Photovoltaic Water Pumping System: Part II - Design Methodology and Experimental Evaluation of Some Photovoltaic Water Pumping Systems

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ABSTRACT

The main objective of this paper is to provide necessary guidelines concerning photovoltaic pumping system sizing. To establish a design methodology, a logical step-by-step procedure was undertakenfor sizing a photovoltaic water pumping system at the ENEA research center, Trisaia, and the results obtained are discussed in this paper.

1. INTRODUCTION

The Basilicata region in southern Italy enjoys significant number of sunshine hours, annually, which is among the highest in Italy. The monthly daily averages vary from about 2.8 kWh/m^2 in July corresponding to a tilt angle of 30° due facing south. So, it can be stated that solar energy at acceptable level is available for long hours in this region for its serious utilization.

In fact, the interest of this particular region in solar energy covers a number of research and application areas. The characteristics of solar radiation and its prediction have been studied thoroughly since 1980. The development of innovative collectors for different thermal applications such as solar water heating, solar air heating, solar refrigeration, solar active and passive heating and cooling etc. have been considered. However, the use of solar energy for photovoltaic water pumping systems, particularly in reference to the areas in question, is in its initial phases of study and implementation.

Most system designers have their own methods and computer software for sizing, the details of which are often kept confidential. To establish a design methodology, a logical step-by-step procedure for sizing a photovoltaic water pumping system has been set out. Finally, experimental evaluation of a few PV water pumping systems installed at ENEA research center, Trisaia, was undertaken and the results obtained are discussed in this paper.

2. PHOTOVOLTAIC WATER PUMPING SYSTEM SIZING

The sizing of a photovoltaic water pumping system is not very straightforward. It strongly depends on a number of parameters; site selection, type of applications and many other considerations. The major field variables in the photovoltaic water pumping system's design are:

1. The daily average solar radiation and other weather parameters, such as the ambient temperature, wind velocity, dust accumulation, etc. Solar radiation is the energy input of the system while the other parameters affects the conversion efficiency of the photovoltaic panels.
2. The required daily load of a pumping system. It is the electric power needed to run the electric prime mover of the pump directly. Usually, as the pumping equipment and photovoltaic modules are connected directly, no storage batteries are used in this type of application.
3. The power rating of the available photovoltaic panels and the temperature at which the rating is stated. Also, the electric characteristics of the designed electric circuit.
4. The efficiencies of the various components of the system. As mentioned above, the input solar energy to the photovoltaic array undergoes several conversions before it is actually made available as mechanical energy for pumping water. Each conversion is associated with a certain amount of energy loss which ultimately influences the system overall efficiency.

It is in this context that the efficiencies of energy conversion, in other words, the efficiencies of the various components involved, in each of these stages are of critical importance.

For designing photovoltaic water pumping systems, some sophisticated concepts have already been applied by a few researchers. Detailed models have been developed. However, it is to be noted that more sophisticated these concepts are, the less they reflect the decision making process of an actual user. Moreover, the models available are sometimes too complex to be understood and consequently their use remains limited to a group of highly qualified personnel. It can, therefore, be concluded that there is an urgent need to establish a simple methodology to deal with the problem.

3. SIMPLE METHODOLOGY PROPOSED

After getting acquainted with the various components needed to install a photovoltaic water pumping system, the next important step is to determine the size of all such components for a given power load. So the system sizing is the process of determining the cheapest combination of various components that will meet the load requirement with an acceptable level of security over the expected life time of the installation.

Because the solar radiation varies, and in many cases the load demand cannot be predicted accurately, sizing is necessarily an approximate calculation, based on probabilities. A simple methodology of sizing calculation is proposed and is discussed in the following text.

The load of a pumping system is computed on the basis of the desired daily pumped volume of water, 'V', in cubic meters, and the total pumping head, 'H', in meters through which it is pumped. Thus, the daily energy input E_h to the water (in the form of potential energy) is given by the following equation, provided that both the well and the storage tank are open to the atmosphere as well as the tubes carrying water are of the same diameter:

$$E_h = \rho g V H \tag{1}$$

where 'ρ' is the density of the pumped water and 'g' is the local acceleration due to gravity. The density and acceleration are taken as 1000 kg/m^3 and 9.81 m/sec^2, respectively.

Thus, the daily energy, in 'kWh' is given by the following expression:

$$E_h = 0.002725\ V\ H \tag{2}$$

Here,

$$H = Hg + \{(P'' - P')/\rho\ g\} + P \tag{3}$$

where

Hg	=	geodetical height (m)
$(P'' - P')$	=	pressure difference existing actually at the open space just above the suction and discharge head (N/m^2)
P	=	pressure loss due to friction; as in the pipes, valves, bends, etc. (depending on d, L and number and type)

Now provided that both the well and the storage tank are open to the atmosphere, i.e. $P'' = P'$, the Eq. (2) can be modified as:

$$E_h = (Hg+P)\ \rho g V \tag{4}$$

The pressure loss due to friction, as mentioned above in Eq. (3) can be calculated using different formula available in the literature such as one discussed by Dott. Ing. Carlo Alberto Cavalli.

For example, to have an idea about the loss of pressure due to water in the tubes, the formula mentioned below, given by Darcy, can be used,

$$p_c = BLQ^2/D^5 \tag{5}$$

where

L	=	length of the tube (m)
D	=	diameter of the tube (mm)
B	=	coefficient dependent upon the characteristics of the tube (on average B = 0.0-0.25)

Similarly, other local pressure losses due to valves, bends, etc., are calculated as below. In the mathematical expression listed below, `v' is the velocity of water in the tube measured in m/sec.

1. Sudden Expansion :

$$p_a = \alpha\,(v_1 - v_2)^2/2g \tag{6}$$

2. Sudden Squeeze:

$$p_s \cong 0.5v^2/2g \tag{7}$$

3. Elbow :

$$p_g = \alpha\, v^2/2g \tag{8}$$

Where α being the function of angle is given by :

Angle	=	40°	60°	80°	90°
α	=	0.14	0.36	0.74	0.98

4. Pipe Fitting

$$p_r = \alpha\,(\theta/90^\circ)\, v^2/2g \tag{9}$$

for	r/D	=	4,	2,	1
	α	=	0.13	0.15	0.28

So, considering all the losses together, the net pressure loss due to friction is:

$$P = p_c + p_a + p_s + p_g + p_r \tag{10}$$

now, assuming that the system (electric motor and pump) operates at an average efficiency of η_{pp}, thus the daily energy input to the above system (to be generated by photovoltaic generator) becomes:

$$E_{elec} = \{0.00272\ (Hg + P)\ V\}\ /\ \eta_{pp}\quad \text{(kWh)} \tag{11}$$

Once the above calculations are completed and the daily demand to be generated by photovoltaic array is known, the next step on how to achieve this load using photovoltaic technology is discussed in the following sections.

3.1 PV - Generator Sizing

To make available the electrical energy needed E_{elec} to supply V (m^3) of water per day with a total head of h (m) and with η_{pp} as the motor-pump efficiency, the design of photovoltaic array is discussed below.

The design of photovoltaic generator is possible only if data on the solar radiation at the location of the system are available. Moreover, since in photovoltaic system, away from the equator, one normally inclines the modules, the knowledge of the global radiation on an inclined plane is necessary to size the system. The solar radiation on the array surface must be evaluated on a monthly basis.

The second important factor concerning photovoltaic generator sizing is the type of solar cell module selected and its performance at the working temperature under real operating conditions. A simple method, discussed here, can be used for the purpose of photovoltaic array sizing.

From meteorological data for the site, take the monthly mean daily irradiation figures, in kWh/m^2, per day at three different tilt angles. Determine the tilt angle corresponding to the highest value of the solar radiation. However, for the system to be used throughout the year, it is advisable to have a tilt angle corresponding to the latitude of that place.

Determine the highest ambient temperature, the array is likely to experience, on a probability based on the required level of security. Then add the estimated temperature rise in the selected type of module to give the estimated maximum operating temperature.

From the I-V characteristics of the selected modules at the maximum operating temperature (as discussed above) and an irradiance of 1000 W/m^2, determine the voltage at which maximum power is delivered. Bearing in mind the manufacturer's tolerance of about 10%, calculate the working voltage, to allow for variation from the nominal performance.

Calculate the number of series - connected modules required to generate the chosen DC bus voltage. Using the efficiency of selected module (measured experimentally or provided by the manufacturer), the area of the photovoltaic array needed to supply required electric power can be determined. This is illustrated as below:

To design a photovoltaic system with DC bus voltage of 24 volts, the following are computed:

- Number of modules per string = $\dfrac{24+1 \text{ (allowance for blocking diode)}}{\text{working voltage } (V_{working})} = \eta_{mod.}$

- Mean daily output available from PV modules = $G * \eta_{mod.}$
  (kWh/day /m² photovoltaic solar cell surface area of 1 m²)

where:

$\eta_{mod.}$ = efficiency of the solar module
G, kWh/m² = Mean daily solar radiation available on the tilted photovoltaic array

- Gross mean daily output available from = $0.98 * G * \eta_{mod.}$
  (kWh/day/m² photo voltaic module area of 1 m²)

Assuming array losses due to module mismatch, blocking diodes, dirt and degradation is 2%

- Area of PV modules required = $\dfrac{E_{elec}}{0.98 * G * \eta_{mod.}}$ (m²) = A (m²)

where:

E_{elec}, (kWh/day) = mean daily load required

- Therefore, number of PV modules required = $A/a = N$ (should be a round figure)

where:

a (m²) = area of standard PV module selected

- So, to have a minimum bus voltage of 24 volts :

Minimum number of modules strings = $N / \eta_{mod.} = N_{string}$

After the above exercise, the next step is to select a most suitable `motor-pump' system that can provide the required amount of water from a specified pumping head while working for a specified number of hours in a day (depending upon the prevailing meteorological conditions at the site).

In general, there are two main types of pumps used in solar pumping systems: 1) centrifugal pump and 2) volumetric pump. The pumps are available both in submersible as well as non-submersible configuration. Comparing the performance for both types of pumps available in the market and commonly used in most pumping applications, it can be stated that for favourable sunshine conditions, the difference is negligible. But at unfavorable days, the system's performance are remarkably different. Threshold limits do not allow the centrifugal pump to start. Therefore, the energy delivered from the photovoltaic panels is not used.

Standard pumping equipment for photovoltaic applications uses multistage centrifugal pumps. In the wide field of applications, where low pressure levels prevail, multistage centrifugal pumps are the best choice, if some disadvantages can be overcome.

This is a reliable and efficient technique for low head pumping. But when used in deep well applications, impeller pumps with submerged AC motors do not perfectly match the needs for PV pumping. Centrifugal pumps show best performance at (or near to) rated power. However, the multistage technology has disadvantages at partial load, which is the most probable operation condition for any solar system. The decrease in power conversion factors at partial load can significantly reduce daily output values at low insolation levels/days.

Considering the performance data for such pumps, it can be stated that higher speeds could increase pump efficiency. A design with an optimal efficiency at partial load conditions could influence the utilization by augmenting the energy output at low insolation levels.

Displacement pumps on the other hand are best suited for high water heads and low flow regimes. Thus piston pump, which could easily be powered by DC- motor, seems to be a promising alternative. Due to good partial load efficiency of the pump, the hydraulic energy output is quite good even at very bad weather conditions.

As mentioned above, the technique is well established and efficiency is excellent but there are some difficulties as well. The problem of non-steady operation, severe start-up conditions, and torque should be treated carefully, if photovoltaic operation is envisaged. It is hoped that by combining a rotating displacement pump with a conventional submerged AC-motor, the system performance at medium water head can be increased.

A comparative plot (hydraulic output) of systems with centrifugal and progressive cavity pumps has demonstrated about 20% - 25% better partial load performance of the displacement concept compared to the submerged centrifugal pump.

Keeping in view the facts mentioned above along with other parameters such as, the maximum pumping head values from which the water is to be pumped, the range of water flow values to be encountered during real operating conditions, and the calculated power load required to pump given amount of water, etc., suitable selection can be made.

Pump performance is based on the water flow, Q (m^3 /hr), an electric pump delivers at a given pumping head. The manufacturer provides pump performance data in graphical or tabular form. So from these technical performance data, as presented in Tables 1a,b, c, suitable pump size able to deliver water at a desired flow rate from a given pumping head value can be selected.

In general, while selecting a suitable electro-pump unit, the following points must be taken into consideration.

- The pump size is normally designated by the horsepower (Hp) of the pump motor, but the pump unit should never be selected barely on the basis of horsepower alone because (1) water flow for pumps of the same horsepower varies, (2) horsepower alone gives little indication of the water flow rate at a given pumping head, and (3) rated power is also not a good indicator of the power required to operate the pump motor.
- It is also advisable to compare the electric-pumps for their water flow rate per watt value. This parameter is important as it is a measure of the pump's electrical efficiency.
- While selecting the horsepower (Hp) of the motor, it should always be kept in mind that this should never be less than the P_c, peak (Peak power generated by the photovoltaic array).
- There exist an average value for the water flow rate, i. e. Q_{ave}, during the day, but keeping in mind that the centrifugal pump is not having a constant torque as well as the power generated by the photovoltaic array is little low in the early morning and late evening hours, it is always desirable to select a pump with little higher Q value than the one averaged over the day i.e. Q_{ave}.

So from the discussion made so far concerning the sizing of a photovoltaic water pumping

Capacity	Q (m^3/h)	0.3		0.6		0.9		1.5		2.4		3.6		4.8		6.0		7.5	
Type		h	kW	h	kW	h	kW	h	kW	h	kW	h	kW	h	kW	h	kW	h	kW
BT 201	B R	25	0.48	23	0.45	20	0.40	15	0.35	08	0.25								
BT 202	A	50	0.90	46	0.80	40	0.75	30	0.60	15	0.45								
BT 203	N C	74	1.30	70	1.20	60	1.10	45	0.90	21	0.60								
BT 204	H	98	1.65	92	1.55	80	1.40	60	1.20	28	0.80								
BT 205	E	123	2.10	114	1.90	100	1.75	75	1.50	35	0.90								
BT 206	S Ø = 20	148	2.50	139	2.30	120	2.05	90	1.70	40	1.10								
	NPSH m	2		2		2		2.2		3.1									
BT 291	B R			34	0.65	31.5	0.60	28	0.55	20	0.45	10	0.35						
BT 292	A			68	1.25	63	1.20	56	1.15	40	1.00	20	0.80						
BT 293	N C			102	2.00	94.5	1.90	82	1.75	60	1.45	30	1.20						
BT 294	H			136	2.65	126	2.60	109	2.35	80	2.00	40	1.55						
BT 295	E			170	3.40	157	3.25	137	2.95	98	2.50	50	1.90						
BT 296	S Ø = 32			204	4.10	190	4.00	137	3.50	119	3.10	60	2.35						
	NPSH m	1		1		1.1		1..2		1.5									

Table 1a. Technical data for centrifugal pumps manufactured by Garbarino Electro Pump Ltd.

Capacity	Q (m^3/h)	0.3		0.6		0.9		1.5		2.4		3.6		4.8		6.0		7.5	
Type		h	kW	h	kW	h	kW	h	kW	h	kW	h	kW	h	kW	h	kW	h	kW
BT 301	BRANCHES ⌀ = 32					40	1.00	35	0.90	25	0.75	16	0.55	8	0.35				
BT 302						80	2.95	70	1.85	55	1.50	35	1.10	16	0.75				
BT 303						120	2.95	105	2.50	80	2.20	50	1.60	21	1.10				
BT 304						159	4.05	140	3.70	108	3.00	70	2.80	30	1.60				
BT 305						198	5.00	170	4.55	130	3.85	85	3.30	39	1.85				
BT 306						235	5.90	205	5.30	160	4.40	101	3.35	45	2.20				
	NPSH m					1.1		1.1		1..2		1.5		2.2					
BT 311	BRANCHES ⌀ = 32											25	0.95	20	0.75	12	0.55	6	0.35
BT 312												50	1.85	40	1.55	25	1.20	12	0.75
BT 313												78	2.85	60	2.35	40	1.75	18	1.10
BT 314												104	3.85	80	3.15	54	2.35	24	1.50
BT 315												129	4.80	98	4.05	69	2.95	30	1.85
BT 316												153	5.65	117	4.80	80	3.45	36	2.20
BT 317												180	6.60	135	5.50	92	4.05	40	2.50
	NPSH m											1.6		1.7		2.2		3	

Table 1b. Technical data for centrifugal pumps manufactured by Garbarino Electro Pump Ltd. (contd.)

Capacity	Q (m³/h)	6		7.5		9		10.5		12		15		18		21		24		30		36	
Type		h	kW	h	kW	h	kW	h	kW	h	kW	h	kW	h	kW	h	kW	h	kW	h	kW	h	kW
BT 401	BRANCHES	32	1.7	28	1.50	20	1.35	12	1.35	7	0.9												
BT 402		63	4.25	50	2.85	40	2.30	27	2.00	14	1.50												
BT 403		95	4.95	78	4.25	60	3.55	40	2.85	21	2.15												
BT 404		125	6.55	100	5.75	78	4.70	52	3.70	29	2.95												
BT 405		155	8.10	125	7.00	95	5.90	66	4.80	35	3.60												
BT 406	Ø = 40	185	9.55	130	8.10	115	6.90	80	5.50	42	4.25												
	NPSH m	2		2.1		2.5		3		3.7													
BT 501	BRANCHES							35	3.85	32	3.70	26	2.95	20	2.60	11	2.15						
BT 502								75	7.95	68	7.35	53	6.25	40	5.15	26	4.05						
BT 503								110	11.5	100	10.7	80	9.20	59	7.50	39	6.0						
BT 504								150	15.1	135	14.0	105	12.1	80	9.90	50	8.0						
BT 505								185	19.0	169	17.6	132	15.1	100	12.5	64	9.85						
BT 506	Ø = 50							220	22.1	200	20.6	159	17.6	119	14.7	78	11.80						
	NPSH m							2.4		2.5		2.7		3		3.5							
BT 651	BRANCHES													37	6.40	31	5.60	27	5.50	17	4.4	7	3.5
BT 652														74	12.5	65	11.0	53	9.90	33	8.1	13	5.5
BT 653														110	18.0	95	16.2	80	14.7	48	11	18	8.1
BT 654														145	23.5	127	21.0	106	19.1	63	14.7	23	9.9
BT 655														185	28.7	160	26.5	132	17.5	78	17.5	28	12.5
	Ø = 60																						
	NPSH m													4		4		4.5		4.5		5	

Table 1c. Technical data for centrifugal pumps manufactured by Garbarino Electro Pump Ltd. (contd.)

system, it can be concluded that to lift a specified quantity of water through a given water head, at a given site, the overall sizing of the system depends upon a number of important considerations such as:

- Type of the solar cell panel (in terms of their efficiency and performance).
- Efficiency of the rest of the system i.e. the pump-motor- controller system.

Taking into consideration the recent developments, it can be stated that the electrical demand can be reduced significantly by making use of different components with high efficiency and durability such as:

1. Water pumps with high efficiency such as piston pump or progressive cavity pump.
2. DC brushless motor with high efficiency (upto 90%), and
3. A pulse - width - modulated controller with an efficiency of 95%.

It is true that a directly coupled DC motor photovoltaic water pumping system is easy to design and easy to operate. But as they are more expensive, difficult to obtain, and not as reliable as expected, it is also advisable to make use of AC motor.

The AC system performs better compared to DC ones but such a system needs an Inverter, which may require additional cost. It is therefore very important that due consideration be given to all such points while designing a PV water pumping system.

4. DEMONSTRATION OF THE METHODOLOGY PROPOSED

The use of the methodology has been demonstrated while designing a photovoltaic water pumping system to supply 40 m^3 of water a day from a total pumping head of 10 m, required by a farm house situated in Basilicata region of southern Italy. It is assumed that the daily operation of the pumping system is to last for 8 hours a day.

The electrical energy needed to supply 40 m^3 water in a day (flow rate varying from $3 m^3/hr$ - 8 m^3/hr) from a total pumping head of 10 m is given by

$$E_{elec} = \rho g V H / \eta_{pp} \tag{12}$$

$$= 2{,}725 \text{ kWh/day}$$

Where η_{pp} = 0.40, average motor-pump yield. To design DC bus voltage of 24 volts using the equations previously established, compute the following:

- Number of modules per string = $\dfrac{24+1(\text{allowance for blocking diode})}{13\ (\text{working voltage})}$

  = 25/13 = 2

(for photovoltaic generator, commercial 18 volts, 34 Wp crystalline silicon type PV modules manufactured by ANSALDO are considered in the present exercise).

Mean daily solar radiation available on the inclined plane (average in the month of December) = 3.10 kWh/m^2-day

Efficiency of the photovoltaic module = 10%

- Mean daily output available from the PV module surface area of 1 m^2
  = 3.10 * 0.10
  = 0.310 kWh/m^2-day

Array losses due to module mismatch, blocking diodes, dirt and degradation
= 2%

- Gross mean daily output availablefrom module surface area of 1 m^2
  = 0.310 * 0.98
  = 0.304 kWh/m^2 - day

Mean daily load required = 2.725 kWh/day

- Total area of PV modules required = (2.725 / 0.304)m^2
  = 8.96 m^2

Area of standard PV module used in the exercise = 0.42 m^2

- Therefore, number of PV modules required = (8.96 / 0.42)
  = 21.33 (22)

- So, minimum number of module strings = 22/2
  = 11

Now, once the sizing of the photovoltaic generator is finalized, the next step is to choose a suitable motor-pump unit that can deliver the water in the flow range 3m^3/hr - 8 m^3/hr from a pumping head of 10m - 15 m.

Considering the centrifugal pumps available in different configurations and after careful assessment of the technical data provided by the manufacturer (following the procedure discussed earlier), it has been observed that both the models BT 312 as well as BT 313, with pump output of 32 mm, manufactured by Garbarino Electric Pump Company Ltd. can be used to meet the demand. The pumps can be run by an electric motor of power 750 watts. However, for security reasons, it is advisable to use a motor with electrical power equal to 1.1 kW capable of lifting water from a total pumping head of more than 20 m or so.

5. DESCRIPTION OF THE PV WATER PUMPING SYSTEMS

The photovoltaic water pumping systems under investigations are shown in Figs. 1-2. The differences between both the systems are the static head, type of the pump, size of the motor and capacity of the photovoltaic generator.

The first of these two systems (Fig. 1) is a low capacity pumping system designed to pump water from a total pumping head of approximately 5m - 10 m. The pumped water from the well is taken to a storage tank of capacity 2 m³ which in turn is connected to the well through a piping system.

The solar generator is formed of solar cell modules of polycrystalline silicon cell. Each solar module consists of 36 solar cells connected in series with peak power of 34 Wp. Hence, the generator peak power is 340 Wp. Each solar module produces an open circuit voltage of 18 volts when it is not connected to the electrical system.

The specification of the solar cell module as provided by the manufacturer are presented in Table 2. The modules are connected in series of 2 modules to form 5 strings. The photovoltaic array thus comprises of 5 strings connected in parallel.

The pump is a submersible electric pump, Model EPS 005 CC, manufactured by Tamagnini Electropumps Industries Ltd. The said pump is run by DC brush motor of 0.5 Hp at 24 volts. The technical data for the said pump is presented in Fig. 3.

The second system (Fig. 2) was designed for pumping water from the horizontal base of a water distillation plant (installed during the period 1989-90) in a 20 m³ capacity storage tank through a pumping head of approximately 5 m-15 m.

The photovoltaic generator comprises of 9 solar modules of monocrystalline silicon solar cell

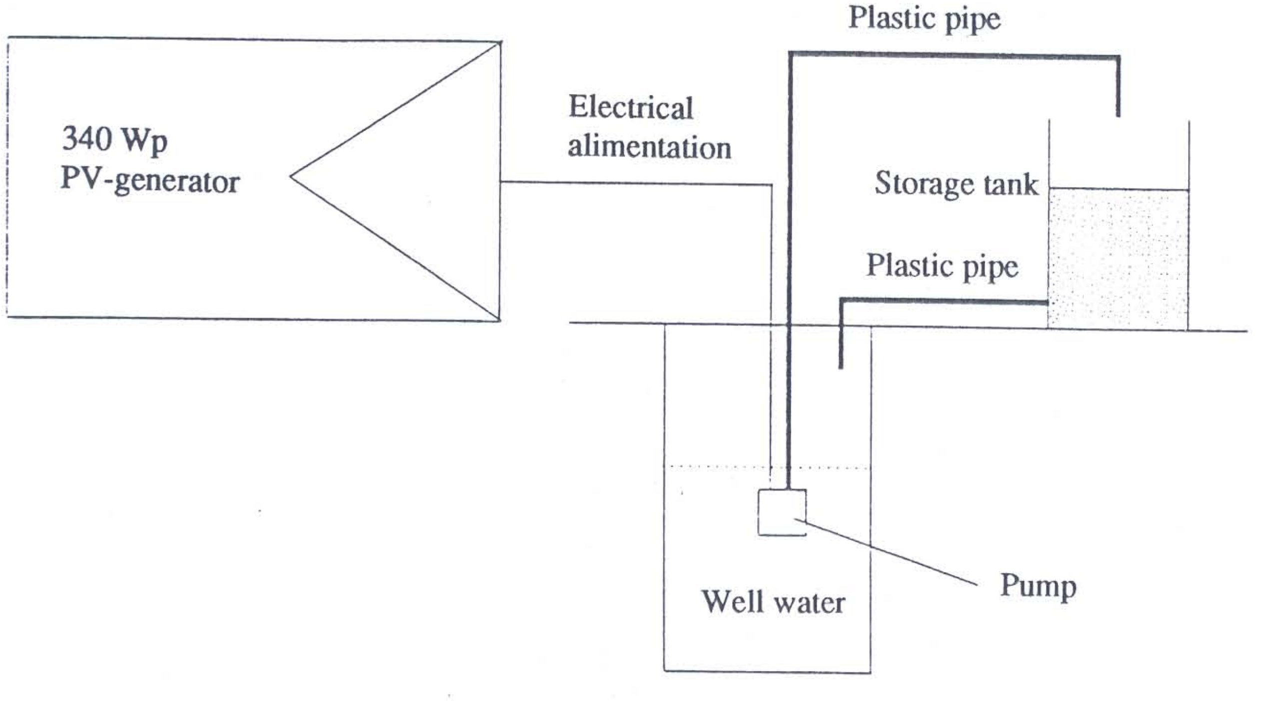


Fig. 1. General sketch of 340 Wp PV- water pumping system.

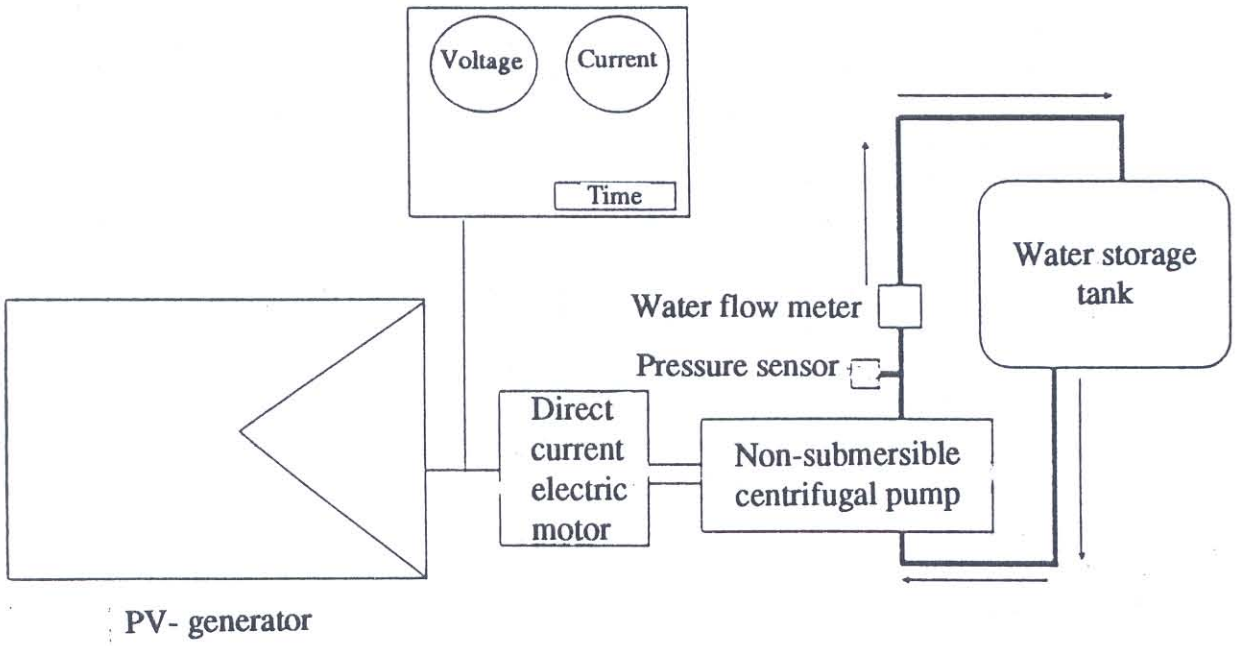
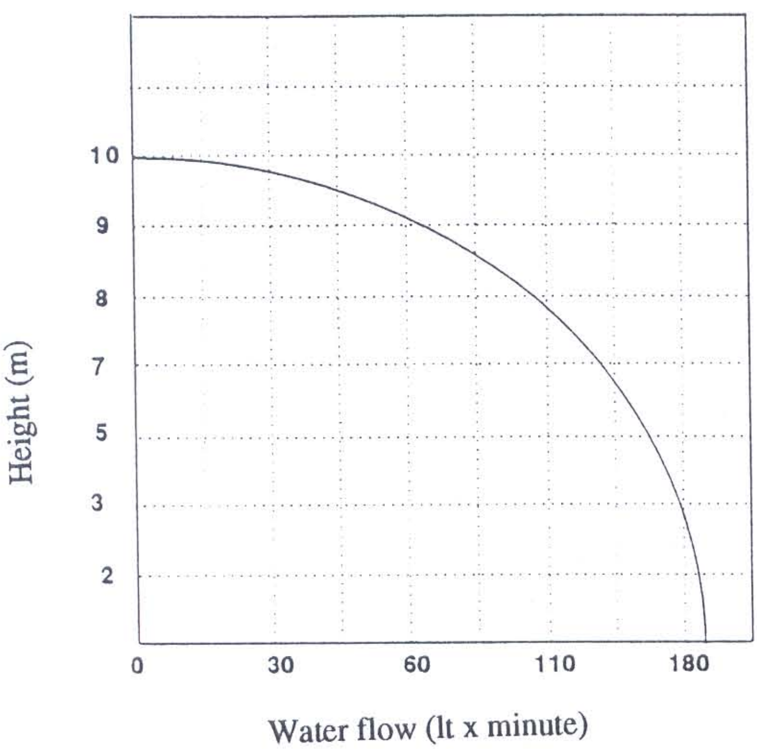


Fig. 2. General sketch of photovoltaic water pump system with non-submersible vertical centrifugal pump.



Pump type: EPS 005 CC

Technical data:

Volt:	12 or 24 CC
Rating:	HP 0.5
Poles:	2
Revolutions:	2800 /min

Fig. 3. Performance curve as well as technical data of submersible pump type EPS 005 CC.

manufactured by Italsolar. Each solar module consists of 12 circular shaped solar cell connected electrically in series and parallel. The overall dimensions of each module are 130 x 68 cm^2, with net solar cell area for each module equal to 0.56 m^2. Open circuit voltage is of 6.785 volts.

Each module has a peak power of 58.5 Wp and hence the peak power of the photovoltaic generator is approximately 528 Wp. The three modules are connected in series to form a string. So the PV generator comprises of three strings connected in parallel. The specification of the solar cell module provided by the manufacturer are presented in Table 2.

The pump used in the system is a multistage vertical centrifugal pump, Model 50 CV 7, manufactured by LOWARA Electropumps Industries. The pump is run by one horsepower DC brush motor at 18 volts.

The main characteristics of the vertical multistage pump is the plurality of the stages which, arranged in series, assure constant rates of flow with varying heads depending on the number of the stages involved. The suction and discharge connections may be oriented with respect to each other to different positions by upto 90°, by simply unscrewing the tilt rod bolts. The typical characteristics of the pump used i.e. non -submersible multistage vertical centrifugal pump, are presented in Fig. 4.

Table 2. Specification of the solar cell modules provided by the manufacturer (measured at 1 sun and 25 °C)

Type of Module	No. of solar cells used in a module	Area of each solar cell cm^2	Voc (Volts)	Isc (Amp)	Vpm (Volts)	Ipm (Amp)	Pmax (Watt)
ANSALDO	36 (square shaped polycrystalline silicon solar cell)	100	18	3.116	12.68	2.70	34.20
ITALSOLAR	72 (circular shaped monocrystalline silicon solar cell)	78.57	6.78	13.82	4.78	11.82	58.53

6. INSTRUMENTATION

Instrumentation was used to measure solar radiation, ambient temperature, water flow rate, current and voltage characteristics of photovoltaic generator, etc. The solar radiation was measured by means of a pyranometer placed at the plane of the photovoltaic array i.e. at an inclination of 45° facing due south.

Ambient temperature was recorded using PT - 100 sensors at regular interval of 10 minutes or so. An 4 m^3/hr water flow- meter (model PI3 3100) was used to determine the water flow rate. The pressure observations were recorded using a pressure sensor. The daily yield of the water pumped by the system under investigation was also recorded. A direct read-out of the voltage and current intensity generated by photovoltaic array was possible from the main switchboard of the plants.

7. EXPERIMENTS

The main idea of this exercise was to establish the overall efficiency of the system by measuring

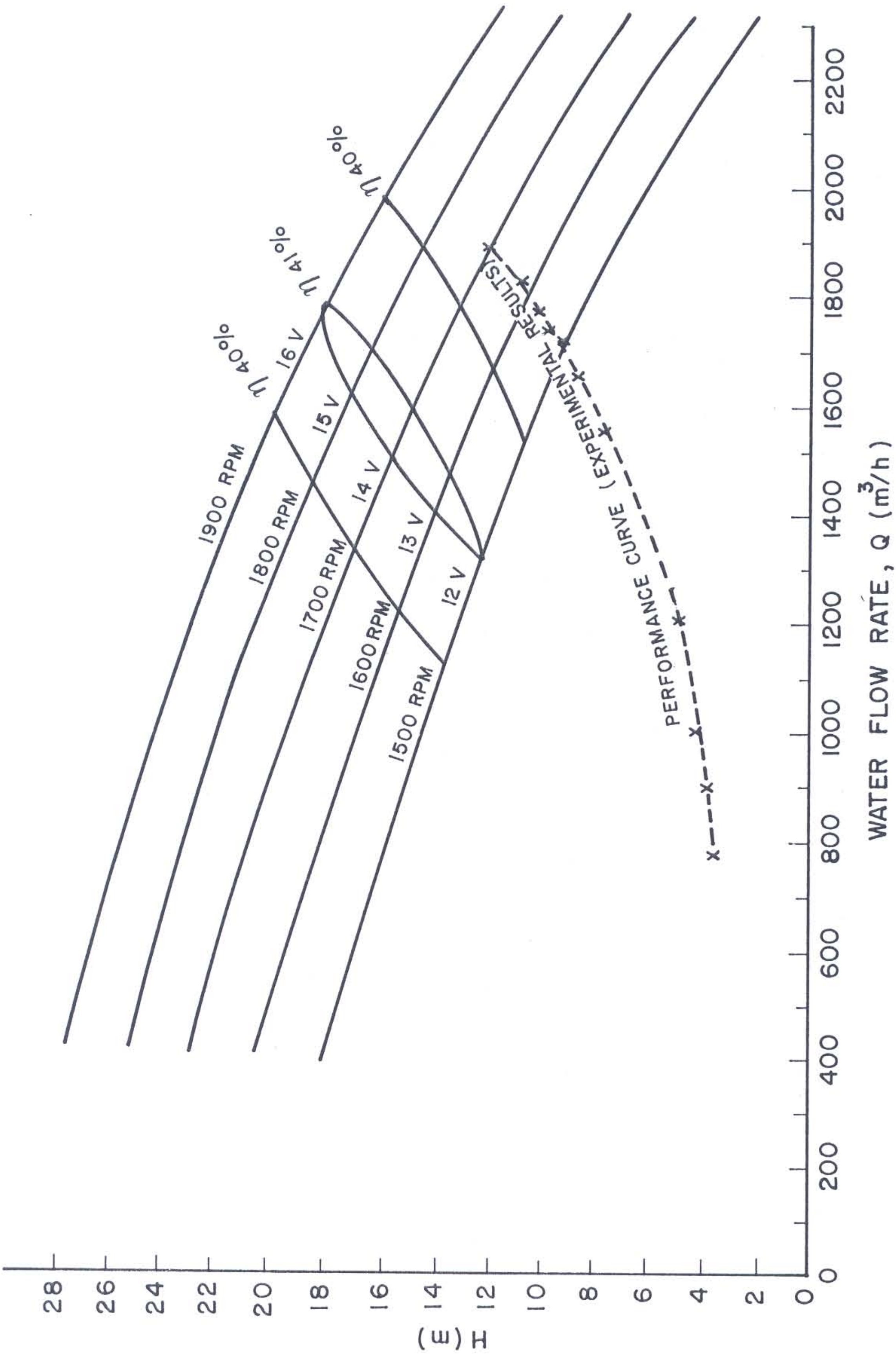


Fig. 4. Technical performance curves of multi stages centrifugal pump Lowara Model 50CV7.

both the solar global radiation, the pumping output and electrical voltages and currents. To measure module temperature PT-100 sensor was attached to the solar cell module. A series of experiments were conducted during the months of November and December, 1994 at ENEA Research Centre Trisaia. The experiments were conducted on clear sunny days and observations such as global solar radiation, water flow rate, voltage and current intensity, etc. were recorded at a regular interval from 8 am till 4 pm in the evening. However, because of the shadow problem caused by the office building as well as some trees nearby, it was not possible to record the experimental observation before 8.50 in the morning and after 3.20 in the evening.

8. PERFORMANCE EQUATIONS

In order to evaluate the performance of photovoltaic water pumping systems under investigation, the data collected experimentally was used to calculate the following quantities :

The Solar Power, P_{photo}, is given by

$$P_{photo} = A_{pv} I_{gt} \tag{13}$$

Where A_{pv} = net cell area of the photovoltaic array in m^2 and Igt is the global solar radiation incident of tilted plane of PV array measured in W/m^2.

$$P_{electric} = V_o I \tag{14}$$

Where V_o = measured voltage in volts and I is the current in amperes.

The mechanical power delivered by the motor can be taken to be the same as the hydraulic power delivered by the pump of mechanical efficiency η_{pp}, i.e.

$$P_{hydraulic} = \rho g V H = 2725\, V H \text{ (watts)} \tag{15}$$

Here 'H' is the water head in meters and 'V' is the volume of water pumped/day (m^3), calculated using the water flow rate, Q, measured in m^3/hr.

The photovoltaic conversion efficiency, η_{pv}, is given by

$$\eta_{pv} = [P_{electric} / P_{photo}]\ 100 \tag{16}$$

The total daily average efficiency of motor - pump unit, η_{mp}, is given by

η_{mp} = (Pump Hydraulic energy output per day ,Wh) / Photovoltaic energy output per day, (Wh) x 100

The total daily efficiency of the photovoltaic water pump system, $\eta_{(total\ system)\ ave.}$ is given by

$\eta_{(total\ system)\ ave}$ = Pump hydraulic energy output per day (Wh) / Solar power incident on the system per day (wh)

Where, pump hydraulic energy output per day = $2.725\ V\ H$ (Wh)
V = Volume of water pumped/day (m^3)
H = Total water head (m)

and, Solar energy incident on the system per day = $\int_{t_i}^{t_f} I_{gt}(t)\, A_{pv}\, dt$

9. PRELIMINARY RESULTS AND DISCUSSION

The experimental data for both the systems have been analyzed and the results obtained are discussed below.

9.1 PV - Water Pump System (with submersible centrifugal pumps)

The power intake of motor pump in terms of operating voltage and current, power available from PV generator, water flow rate, etc. have been collected while operating the system under real field conditions. The significant curves and the essential physical values have been plotted in Figs. 5-8. Fig. 5 presents the solar insolation data on the day of experimentation i.e. December 13, 1994.

To start operation, the motor/pump unit requires a certain amount of power to overcome the starting torque. A centrifugal pump has a relatively low starting torque and will readily start to rotate slowly even if the solar irradiance is low. There will not be any significant water output, however, until the irradiance increases to a level where array power is sufficient to develop the rotational speed required for pumping water through certain height. Typically, a photovoltaic water pumping system starts pumping water when the irradiance rises above this threshold level. Experimentally, it has been observed that in the present case this threshold value correspond to a power of approximately 60 Watts.

From Fig. 6, we can see that the array efficiency varies with solar insolation level. This may be because of the fact that series resistance of the solar cell varies with the insolation. The series resistance of the solar cell decreases with the increase of solar insolation. However, it is to be noted that at higher solar insolation levels, the array efficiency may be reduced. This is especial]y true in summer seasons with higher temperature values. In the present experimental setup, PV array has a maximum efficiency of approximately 6.4 %.

The system has a maximum flow rate of 2.06 m^3/hr at an operating head of 6.8 m and at an insolation level of 902 W/m^2. The instantaneous performance of the motor pump unit is presented in Fig. 7. The maximum motor-pump unit efficiency of the system under investigation has been recorded to be 18.89%.

The daily average efficiency of the system (Fig. 8) is 0.9% with maximum instantaneous efficiency value of 1.2% recorded at an insolation level of 839 W/m^2.

The average daily water production in the month of October, November and December is 12.5, 12.0 and 11 m^3/day, respectively. The decreasing trend is because of the shadow problems from the nearby trees. This was the reason that the system could not be operated before 9 a.m. and has to be switched off at nearly 3 p.m.

A summary of the results obtained from the system under investigation is presented in Table 3.

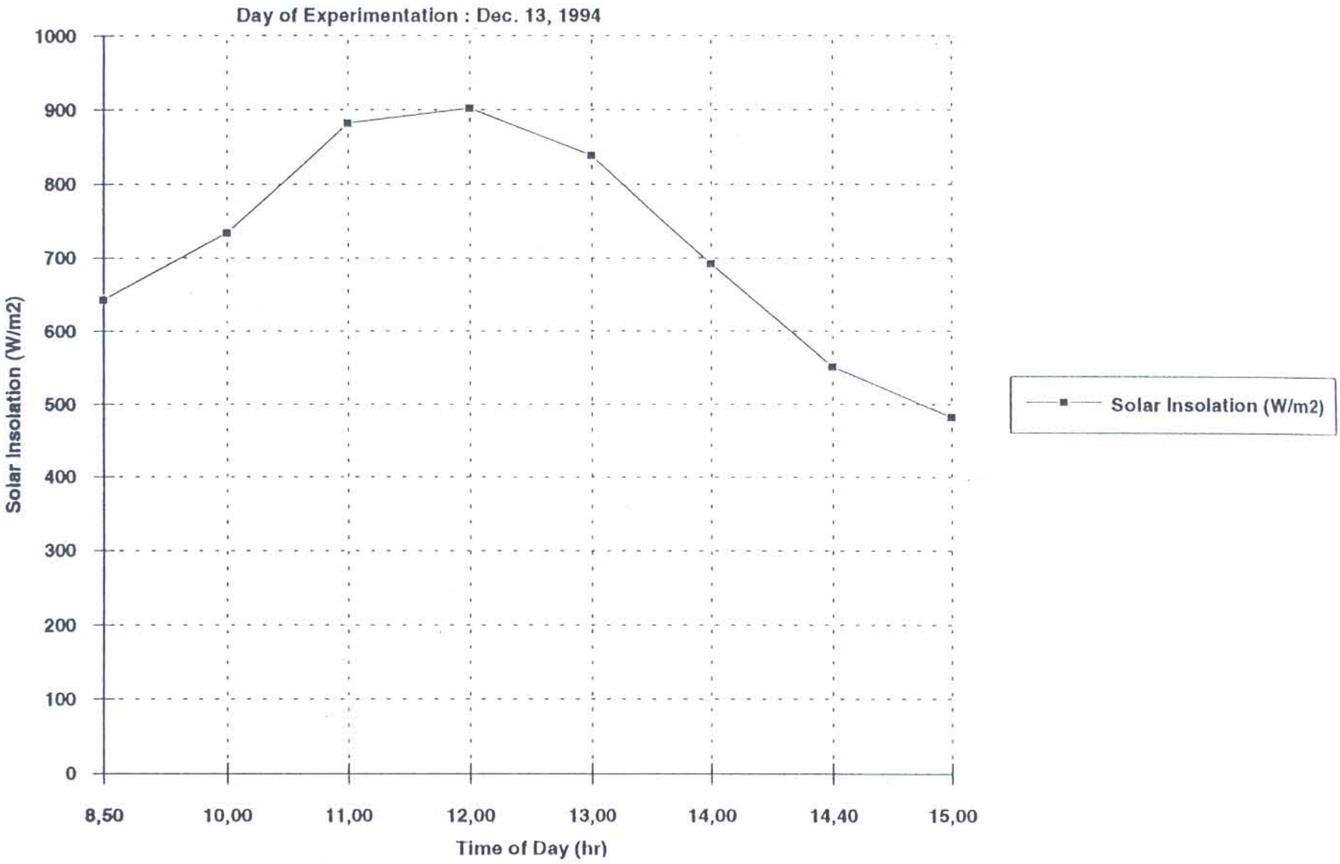


Fig. 5. Solar insolation measured experimentally at an angle of 30° (W/m²).

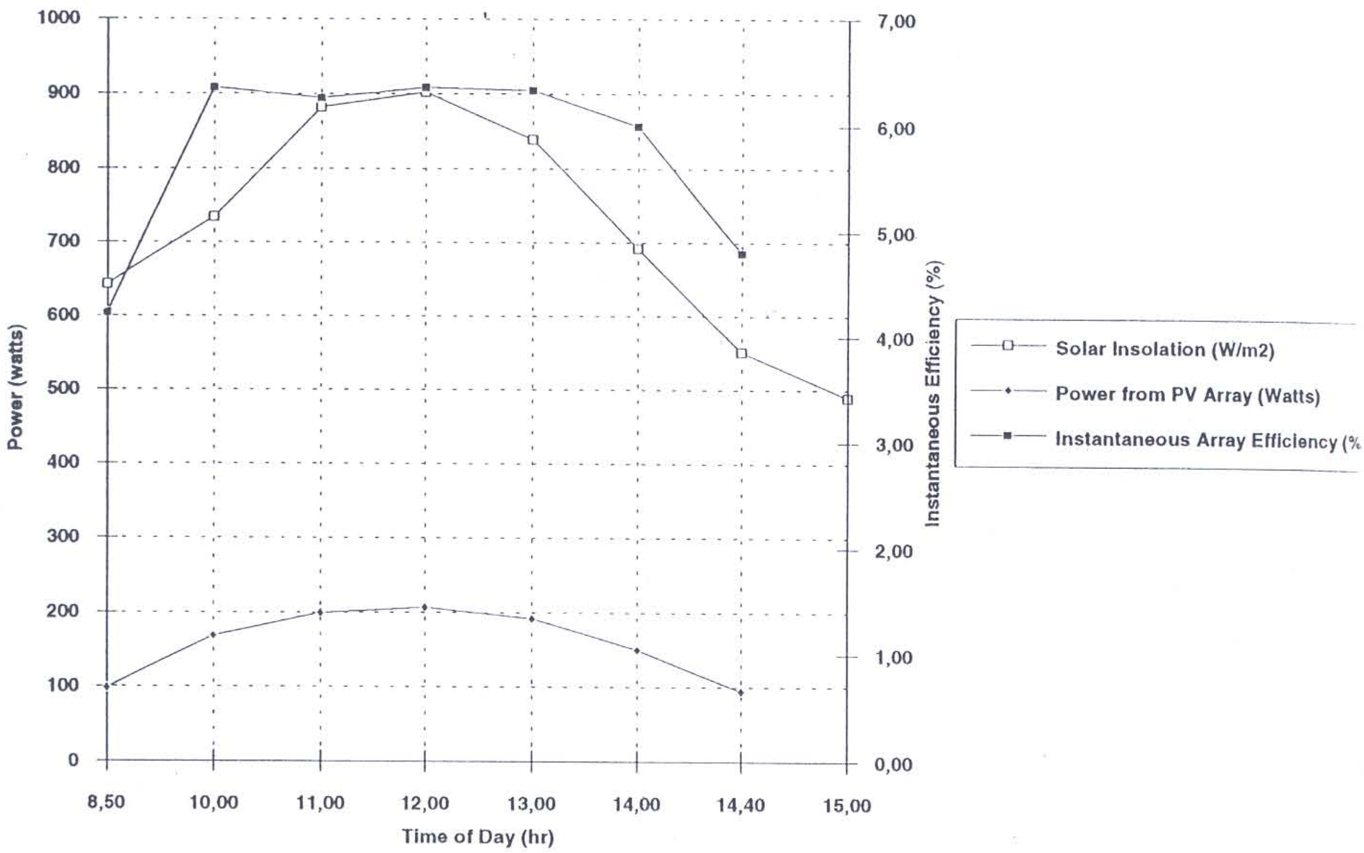


Fig. 6. Experimental evaluation of PV- generator (Date: Dec. 13, 1994)

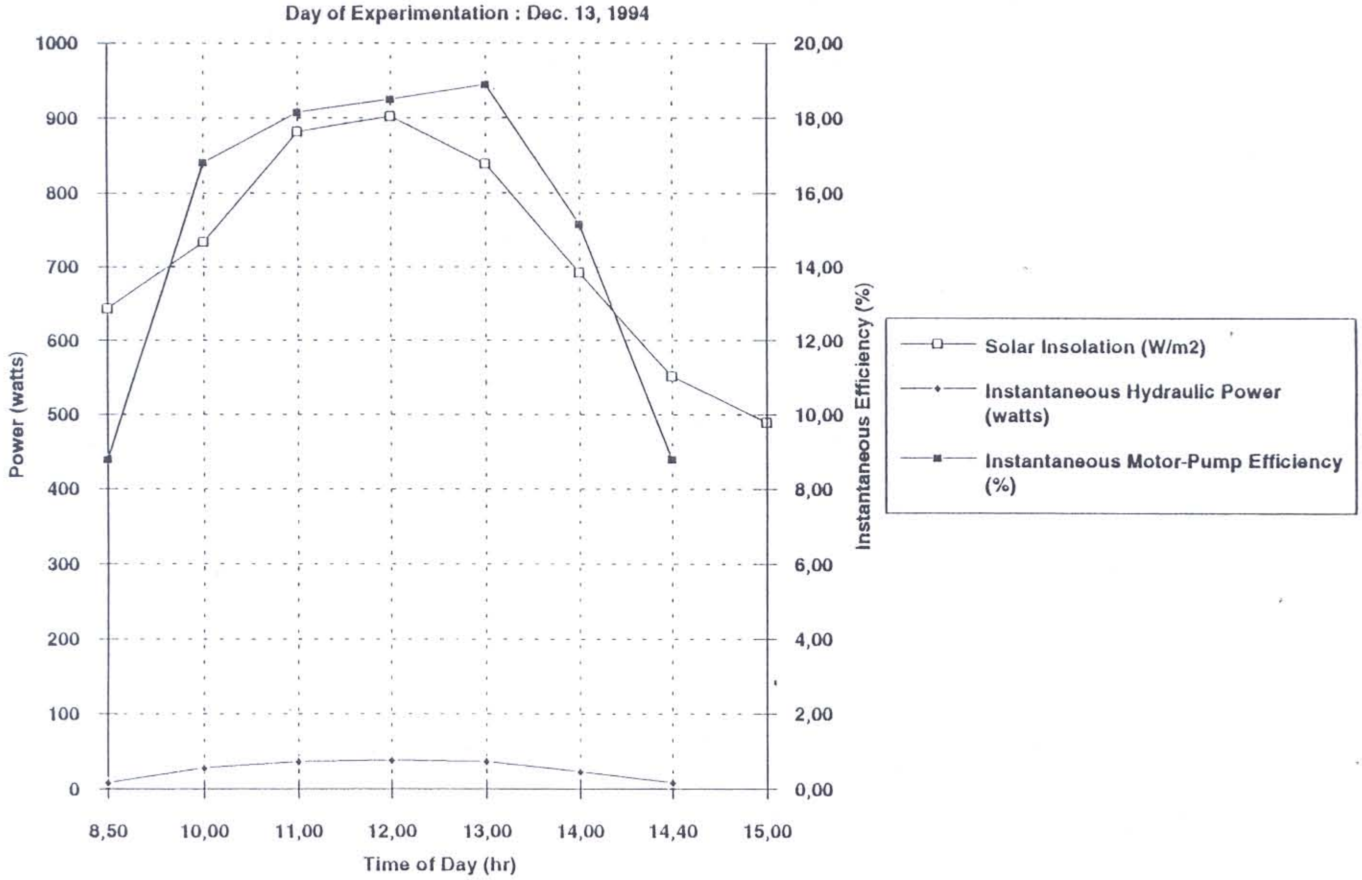


Fig. 7. Instantaneous performance of motor-pump unit (Date: Dec. 13, 1994).

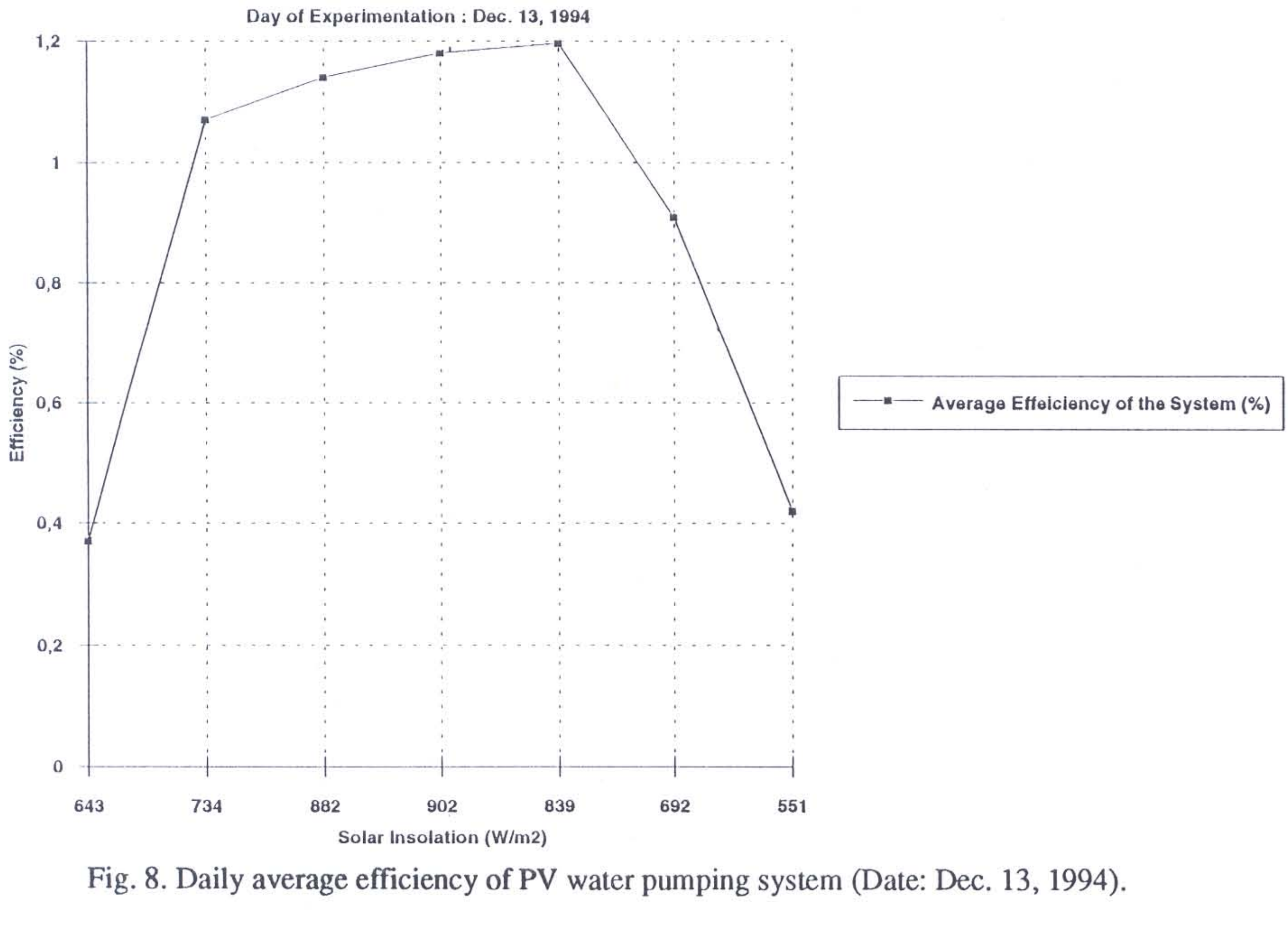


Fig. 8. Daily average efficiency of PV water pumping system (Date: Dec. 13, 1994).

Table 3. Field performance of photovoltaic water pump system (submersible pump Type EPS 005 CC)

(Motor pump efficiency)peak	18.89% at water head = 6.8 m
Maximum water flow rate on the day of experimentation (Dec. 13, 1994)	2.06 m^3 at water head = 6.8 m
Threshold conditions at water head of 3.5 m	Voltage = above 18 volts Current = above 3.5 amps
Maximum instantaneous efficiency	Photovoltaic array = 6.4% Motor pump unit = 18.89% Average efficiency of PV water pump system =1.2%

* It is to be noted that because of shading problems at 2.45 pm, the system was switched off

9.2. PV-Water Pump System with Non-submersible Multistage Centrifugal Pump.

The daily performance of non-submersible multi-stage centrifugal photovoltaic water pumping system is characterized by a typical time delay in the morning. The results obtained after analyzing the experimental data are presented in Figs. 9-12.

Fig. 9 represents the solar insolation incident on PV plane at an inclination of 45° and measured experimentally on the day of experimentation i.e. December 6, 1994.

From the experimental observations it has been observed that the pump in question starts pumping water even at a low solar insolation but typically it start its function when the solar insolation levels reaches nearly 400 W/m^2. Fig. 10 presents the daily performance of the photovoltaic generator. The experimental data for the instantaneous power available from the photovoltaic generator along with the instantaneous efficiency has been plotted in the above figure. Both the terms, as expected, increases with increased level of insolation, as the day progresses.

The array efficiency as seen from Fig. 10, varies with solar insolation. The maximum instantaneous array efficiency recorded from the experimental data at the existing system working conditions, was of the order of 6.4% (solar irradiance of 848 W/m^2 and ambient temperature of 21 °C).

The instantaneous motor pump efficiency varies with the solar insolation level. The combined highest efficiency of the motor-pump unit as measured in the field is approximately 20 % (Fig. 11). However, according to the pump characteristics supplied by the manufacturer, the highest efficiency of the pump is 41 % obtainable at a flow rate between 1.30 m^3/hr and 1.78 m^3/hr. The flow rate corresponds to a total pumping head of 12 m to 18 m. Assuming the efficiency of the motor to be 80% and of the pump 41% (at the design head), the combined efficiency of the motor- pump unit is expected to be 32 %.

As shown in Fig. 12, the overall system efficiency under field conditions (848 W/m^2 irradiance and 21 °C ambient temperature) at actual working head of 10.5 m have been calculated to be 22%.

A summary of the results obtained from the experimental observations recorded on December 6, 1994, are presented in Table 4.

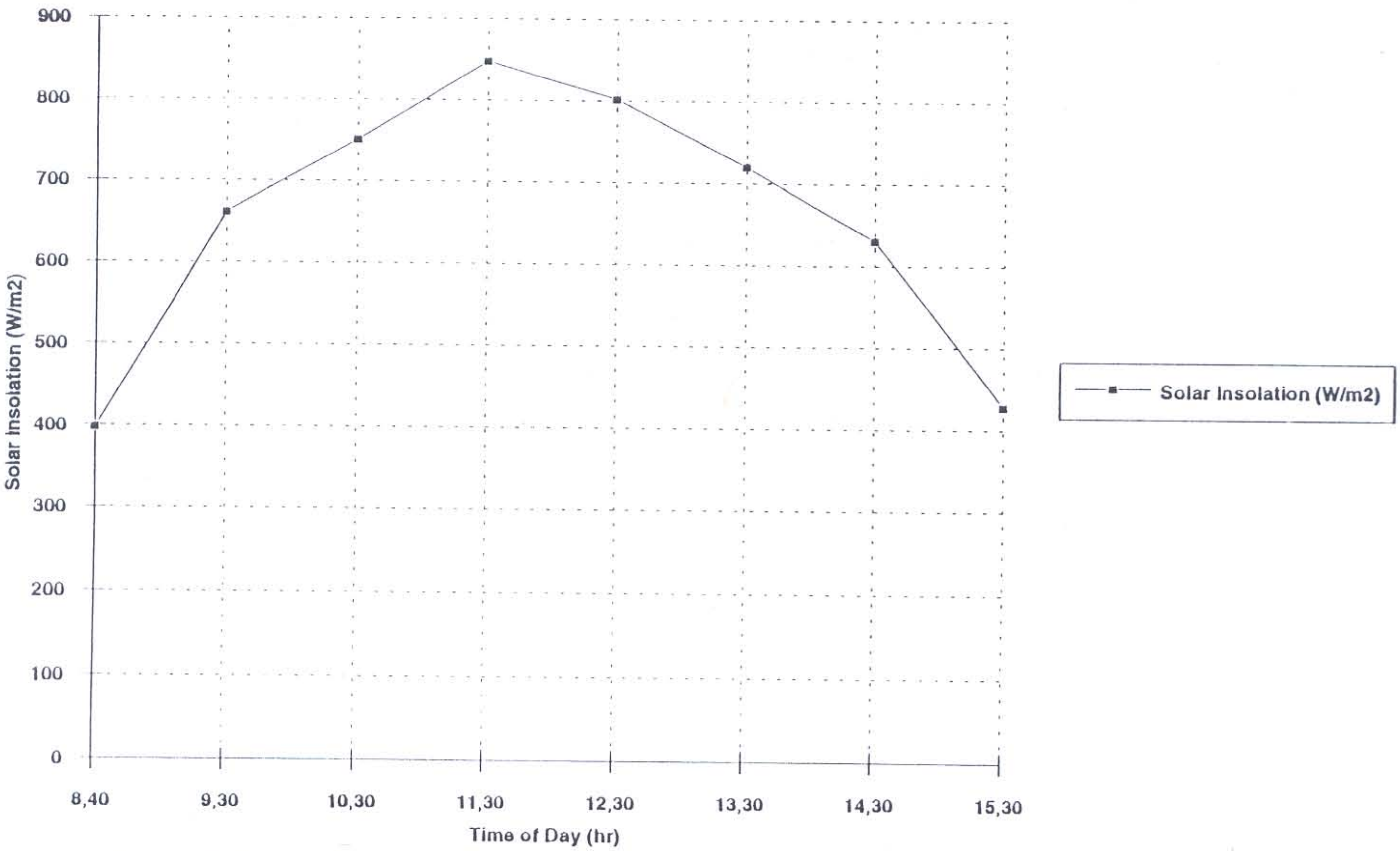


Fig. 9. Solar insolation at an inclination of 45° (Date: Dec. 6, 1994).

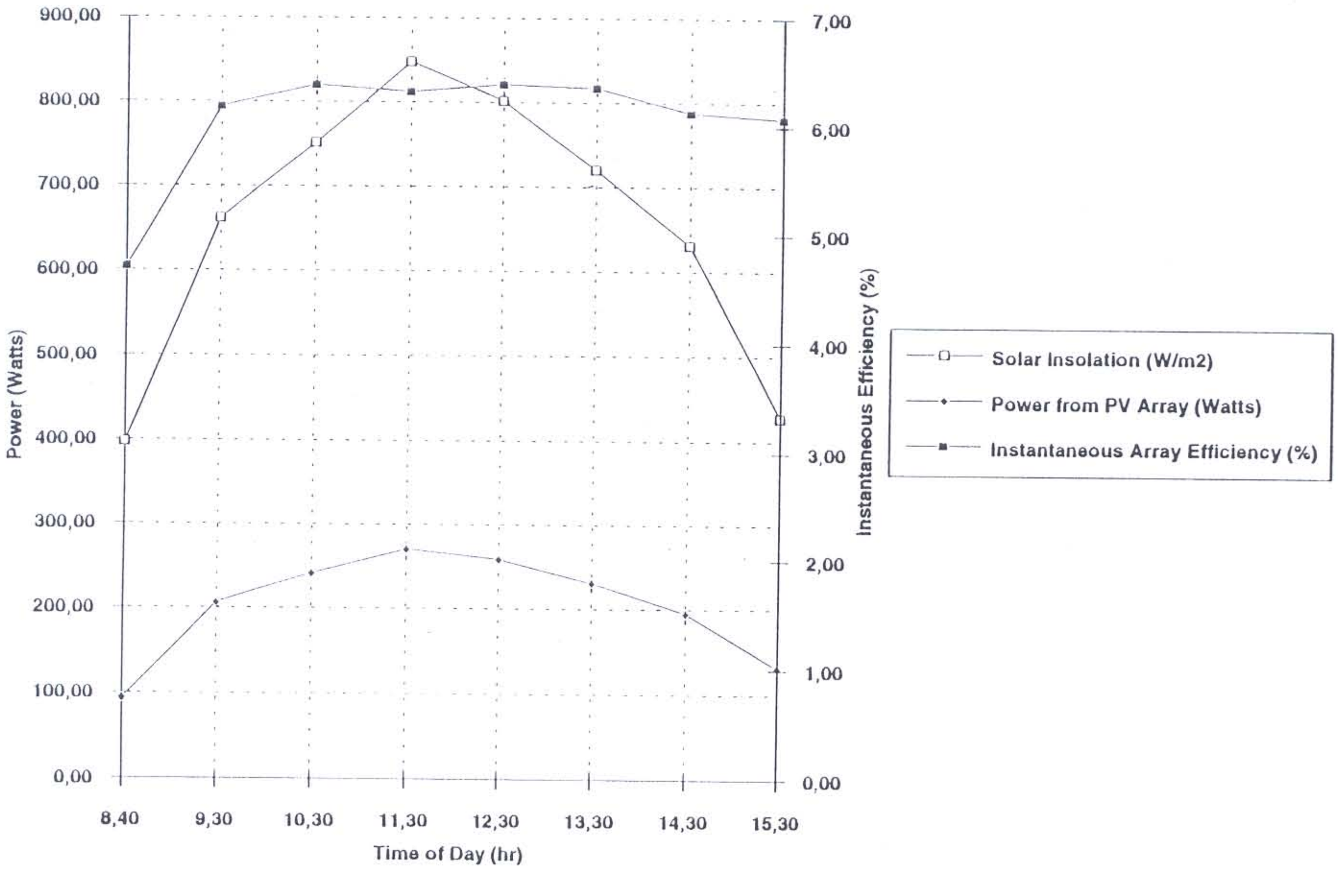


Fig. 10. Instantaneous evaluation of PV-array (Date: Dec. 6, 1994).

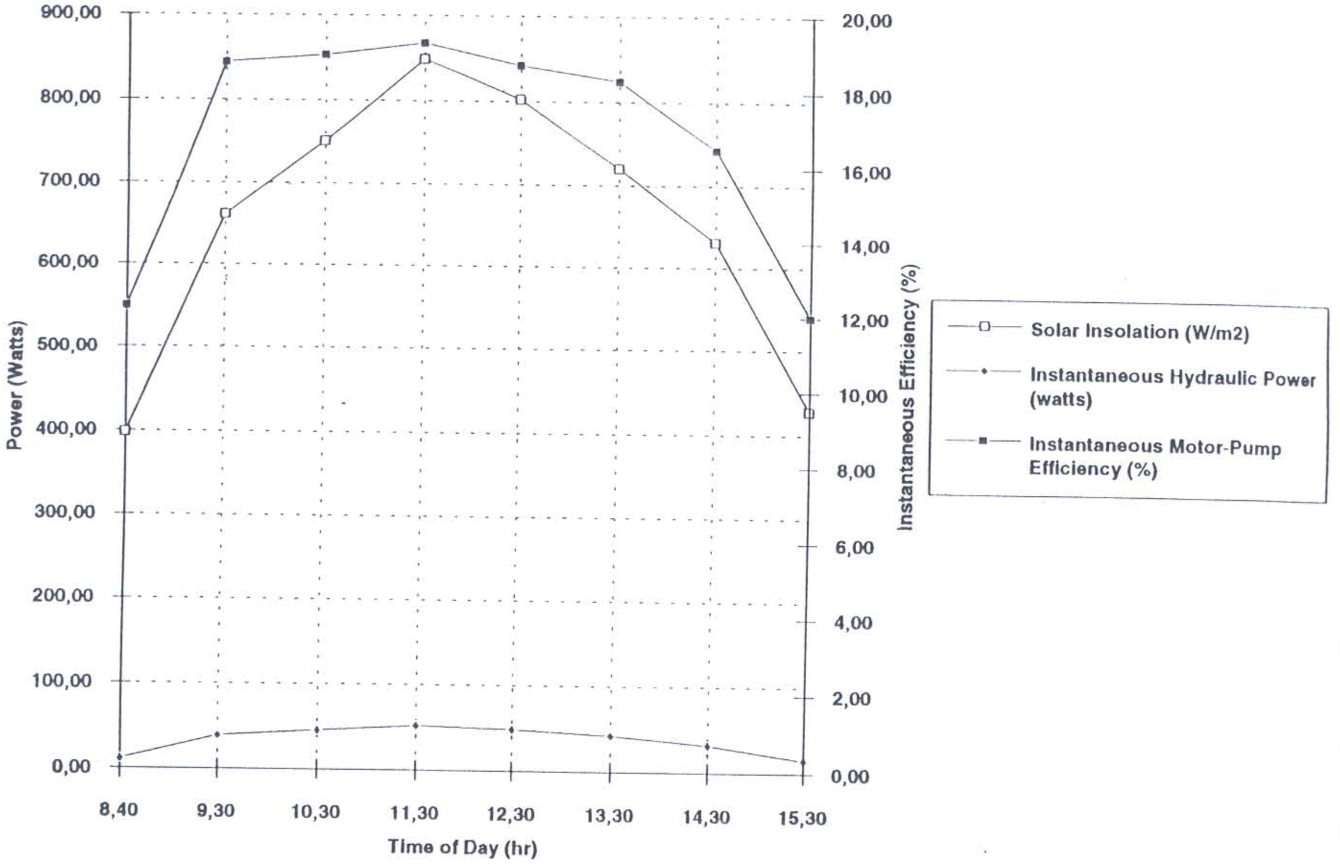


Fig. 11. Performance of motor-pump unit (Date: Dec. 6, 1994).

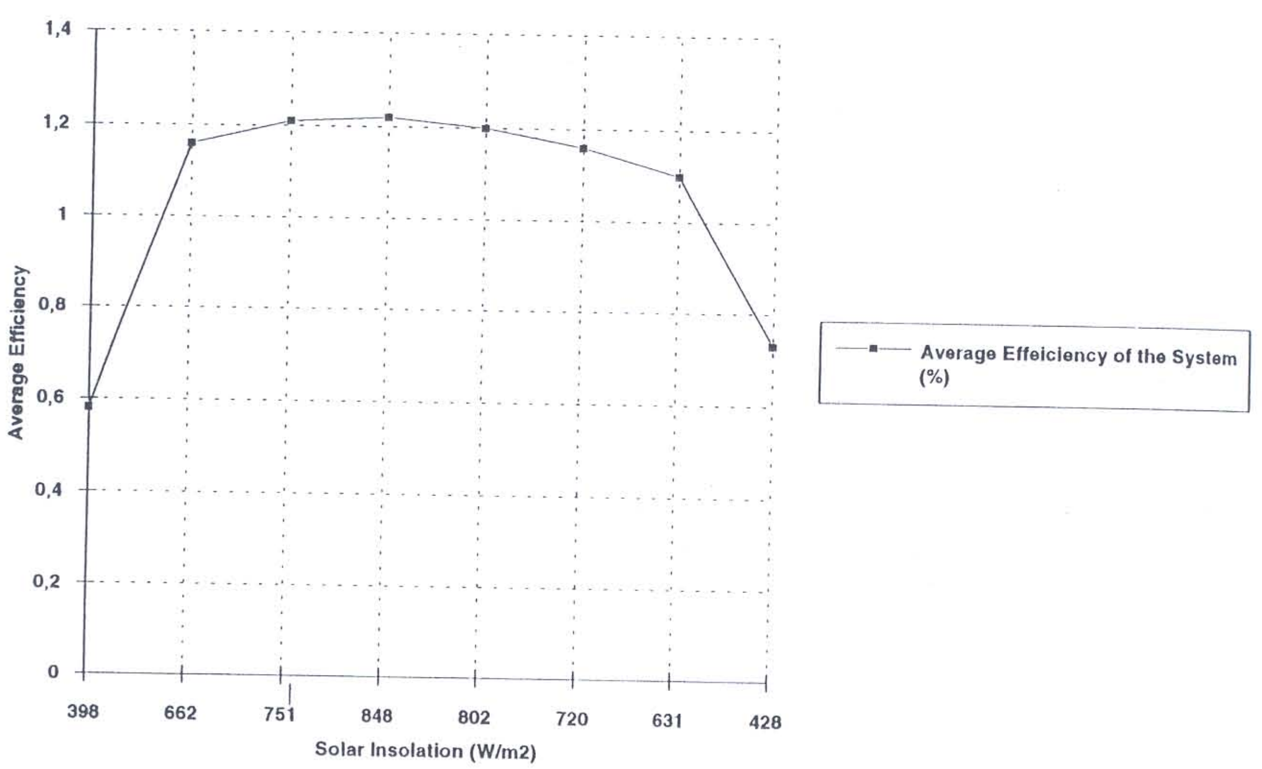


Fig. 12. Average efficiency of PV water pumping system (Date: Dec 6, 1994.

Table 4. Field performance of photovoltaic water pump system
(non-submersible multistage centrifugal pump)

(Motor-pump efficiency)peak	19.27% at water head = 10.5 m
Maximum water flow rate on the day of experimetation (Dec. 6, 1994)	1.85 m^3 at water head = 10.5 m
Threshold conditions at water head of 4.2 m	Voltage = 12 volts Current = 8 amps Solar insolation above 400 W/m^2
Maximim instantaneous efficency	Photovoltaic array = 6.39% Motor pump unit = 19.27% Average efficiency of PV water pump system = 1.22%

* It is to be noted that because of shading problems at 3.40 pm, the syatem was switched off.

10. CONCLUDING REMARKS FROM THE LIMITED EXPERIMENTAL EXPERIENCE

The above studies, conducted at a preliminary level, could not correct]y predict the degree of sub-optimal performance of all the sub-systems due to technical limitations, it however, significantly highlights the critical need to operate the photovoltaic system at its design parameters.

Detailed and long duration experiments are essential to optimize the performance of the systems discussed above, installed at off-design pumping head.

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