Performance of a Direct Coupling Photovoltaic Water Pumping System from a Reservoir for Agricultural Uses : Case Study on an Experimental Plantation, Royal Food Processing Factory-Lahansai

by

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The paper covers the design, installation and testing of a direct coupling photovoltaic water pumping system for the experimental plantation of the Lahansai Royal Food Processing Factory. Field testing of the system over period of yearly two years was conducted. Real system performances were compared the design and system simulation. Preliminary economic analysis on the system was carried out.

The water pumping system is for a 6-rai (0.9 hectare) experimental plot and draws water from a small reservoir to a 24 cubic meter water storage tank. The total head is about 11.5 m. The daily volume of water to be delivered in February, the desing month, is 31 cubic meters. According to the design, the system should incorporate a solar cell array of 940 Wp, 290 m. of water delivery pipe between the reservoir and the tank and 400 m. power line between the array and the reservoir.

In actual installation, the array size was reduced to 752 Wp. Sixteen ARCO Solar panels, Model M75, 47 Wp, were chosen. The diameter of water pipe was reduced from 112 to 40 mm. These were dictated by funding availability. Over the two-year period, three types of McDonald motor/pump systems were installed, namely, a submersible unit (Model 180809 DM, 1100 Wp), two surface mount units connected in series (Model 810203 DJ, 300 Wp each) and one surface mount unit (Model 150813 DS, 1300 Wp).

Both the cell temperature and global radiation determined the system efficiency. Below 35-40 C, it was observed that the system efficiency increased with increasing radiation. However, above 40 C the efficiency dropped even if the radiation increased. It was also noted that the daily system efficiency on clear sky days was higher than that of cloudy days.

Preliminary economic analysis showed that the unit water costs of the systems were 2-3 times higher than that of a comparable diesel pumping unit. The physical nature of the site put constraints on the system installation. The solar cell array and the water storage tank are 400m. and 290 m., respectively, away from the reservoir. This increases both installation costs and electrical and hydraulic losses of the systems. It is proposed that for this type of PV water pumping application surface mount motor/pump units should be more suitable than submersible types due to the nature of reservoir water and ease of repair.

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1. Introduction

Photovoltaic systems were firstly introduced into Thailand on an organized basis in the 1970's, although the installed wattage being of only few kWp, for the purpose of providing electricity for mobile medical teams/health posts and primary schools. In the 1980's, widespread PV installation was undertaken by various government agencies; users with substantial installations are the Provincial Electricity Authority-PEA, the Telephone Organization of Thailand-TOT and the Electricity Generating Authority of Thailand-EGAT. PEA operates 3 stand-alone PV power plants (installed capacities of 60, 60 and 30 kWp). TOT powers more than 50 microwave repeaters with PV. EGAT's applications include tower & bouy warning lights, microwave repeaters, hybrid PV-wind and PV-microhydro grid connected demonstration plants. It is estimated that about 400-450 kWp were installed in the 1980's; 75% of which belongs to these three utilities. (1)

Applications of PV in water pumping over the same period was somewhat limited; about 10-15 kWp were stalled in the 1980's. However, the situation has been changing dramatically in 1990-1991. Nearly 70 PV water pumping units (total capacity of about 60 kWp) have been or are being installed by the Department of Civil Work and the Second Army Region (through the Green Esarn Project). Most of the units are for rural village domestic water supply; about 10% is for irrigation.

Table 1 provides information on installed PV water pumping systems for irrigation in Thailand.

2. Project under Investigation

2.1 Description of Project Site

The PV water pumping system reported in this paper is located at the experimental plantation (Lat. 15 °N, Long. 103 °E) of the Royal Food Processing Plant at Lahansai, Burirum Province. The site area is about 10 hectares and 1 km away from the power line. At the plantation, field trials of various crops are made before they are introduced and promoted to local farmers; farm produces are bought by the Plant at guaranteed prices. In addition, seedlings are produced at plantation nurseries before distribution to farmers. Examples of crops and plants under trial are asparagus, red beans, passion fruits, bamboo and papayas. Provision of water to the plantation is of immense importance during the dry season (November-May) as most plants and seedlings cannot survive the dry season without water in this semi-arid part of Thailand.

The source of water irrigating the plantation is a small reservoir (having storage capacity of less than 0.5 million cubic meters). It is located about 300 m. away from the highest part of the plantation

2.2 System Sizing

The system was initially designed to supply water to about one-tenth of the plantation (0.9 hectare or 6 rais). Based on potential evapotranspiration data of crops and other data such as crop spacing, depth of root systems, types of soil and available meteorological data, estimation of monthly water requirements was made. (2)(3) The sizing methodology is based on the criterion of the design month. (4)(5) The design month is the month in which water demand is highest in relation to the available solar energy. It is the month that the system is most heavily loaded to meet the demand.

Table 2 provides data on monthly available rainfall and volume of water (daily average) to be delivered by the system. February is in this case the design month.

Design of the system including sizing of PV arrays, motor-pump unit and water delivery pipes follow the established guidelines and criteria. (4)(5)

Table 3 gives information on the system specifications.

The following subsystems were firstly selected :

i) PV arrays : ARCO Solar Model M75

ii) Motor/Pump : McDonald submersible type Model 180809 DM

2.3 System Installation

In actual implementation, budget restrictions were encountered and the system had to be scaled down. The PV array size was reduced to 750 Wp and the water delivery pipe diameter to 40 mm.

Note The meteorological data used are those at Nakorn Ratchaseema which is about 150 km. from the site

Moreover, successive failures of two 180809 DM McDonald submersible pump led to a replacement, at first, by two 810203 DJ McDonald surface type units connected in series. This replacement was a temporary measure to supply water to the site; the motor/pump unit severely mismatched the PV array. Subsequently, it was replaced by a more compatible 150813 DS McDonald surface type unit.

Tables 4 compares the design system and three configurations of the actual installation.

Consideration on PV array upkeeping and prevention from possible damages led to installation of the PV array by the plantation keeper residence instead of being adjacent to the motor/pump unit at the reservoir. This results in a separation distance of about 400m. between the array and the motor/pump unit. It entails increased cost of system and introduces electrical losses in the power line. The loss is quite substantial in the second configuration where a severe mismatch took place.

2.4 System Testing and Monitoring

Modelling of PV panels and motor/pump units were carried out in KMITT prior to field installation. The resulting mathematical model can be used to predict the instantaneous performance of the water pumping system including those of the PV array and the motor/pump unit by inputing 2 data, namely, global radiation and ambient temperature. (6)

After field installation two types of measurements were undertaken :

i) measurement of instantaneous performance (at every 10-minute interval) of the system under each configuration for few days (covering clear and cloudy days) in order to test the validity of the system/sub system models developed, and

ii) daily recording of irradiation, volume of water delivered and change in resevior level, if any.

3. Results and Discussion

3.1 Daily Performance of System

Figures 1 and 2 show representative daily performance of the first configuration on clear and cloudy days where as Figures 3 and 4 are for the second configuration.

It is observed that

i) under clear sky condition both cell temperature and global radiation determined the array and system efficiencies. Below about 35-40 °C the system efficiency increased with increasing radiation. Above 40 °C the efficiency dropped even if the radiation increased due to decrease in V_{oc} and fill factor of solar cells as expected. [7] The cloudy sky case is less discernible.

ii) Modelling of the PV subsystem of the first configuration give results that are in good agreement with actual performance. On overall system performance, only qualitative agreement was observed. This may be due to incomplete accounting of losses in power line, hydraulic losses and the motor/pump model itself.

For the second configuration the modelling result is less satisfactory than that of the first configuration. In the PV subsystem modelling, the assumptions made were that all PV panels are identical, no losses in panel interconnection and no panel interaction occurred. These assumptions bore out well for the first configuration (4 x 4) but may not be valid for the second configuration (2 x 8)

3.2 Flow Rate Monitoring

The system was firstly installed as the first configuration (4 x 4 array, 180809 DM submersible pump) in September 1989. Daily global radiation and flow rate were monitored. It was found out that in the beginning of 1990, daily flowrates gradually dropped despite high global radiation typical of the dry season in Thailand. The submersible pump unit stopped functioning in March 1990. A second unit of the same model was put in place. It again stopped functioning after a few weeks. The two units were sent to the manufacturer who later advised that a possible cause of failure was "dry run"; the motor turned without water flow through the pump due to possible blockage of water inlet.

It was noted that due consideration on blockage prevention was made at the installation and during the operation. Additional screen was added to enclose the submersible pumps and regular cleaning took place. However, fine materials and silt could possible slip through protective screens, got accumulated and subsequently blocked the inlet. It was observed that as the reservoir level droped in the dry season, the water became murkier.

Due to the changing quality of reservoir water throughout the year it was decided that submersible pumps were not appropriate and surface mount units were selected. Moreover, surface mount units can be locally repaired. This is of utmost importance if PV pumps are to be used in rural area.

As water was urgently needed during the dry season, surface mount units were secured on first available basis. This resulted in adopting 2 units connected in series such that the pump/motor characteristics were compatible with the available PV panels and the required head. This led to the second configuration (2 x 8 array, two 810203 DJ surface-mount units connected in series). The mismatch between the PV array and the motor/pump unit was quite substantial; the motor/pump unit drew large current at low voltage causing high losses in the power line. These losses together with a lower motor/pump efficiency (in comparison to that of the submersible unit) resulted in low daily flow rate. The second configuration was in place between April 1990-April 1991 before a more suitable surface mount unit was available.

Replacement by a third configuration (4 x 4 array, 180513 DS surface mount type) took place in May 1991 and is the present system under operation.

Daily radiation and flow rate are still being measured. To our knowledge, this PV water pumping system is the only one in the country that remains continuously being monitored since installation.

Figures 5 and 6 show the monthly average of the measured values of daily irradiation and flow rate over a period of two years. For comparison the design values of global radiation used in system sizing and the predicted values of flow rate are also displayed. It can be noted that

i) the 180809 DM submersible unit and the 180513 DS surface mount unit are better matched to the PV array. They also have higher efficiencies than that of the 810203 DJ surface mount unit; the difference in efficiencies is about 2.5 times [8], and

ii) the actual system delivered less water than prediction. Unaccounting and underestimating of electrical losses in power line, PV panel mismatch and hydraulic losses can partly explained the difference. This can be resolved by improved modelling of the subsystems/system.

Concurrently, a long term monitoring of a PV water pumping system from a deep well (static head is about 22 m.) is being undertaken at KMITT. [6] About 4 years of uninterrupted data are available. It is observed that evenwith modelling improvement, the system as determined by the established design/sizing criteria is slightly undersized, by about 10%. Detail analysis of this deep well system at a later stage would help clarify the situation.

3.3 *Efficiency of the Overall System*

Figure 7 shows the plots of daily hydraulic energy and daily solar energy input of the system under the three configurations. Linear regression analysis yield straight line fittings whose slopes are average overall efficiencies of the system under three configurations. It is found that the average daily system efficiencies are about 2.6%, 1.0% and 2.6% for the first, second and third configuration, respectively.

3.6 *Unit Water Costs*

Unit water costs of the PV water pumping systems under the first and third configuration are compared to diesel pumps. [(5)(8)] The lifetimes of the PV array and the motor/pump are taken to be 20 and 10 years, respectively, and that of the diesel pump 10 years. The discount rate of 15% is adopted.

Figure 8 illustrates the unit water costs comparison.

It can be seen that under typical operating condition where the daily volume of pumped water is between 10-20 m^3/day, depending on the nature of irradiation, the unit water cost of the PV system were about 2-3 times that of the diesel pump. The physical nature of the site put constraints on the system installation. The PV array and the water storage tank are 400 m. and 290 m, respectively, away from the reservoir. This increases both PV system installation costs and electrical and hydraulic losses of the PV water pumping system.

4. Conclusions

Field performance of a direct-coupling PV water pumping system for irrigation is reported. Submersible and surface-mount type motor/pumps were employed at separate time. It is suggested that surface-mount units may be more suitable due to the nature of reservior water and ease of repair. Preliminary economic analysis shows that the unit water costs of the PV system is 2-3 times that of the diesel pump.

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Table 1 : Location of PV Water Pumping Systems for Irrigation in Thailand

Location (Operational Year)	PV Array Power(kWp)	PV Model/ Pump Model
1. Rural Village Integrated Development Center, Kheng Krachan, Muang District, Maha Sarakham Province (1982) (A)	0.26	ARCO Solar ASI 16-2300/ Solar Electric International
2. Royal Recommended Project at Kao Hin Sorn, Panom Sarakham District, Chachoeng Sao Province (1984)	1.12	ARCO Solar ASI 16-2000/ Arco Solar CSB 100 D
3. Royal Recommended Project at Huay Sai, Cha Am District, Petchaburi Province, (1985) (A)	5.67	Kyocera LA 361 J45AV/ Grundfos CP 8-60
4. Royal Recommended Project at Khao Kor, Ban Matulee, Khao Kor District, Petchaboon Province (1987)	2.24	ARCO Solar ASI 16-2000/ ARCO Solar CSB 100 D
5. Nong Sanoa Reservior, Ban Nong Pai, Nong Rua District, Khon Kaen Province, (1987)	0.38	ARCO Solar M75/ ARCO Solar CSB 33 D
6. Experimental Plantation of Royal Food Processing Factory at Lahansai, Lahansai District, Burirum Province, (1989)	0.75	ARCO Solar M75/ McDonald 180809 DM, 810203 DJ, 150813 DS
7. Suranaree Army Barrack, Muang District, Nakorn Ratchaseema Province, (1990)	0.66	Solartron M75/S47/ Grundfos SP 4-8
8. Ban Bung Sibsee, Tambon Kud Laoh, Kaset Samboon District, Chaiyapoom Province, (1990)	1.70	Solartron M55/S53 Grundfos SP 16-2
9. Ban Khok Paeng Puay, Tambon Lahan, Chaturas District, Chaiyapoom Province, (1990)	1.70	Solarex MSX/ Grundfos SP 4-8
10. Ban Khok Klang, Tambon Don Mun, Pratai District, Nakorn Ratchaseema Province, (1991) (B)	1.70	Solartron M55/S53 Grundfos SP4-8
11. Ban Non Ta Taen, Tambon Non Ta Taen, Non Daeng Sub district, Nakorn Ratchaseema, (1991) (B)	0.74	Solartron M55/S53 Grundfos SP4-8

<u>Note</u> (A) The units are not longer operational
(B) The units supply water for both domestic uses and irrigation

Table 2 : Monthly Available Rainfall and Daily Water Requirement to be Supplied by the System

Month	Available Rainfall (mm)	Daily Volume to be Supplied by System (cubic meters/rai)
Jan	4.8	4.78
Feb	22.7	5.19
Mar	43.9	4.32
April	68.3	3.04
May	145.2	0
June	111.6	0
July	132.6	0
Aug	130.4	0
Sept	261.5	0
Oct	154.1	0
Nov	30.0	3.58
Dec	3.6	4.49

Note 1. Monthly available rainfall data are those of Buriram meteorological station.

2. Zero water requirments indicate that water available from rainfall exceeds plants requirements.

Table 3 : Specification of the System

1. Site Location : Buriram (Lat. 15 °N, Long. 103 °E)

2. Water Storage and Delivery System
   - : static head 10.5 m
   - : PVC water delivery pipes (from reservior to storage tank) of 290 m in length, Ø 112 mm.
   - : storage capacity 24 m^3

3. Design Month Data (February)
   - : End use water requirement : 29.27 m^3/day
   - : Water to be delivered by system 31.14 m^3/day
   - : Hydraulic energy requirement 3.53 MJ/day
   - : Solar irradiation on PV array 17.07 MJ/m^2-day

4. System Performance

Month	Irradiation (MJ/m^2-day)	End Use Water Requirement (m^3/day)	Pumped Water by System (m^3/day)
Jan	17.71	28.68	32.31
Feb	17.07	31.14	31.14
Mar	16.75	25.92	30.56
April	16.76	18.24	30.57
May	17.24	0	31.45
June	14.99	0	27.35
July	14.97	0	27.31
Aug	14.71	0	26.83
Sept	14.69	0	26.80
Oct	17.15	0	31.26
Nov	17.57	21.48	32.05
Dec	16.99	26.94	30.99

5. PV Water Pumping Specification

Array size : 940 Wp
Array tilt angle : 15°
Average motor/pump (energy) efficiency : 28%
Average motor/pump (power) efficiency : 40%
Rating of motor : 940 W
Rating of pump 3.32 lit/sec at 11.55 m total head.

Table 4 : Comparison of the Design System and Three Configurations of Actual Installation

	Desian System	Installed System Configuration		
		First	Second	Third
PV array (Wp)	940	752	752	752
PV model and configuration (series/parallel)		4 x 4 ARCO Solar M75	2 x 8 ARCO Solar M75	4 x 4 ARCO Solar M75
Rating of motor pump (W)	1100	1100	300 x 2	1300
Pump model		McDonald 180809 DM submersible	McDonald 810203 DJ surface mount	McDonald 150813 DS surface mount
Water pipe diameter (mm)	112	40	40	50
Installed period		Sept 89-Mar 90	April 90-April 91	May 91-present

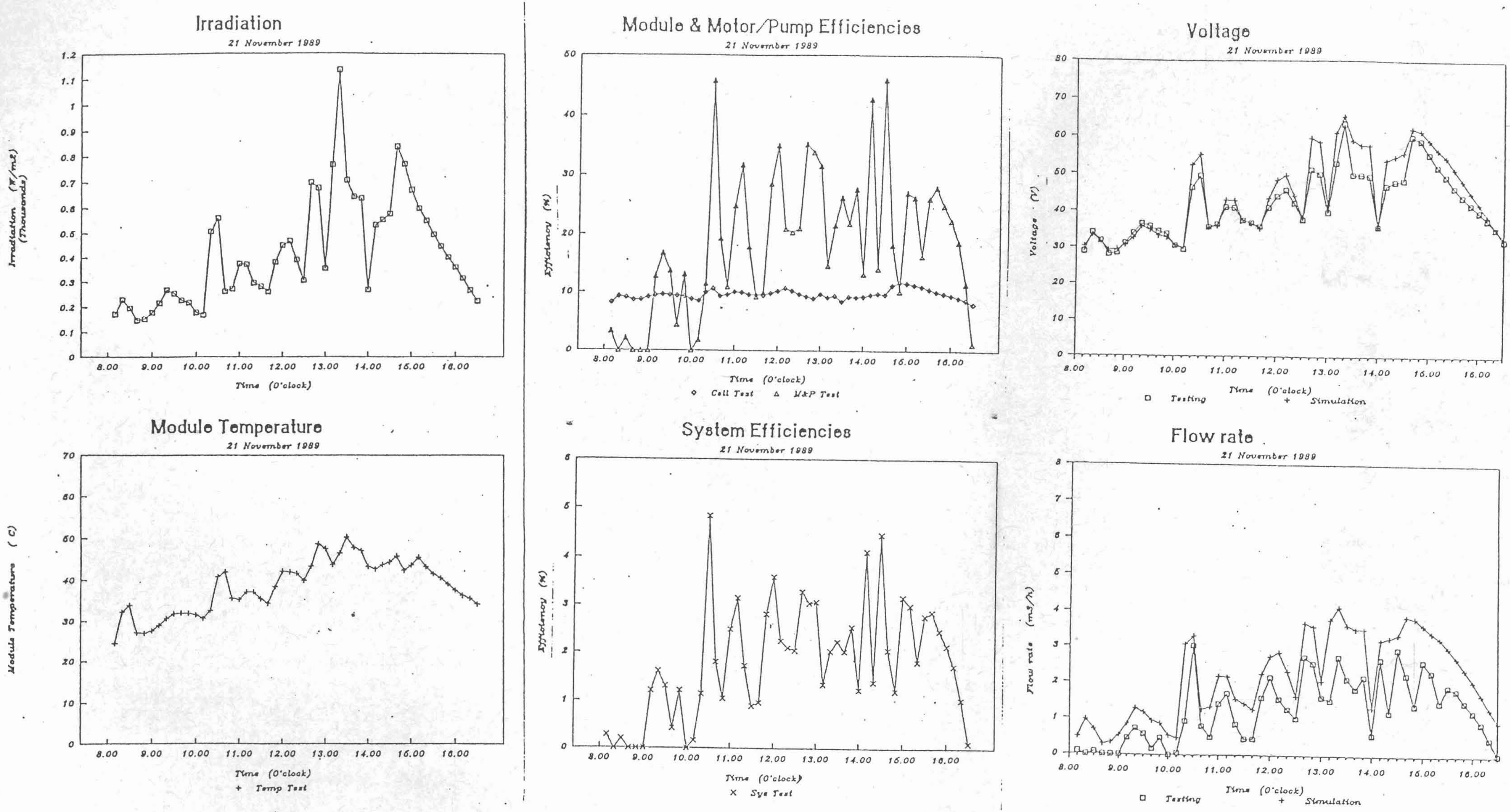

Figure 1 : Performance of the PV Water Pumping System (First Configuration) on a Cloudy Day.

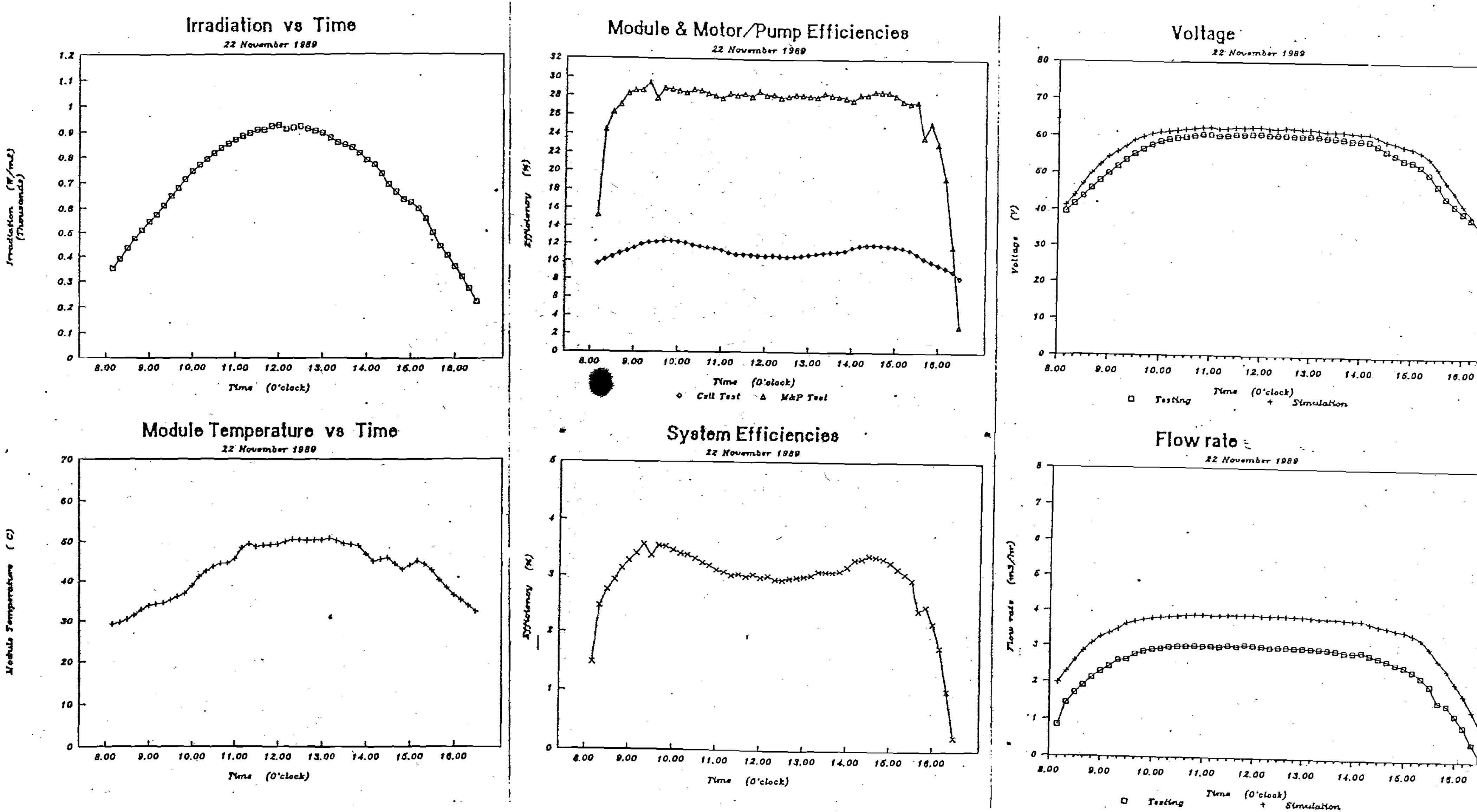

Figure 2 : Performance of the PV Water Pumping System (First Configuration) on a Clear Day.

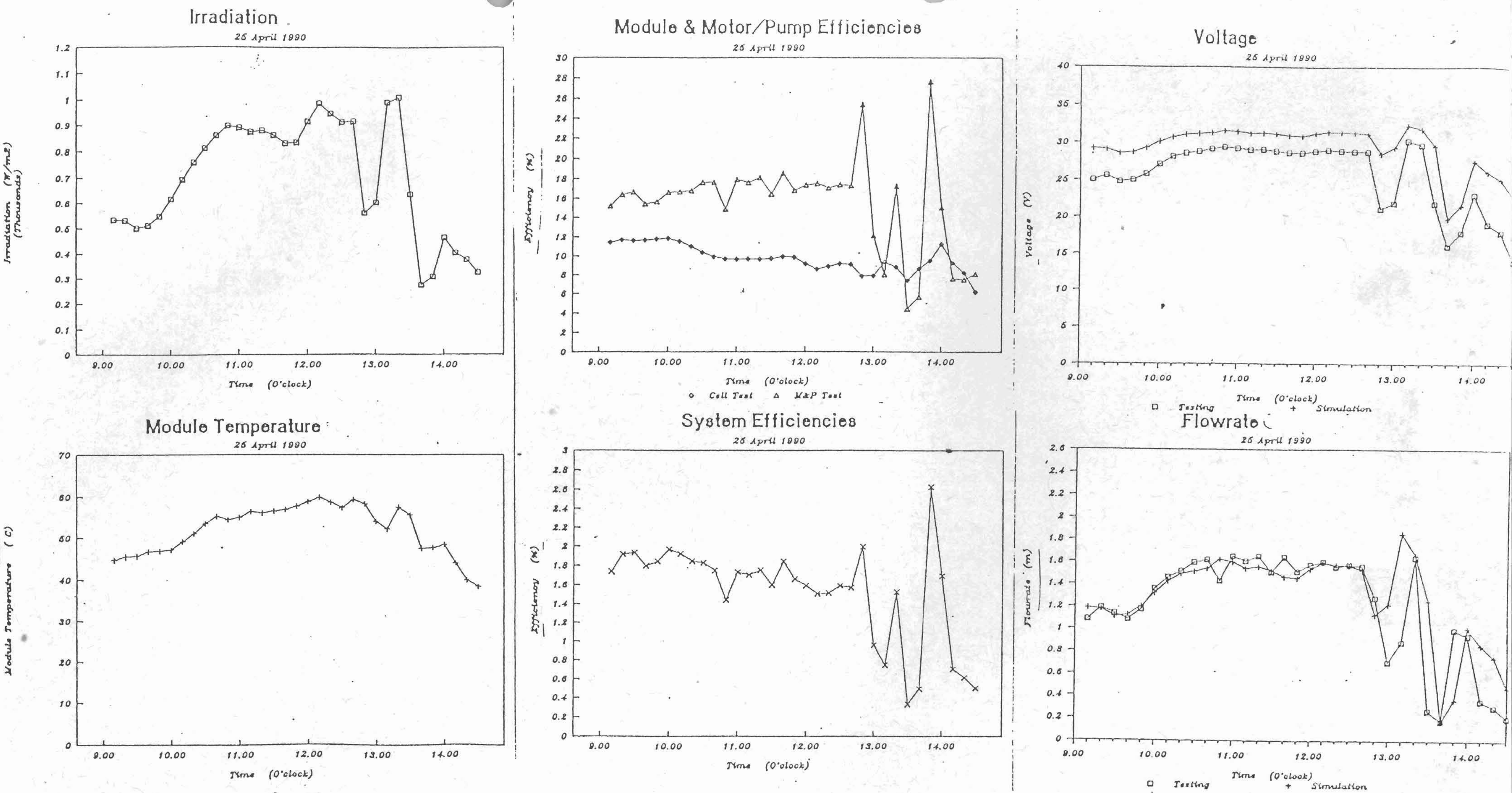

Figure 3 : Performance of a PV Water Pumping System (Second Configuration) on a Clear Day.

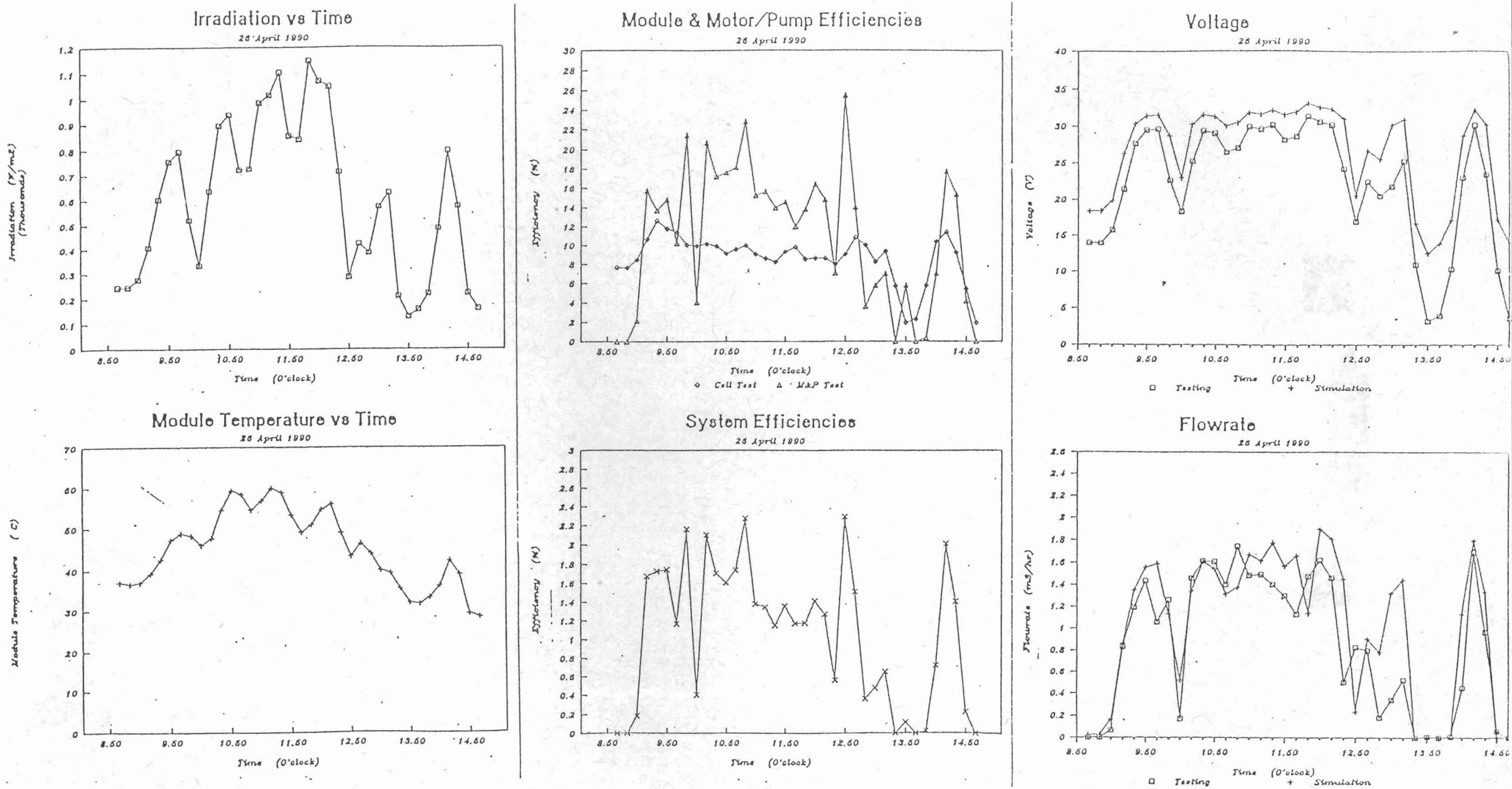

Figure 4 : Performance of a PV Water Pumping System (Second Configuration) on a Cloudy Day.

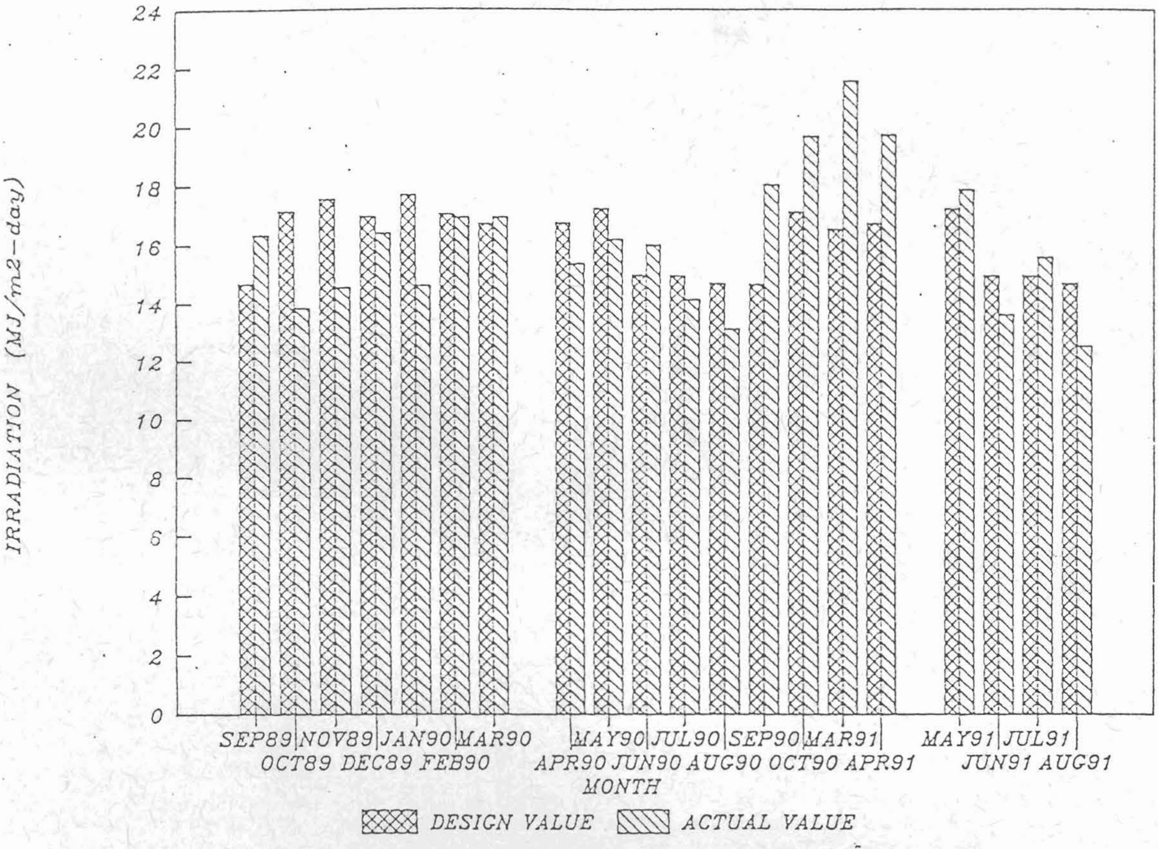

Figure 5 : Monthly Average of Daily Irradiation Values

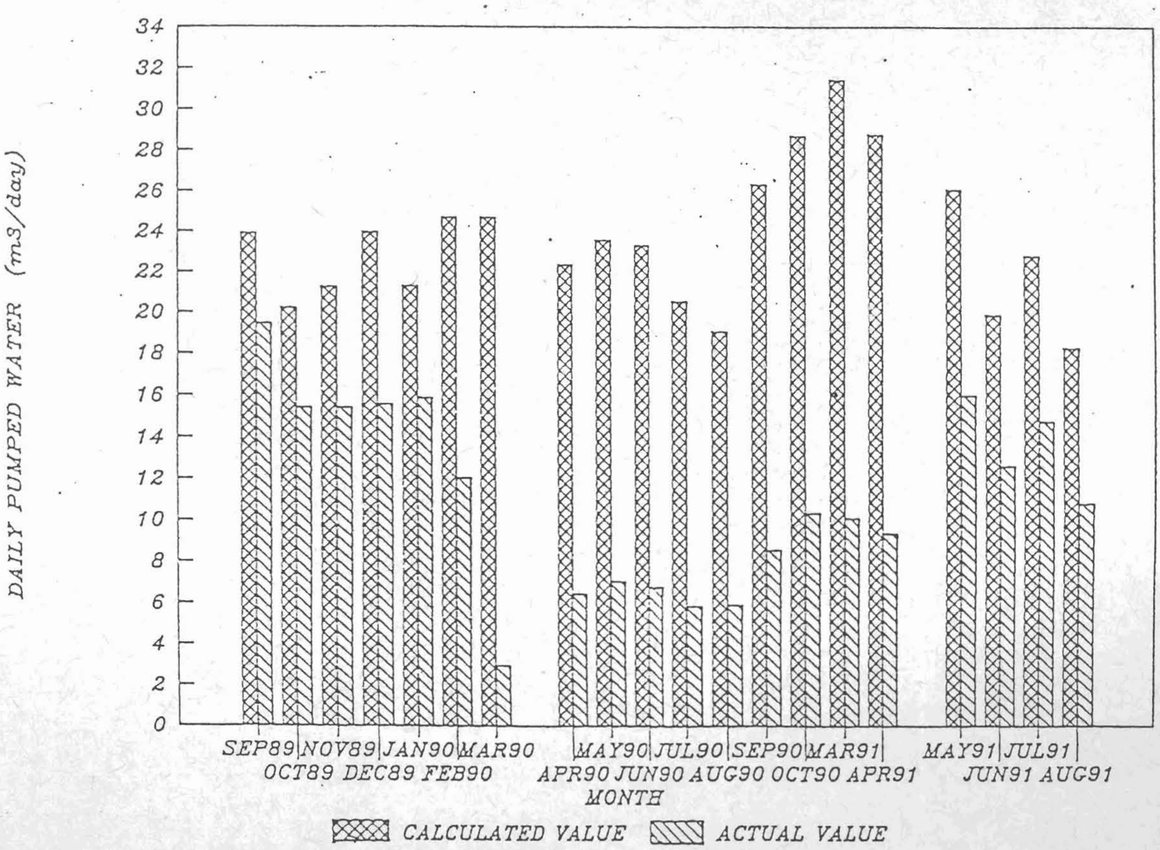

Figure 6 : Monthly Average of Daily Pumped Water

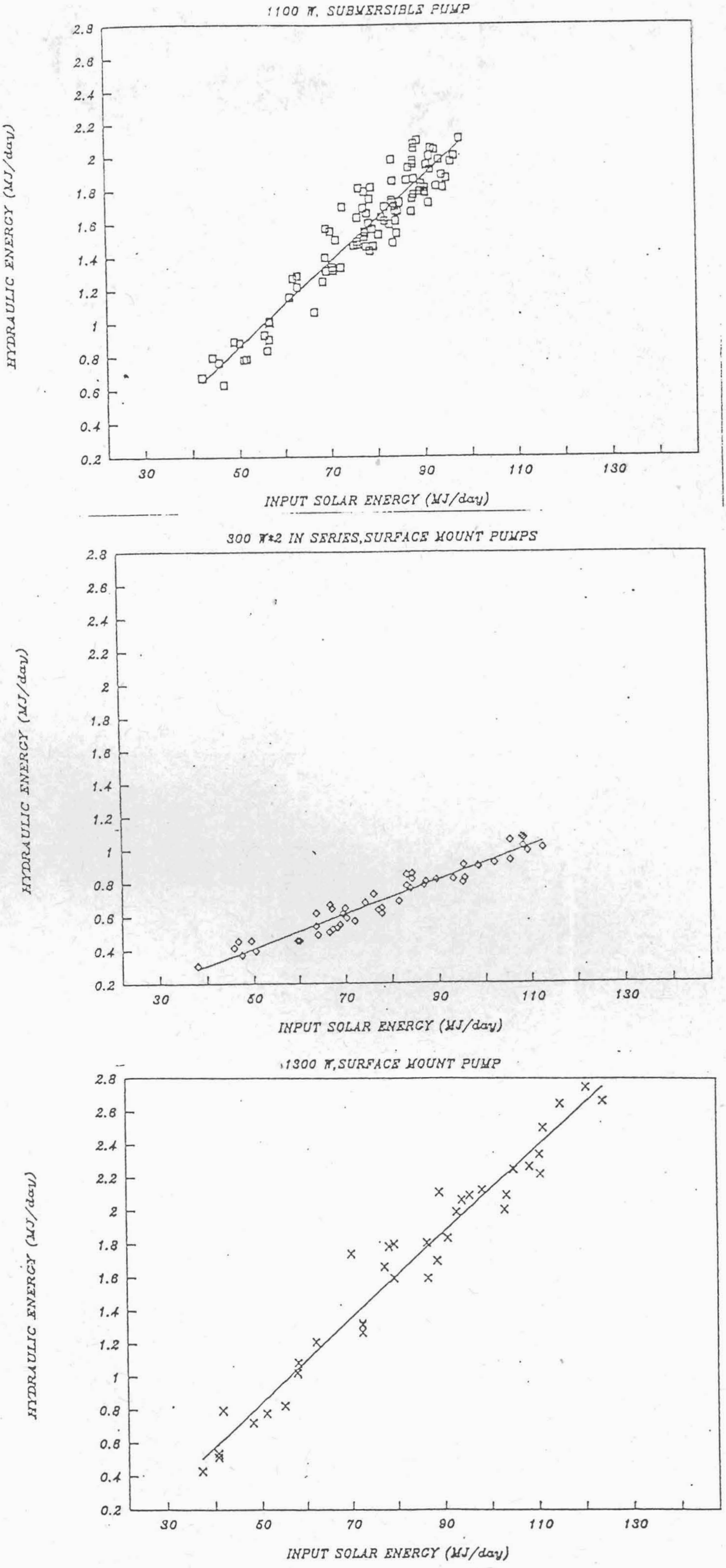

Figure 7 : Daily Hydraulic Energy and Solar Irradiation

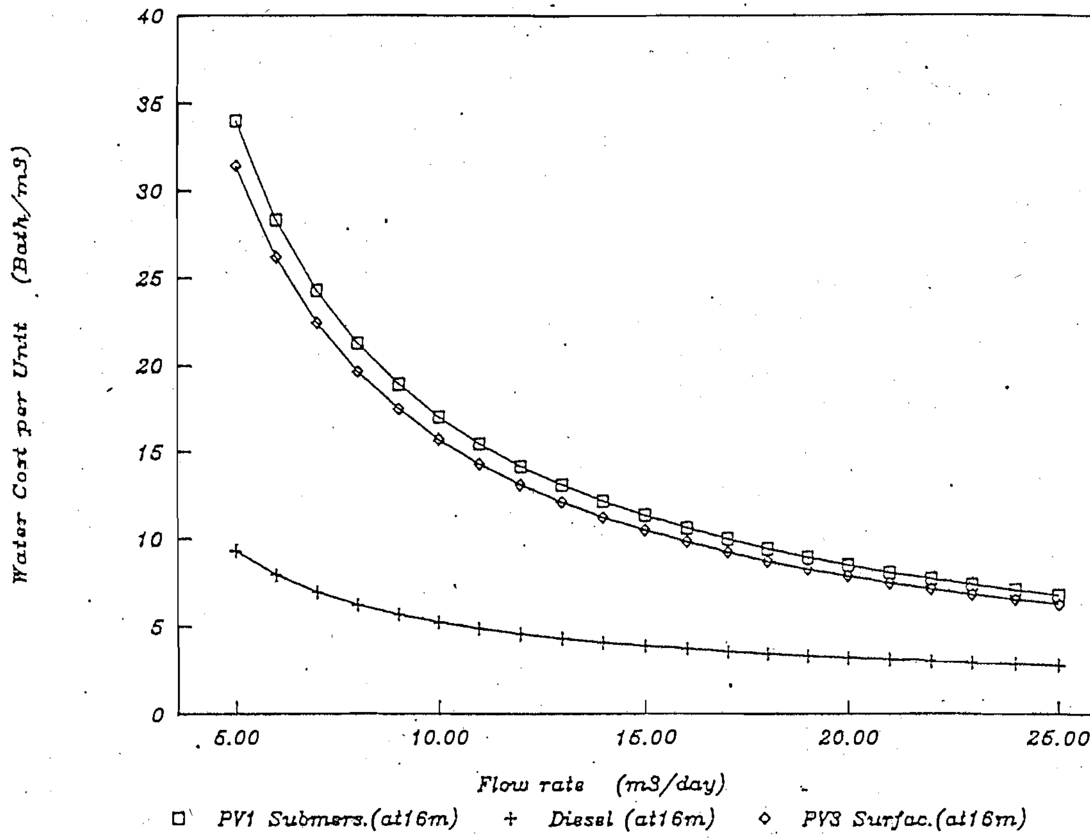

Figure 8 : Comparison of Unit Water Costs