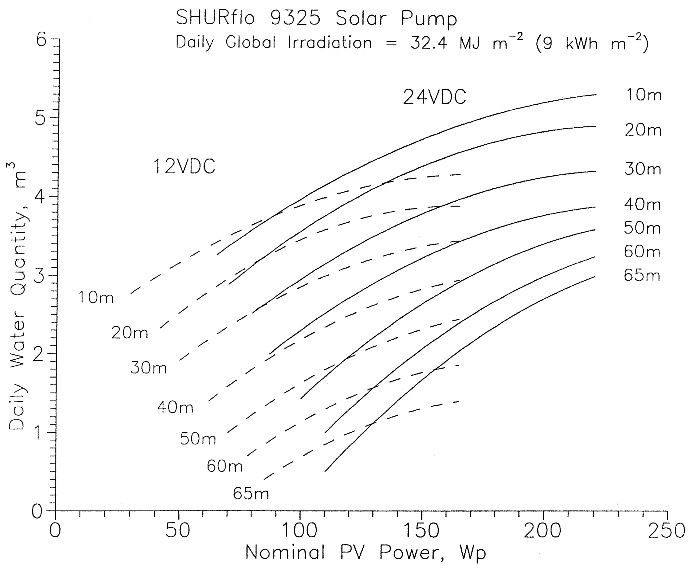

Fig. 26. SHURflo daily water delivery, $H = 32.4$ MJ m^{-2} daily.

Table 2. Cost breakdown for a SHURflo solar pumping system

Item	Cost ($US), 1999 prices
Pump, type 9325	650
Controller, type LCB-G75, including well probes and other accessories	235
200 Wp PV array	1200
System total	2085

The hydraulic energy cost is then

$$C_{\mathrm{hyd}} = C_{\mathrm{tot}} E_{\mathrm{hyd}}^{-1} = \$\mathrm{US}\ 3805 \times (5714.7\ \mathrm{MJ})^{-1} = \$\mathrm{US}\ 0.67\ \mathrm{MJ}^{-1}$$

More indicative is the specific cost of water pumped. This is calculated by

$$C_{\mathrm{U}} = C_{\mathrm{tot}}\, U_{\mathrm{tot}}^{-1} = \$\mathrm{US}\ 3805 \times (14{,}563.5\ \mathrm{m}^3)^{-1} = \$\mathrm{US}\ 0.26\ \mathrm{m}^{-3}$$

The assumptions and the results for a SHURflo solar pumping system presented above are summarised in Table 3.

The system lifetime cost analysis shows that this ‘second generation’ pumping system has a specific cost of $US 0.26 per m^3 water pumped. This is comparable, if not lower, to the present tariff policy that water distribution companies follow in Europe.

As an example, the cost of potable water in

Table 3. Solar water pumping system lifetime cost analysis

System	Pump type:	SHURflo 9325
	Controller:	LCB-G
	Voltage:	24 V
Assumptions	Average daily H:	18.0 MJ m^{-2} (5 kWh m^{-2})
	PV array:	200 Wp
	Head, h:	40 m
	PV cost per Wp:	$US 6.0
	Total capital investment, C_c (Table 2):	$US 2085
	Annual O&M cost:	$US 86
	Pump availability, a:	95%
	System lifetime:	20 years
Calculations	Daily water delivery, Fig. 22:	2.1 m^3
	Total energy, E_{hyd}, Eq. (4):	5714.7 MJ (1587.4 kWh)
	Total water pumped, U_{tot}:	14,563.5 m^3
	System lifetime cost, C_{tot}:	$US 3805
	Energy cost, hydraulic, C_{hyd}:	$US 0.67 MJ^{-1}
	Cost of water pumped, C_{U}:	$US 0.26 m^{-3}

Table 4. Water tariff in the household sector in Greece

Water consumption (m^3)	Cost of potable water in Greece, bills every 4 months, 1999 prices	
	(Drs m^{-3})	(\$US m^{-3})
Up to 30	130	0.42
31 to 60	150	0.48
61 to 100	200	0.65
101 to 150	300	0.97
More than 151	350	1.13

Greece as function of consumption is presented in Table 4.

7. CONCLUSIONS

The performance of a low-cost SHURflo 9325 solar pump coupled through a dedicated controller to a small PV array was analysed in this paper. This 'second generation' water pumping system has two operational modes, i.e. 12 V and 24 V. The experimental results refer to both instantaneous pump operation and daily performance under different global irradiance profiles.

The instantaneous water flow versus head characteristics were functions of the global irradiance on the array plane and the PV input power. The hydraulic efficiency was calculated with respect to head and reached 60% at 12 V operation. From the measurements, it was concluded that the 12 V system mode is preferable when the available PV array is in the order of 80 Wp to 130 Wp and head is below 30 m. For higher heads up to 70 m and maximum daily water delivery, the voltage should be set at 24 V, provided that adequate PV input power is available, e.g. more than 150 Wp.

The daily operation charts of the SHURflo 9325 pumping system can be used for sizing, taking into account the required daily water quantity, the lift, the nominal PV power, the daily total solar energy of the site and the system voltage.

The economic assessment showed that the 'second generation' solar low-power pumping systems have a relatively low investment cost. More important to the end user is the fact that, on the lifetime basis, the cost per m^3 discharged water is of the order, if not lower, of the present prices of water utility companies in urban areas.

NOMENCLATURE

- a availability
- C cost, (\$US)
- E energy, (J)
- h head, (m)
- H global irradiation, (J m^{-2})
- I current, (A)
- g gravity, (m s^{-2}), $g = 9.81$ m s^{-2}
- G global irradiance, (W m^{-2})
- MPP maximum power point of a solar module/array
- p parallel electrical connection
- P power, (W)
- Q water flow rate, (m^3 s^{-1}) in equations, (l h^{-1}) or (l s^{-1}) in figures
- s series electrical connection
- t time
- T temperature, (°C)
- U water volume, (m^3)
- V voltage, (V)

Greek symbols

- β surface tilt, (degrees)
- γ azimuth angle, (degrees)
- ρ density, (kg m^{-3}), for water $\rho = 1000$ kg m^{-3}
- η efficiency, (%)

Subscripts

- c capital cost
- hyd hydraulic
- M pump motor
- max maximum
- p peak
- tot total

APPENDIX A

The main results obtained in the AVICENNE project, contract No. AVI-CT94-0004, from laboratory testing of solar-powered pumps are presented in this section. The experimental data were kindly provided by Oldach (1999), and the crucial figures were reproduced for use in this paper.

Most of the pumps chosen for testing were 'second generation' pumps, representing the state of the art in pumping technology. Additionally, a 'first generation' centrifugal solar pump was included in the tests to enable comparison of the performance.

A range of tests was carried out as part of the so-called, round-robin test programme, between the participating laboratories. The test programme was split into laboratory testing and field testing. Information on the types of solar pumps tested are presented in Table A.1.

In Fig. A.1 is shown the head versus water flow instantaneous characteristics of six different

Table A.1. Solar pump types tested in AVICENNE No. AVI-CT94-0004 project

Pump ID no.	Type	PV array power (W)
1	Single-acting positive displacement pump (piston pump, 'second generation')	100
2	Centrifugal ('first generation' pump)	400
3	Diaphragm ('second generation' pump)	60
4	Diaphragm ('second generation' pump)	75
5	Helical rotor (progressive cavity, 'second generation' pump)	400
6	Helical rotor (progressive cavity, 'second generation' pump)	400

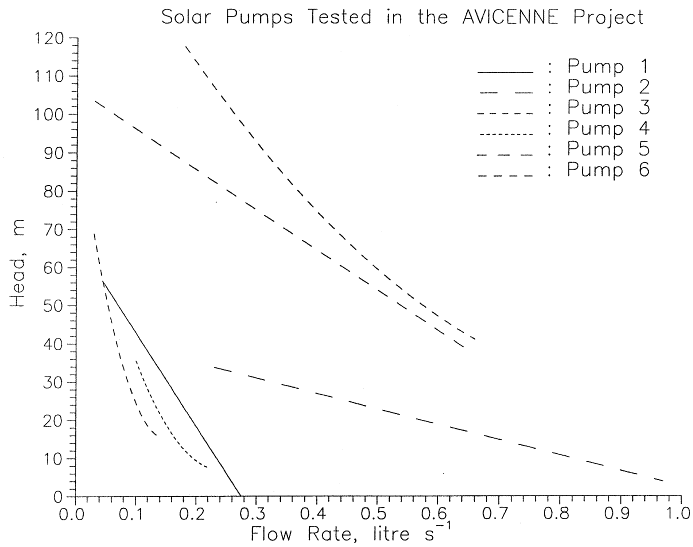

Fig. A.1. Water flow rate vs. head for solar pumps tested in AVI-CT94-0004 project.

pumps, while Fig. A.2 presents the hydraulic efficiency against normalised head for the pumps tested. Heads were normalised by dividing actual values by the optimum head.

The pumps chosen for testing encompass a range of heads, water flow rates and power levels as is illustrated in Fig. A.1. Fig. A.2 shows that there are considerable differences in the performance of the pumping systems tested. In all cases, the maximum hydraulic efficiency was obtained for normalised head = 1. The 'first generation' centrifugal pump (Pump 2), reached a maximum

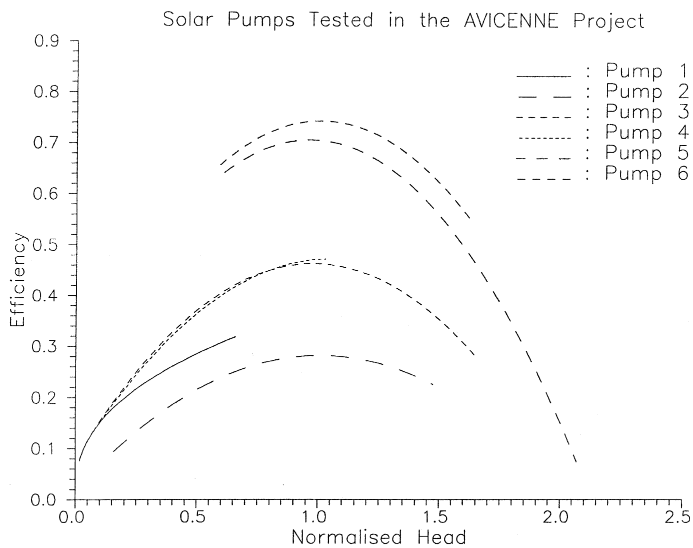

Fig. A.2. Efficiency vs. normalised head for solar pumps tested in AVI-CT94-0004.

Table B.1. PV module response, $T = 25°C$

G (W m^{-2})	Solar module type	
	BP255F P_{max} (W)	BP585F P_{max} (W)
100	4.4	6.7
200	10.1	15.6
300	15.7	24.3
400	21.3	32.9
500	27.0	41.6
600	32.6	50.3
700	38.3	59.0
800	43.9	67.7
900	49.5	76.4
1000	55.0	85.0

efficiency of less than 30%. In contrast, all 'second generation' solar pumps obtained efficiencies of more than 40%. An exceptional performance is noticed for the two helical rotor pumps (Pump 5 and Pump 6), that achieved a peak efficiency above 70%. For the end user, a higher efficiency results in more water being delivered at the same input power.

APPENDIX B

The power at the maximum point as a function of the global irradiance of the two module types used in the experiments with the SHURflo pump is presented in Table B.1.

APPENDIX C

The hourly global irradiation on a daily basis is presented in Fig. C.1. The daily global total irradiation values considered are from 7.2 MJ m^{-2} (2 kWh m^{-2}) the lowest, to 32.4 MJ m^{-2} (9 kWh m^{-2}) the highest, in steps of 3.6 MJ m^{-2} (1 kWh m^{-2}).

The profiles calculated in Fig. C.1 refer to clear blue-sky days and they were used for the calculations of the daily water delivery of a SHURflo 9325 solar pumping system.

APPENDIX D

Solar pump start/stop thresholds are important in assessing the daily performance of a system in terms of water delivery. The test aims to determine the values of the PV array nominal power at which a pumping system will start and stop, as solar power increases from zero and decreases, respectively. The starting and stopping points are a function of array power and nominal head.

The starting and stopping conditions for the 9325 SHURflo pump were kindly provided by Alonso-Abella (1997). In Fig. D.1, the starting and stopping pump characteristics are presented as a function of PV power and head in both 12 V and 24 V modes. These curves were taken into account in the calculations of the pump operation on a daily basis.

The start-up and shut-down characteristics of the 9325 pump strongly depend on the operational mode, i.e. 12 V or 24 V. For example, as it is seen in Fig. D.1, for head $h = 30$ m, the required PV input power for the system to start pumping at 12 V is 28 W. At 24 V mode, the starting point is 21.4% higher, i.e. 34 W. Thus, the 12 V configuration provides longer pump operation due to quicker start-up and later shut-down in a day compared to the 24 V operation. The disadvantage of the 12 V mode is the lower instantaneous water flow at high input power, which may result in lower daily

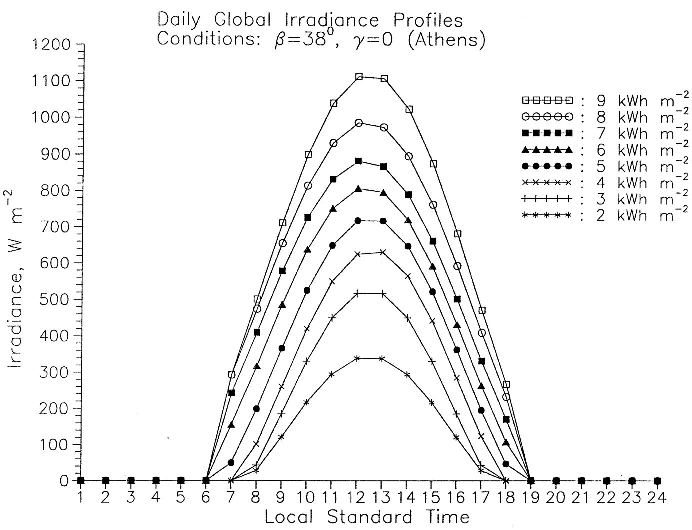

Fig. C.1. Typical hourly global irradiance for several daily irradiation values.

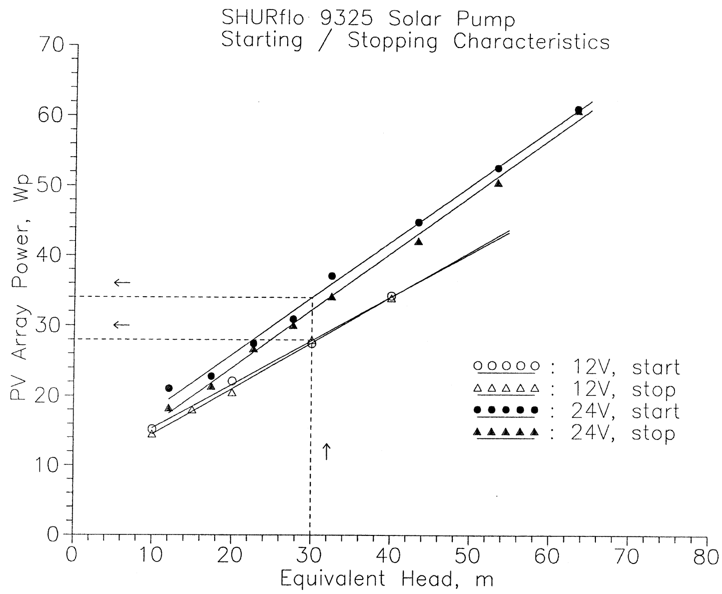

Fig. D.1. SHURflo 9325 starting and stopping thresholds.

water delivery. This also depends on the daily solar resource of the site on a yearly basis and the available PV array power.

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