A Photovoltaic Solar Pump with Microprocessor Control and One-Axis Tracking

Part III: System Performance, Measurements and Analysis

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ABSTRACT

The performance data show that the battery back-up subsystem is necessary to maintain a continuous flow of water and consequently increases the volume of the water collected daily to a level of about 1.3% as compared to the non-battery set-up system of about 0.8%. The data also show that the microprocessor control subsystem improves the efficiency of the system in terms of the management of the solar array current and the battery current, thus making optimum usage of solar energy. Finally, a one-axis tracking system shows an increase in the consistency in the volume of water collected daily.

INTRODUCTION

In this section, the collection of data and the performance evaluation of the photovoltaic water-pumping system with microprocessor control are presented. The results are discussed in terms of the amount of water collected, the number of hours of dependence on solar energy alone, the system output and the overall system efficiency. These results are compared with the forecast performance (Part I)[1]. A discussion of the environmental effects and the reliability of the system is also included.

DATA FORMAT AND COLLECTION

For the statistical analysis of meteorological data described in Part I,[1] and the set-up of the photovoltaic array with a concentration factor of two using mirrors as discussed therein, it was decided to test the system and collect data from 1000 hours to 1600 hours daily so as not to deviate from the key objectives of optimising the usage of solar radiation in water pumping and minimising the usage of the back-up battery. For the purpose of comparison and evaluation, data was collected as early as 0900 hours and collection discontinued at 1630 hours when the weather was favourable. The data was measured instantaneously at equal intervals of 10 minutes and computed into mean hourly data using the trapezoidal rule.

For the complete system, the variables measured are the direct current and the voltage from the photovoltaic array, the global solar radiation, the direct solar radiation, the concentrated solar radiation on the photovoltaic array, the temperature of the photovoltaic array, the alternating current and voltage output from the DC-AC invertor, the flowmeter reading and the period the system is in operation using solar energy alone. Except for the last variable, the rest of the variables were measured at 10 minutes intervals.

The current and voltage were measured using an ammeter (Yew, Type 2501 CL-1) and a voltmeter (Yew, Type 2501 CL-1) respectively. The global solar radiation was measured using a pyranometer. The direct solar radiation was measured using a pyrheliometer. Using standard cell, Solarex # 73, the concentrated solar radiation on the surface of the photovoltaic module was measured at three different locations viz, the two opposite sides and the centre. Two copper (SWG 46)/constantan (SWG 46) thermocouples together with a Keithley Model 9 Digital Voltmeter were used to measure the temperature of the photovoltaic array placed at the centre and the side of the surface of one of the photovoltaic modules. The flowmeter used is of 2.54 cm diameter and the timer used is an RS type model.

Data was collected from July 1982 to September 1983 with intermittent breaks for modification and improvement of the system such as changing of wiring to reduce DC power loss, servicing of pump, testing of hardware and software for the microprocessor control system and installation of the tracking system.

Tables 3.1 to 3.35 show the mean hourly results for three set-up conditions as follows:

CASE I – A non-tracking manual control water-pumping system with no battery back-up sub-system.

CASE II – A non-tracking microprocessor controlled water-pumping system with battery back-up sub-system.

CASE III – A one-axis tracking microprocessor controlled water-pumping system with battery back-up sub-system.

N.B. In the following tables, the abbreviations used are: NR – not recorded; RA – raining; and CL – clouds.

Readings were not taken during set up time. These are left blank in the tables.

Also, the Input Power (W) is the power input to the invertor and the Output Power (W) is the power output from the invertor.

The system performances under these three set-ups, different climatic and environmental conditions are discussed in detail in the following sections.

Table 3.1 Measured data and calculated values of case I set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)	NR	10.37	11.27	11.23	10.06	7.50
DC current (A)	NR	14.12	14.70	14.62	13.77	10.33
Input power (W)	NR	146.42	165.67	164.18	138.53	73.86
AC voltage (V)	NR	161.67	176.67	178.33	156.00	102.33
AC current (A)	NR	0.78	0.82	0.81	0.80	0.59
Output power (W)	NR	126.37	143.99	144.63	124.80	60.03
Output power/Input power	NR	0.86	0.87	0.88	0.90	0.81
Irradiance (mWh/cm^2) side	NR	102.07	120.85	125.25	119.76	80.68
Irradiance (mWh/cm^2) centre	NR	81.22	93.87	97.95	95.65	65.44
Irradiance (mWh/cm^2) side	NR	72.58	85.37	90.38	84.85	59.97
Average irradiance (mWh/cm^2)	NR	85.29	100.04	104.73	98.91	68.70
Global radiation (mWh/cm^2)	NR	72.53	83.98	86.14	81.06	60.17
Direct radiation (mWh/cm^2)	NR	64.64	78.47	76.68	70.56	45.37
Global+Direct (mWh/cm^2)	NR	137.17	162.45	162.82	151.61	105.54
Temperature (°C)		36.50	42.00	43.60	41.30	36.00

Date: 5/8/82
Number of hours using solar array for pumping: 4.5
Number of hours using battery for pumping: Nil
Volume of water pumped: 1900 L
Average volume of water pumped: 422.0 L/h
Average irradiance: 91.5 mWh/cm^2

Table 3.2 Measured data and calculated values of case I set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)	8.15	10.95	11.51	11.53	11.15	10.13
DC current (A)	12.92	14.38	14.88	14.90	14.70	137.00
Input power (W)	105.27	157.50	171.31	171.80	163.91	138.78
AC voltage (V)	117.33	172.50	181.33	183.00	173.67	150.83
AC current (A)	0.76	0.78	0.83	0.84	0.82	0.76
Output power (W)	88.78	134.84	150.50	153.41	142.69	115.13
Output power/Input power	0.84	0.86	0.88	0.89	0.87	0.83
Irradiance (mWh/cm^2) side	90.71	109.87	126.65	132.09	106.64	106.80
Irradiance (mWh/cm^2) centre	68.07	83.26	96.59	101.18	96.55	80.82
Irradiance (mWh/cm^2) side	61.01	78.08	89.43	93.56	86.08	72.17
Average irradiance (mWh/cm^2)	73.26	90.41	104.23	108.94	103.09	86.60
Global radiation (mWh/cm^2)	69.21	77.42	86.92	89.42	85.37	73.03
Direct radiation (mWh/cm^2)	66.44	76.81	85.01	85.30	78.42	61.13
Global+Direct (mWh/cm^2)	135.65	154.23	171.93	174.72	163.79	134.16
Temperature (°C)	42.20	47.60	48.10	47.60	45.60	42.00

Date: 6/8/82
Number of hours using solar array for pumping: 5.33
Number of hours using battery for pumping: Nil
Volume of water pumped: 2332 L
Average volume of water pumped: 438.0 L/h
Average irradiance: 113.3 mWh/cm^2

Table 3.3 Measured data and calculated values of case I set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)		6.62	11.35	11.62	10.75	10.65
DC current (A)		11.95	14.80	14.88	14.03	14.37
Input power (W)		79.11	167.98	172.94	150.86	153.04
AC voltage (V)		94.17	180.00	184.83	164.50	164.67
AC current (A)		0.69	0.81	0.84	0.79	0.79
Output power (W)		65.13	146.09	155.26	129.13	130.36
Output power/Input power		0.82	0.87	0.90	0.86	0.79
Irradiance (mWh/cm^2) side		73.57	119.43	128.32	122.70	110.61
Irradiance (mWh/cm^2) centre		63.58	93.74	99.67	94.85	85.27
Irradiance (mWh/cm^2) side		60.11	82.14	88.45	84.02	75.27
Average irradiance (mWh/cm^2)		65.75	98.47	105.48	100.52	90.38
Global radiation (mWh/cm^2)		58.67	85.03	89.89	83.67	75.36
Direct radiation (mWh/cm^2)		19.99	69.24	70.58	70.09	65.18
Global+Direct (mWh/cm^2)		78.66	154.27	164.47	153.76	140.54
Temperature (°C)		33.90	46.10	44.90	40.20	44.90

Date: 7/8/82
Number of hours using solar array for pumping: 4.33
Number of hours using battery for pumping: Nil
Volume of water pumped: 2090 L
Average volume of water pumped: 483.0 L/h
Average irradiance: 92.1 mWh/cm^2

Table 3.4 Measured data and calculated values of case I set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)		CL	10.95	CL	RA	RA
DC current (A)		CL	14.53	CL	RA	RA
Input power (W)		CL	159.14	CL	RA	RA
AC voltage (V)		CL	170.00	CL	RA	RA
AC current (A)		CL	0.81	CL	RA	RA
Output power (W)		CL	137.70	CL	RA	RA
Output power/Input power		CL	0.81	CL	RA	RA
Irradiance (mWh/cm^2) side		61.28	101.11	53.26	RA	RA
Irradiance (mWh/cm^2) centre		54.12	85.13	52.38	RA	RA
Irradiance (mWh/cm^2) side		52.98	80.43	50.31	RA	RA
Average irradiance (mWh/cm^2)		56.12	88.89	51.98	RA	RA
Global radiation (mWh/cm^2)		54.03	78.45	47.28	24.20	RA
Direct radiation (mWh/cm^2)		CL	44.86	CL	RA	RA
Global+Direct (mWh/cm^2)		54.03	123.31	47.28	24.20	RA
Temperature (°C)		NR	44.10	NR	RA	RA

Date: 8/8/82
Number of hours using solar array for pumping: 1
Number of hours using battery for pumping: Nil
Average volume of water pumped: 314 L/h
Average irradiance: 66.0 mWh/cm^2

Table 3.5 Measured data and calculated values of case I set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)	5.80	5.20	10.25	RA	RA	RA
DC current (A)	11.03	10.17	14.23	RA	RA	RA
Input power (W)	63.99	52.89	145.89	RA	RA	RA
AC voltage (V)	81.67	69.00	154.67	RA	RA	RA
AC current (A)	0.64	0.59	0.80	RA	RA	RA
Output power (W)	52.40	40.51	123.48	RA	RA	RA
Output power/Input power	0.82	0.77	0.84	RA	RA	RA
Irradiance (mWh/cm^2) side	49.37	41.38	106.12	RA	RA	RA
Irradiance (mWh/cm^2) centre	40.96	38.46	89.09	RA	RA	RA
Irradiance (mWh/cm^2) side	38.23	36.47	85.59	RA	RA	RA
Average irradiance (mWh/cm^2)	42.85	38.77	93.60	RA	RA	RA
Global radiation (mWh/cm^2)	56.73	43.09	69.28	13.70	4.98	10.70
Direct radiation (mWh/cm^2)	46.15	CL	46.44	RA	RA	RA
Global+Direct (mWh/cm^2)	102.88	43.09	115.72	13.70	4.98	10.70
Temperature ($^\circ C$)	37.50	37.50	46.10	NR	NR	RA

Date: 11/8/82
Number of hours using solar array for pumping: 1
Number of hours using battery for pumping: Nil
Average volume of water pumped: 470 L/h
Average irradiance: 58.4 mWh/cm^2

Table 3.6 Measured data and calculated values of case I set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)		CL	CL	9.08	9.55	9.77
DC current (A)		CL	CL	13.70	13.60	13.52
Input power (W)		CL	CL	124.39	129.88	132.06
AC voltage (V)		CL	CL	133.75	142.50	148.32
AC current (A)		CL	CL	0.79	0.79	0.76
Output power (W)		CL	CL	106.33	112.58	112.48
Output power/Input power		CL	CL	0.85	0.87	0.85
Irradiance (mWh/cm^2) side		CL	CL	80.23	97.14	90.90
Irradiance (mWh/cm^2) centre		CL	CL	73.45	84.66	75.29
Irradiance (mWh/cm^2) side		CL	CL	71.28	81.16	70.00
Average irradiance (mWh/cm^2)		CL	CL	74.99	87.65	78.73
Global radiation (mWh/cm^2)		30.81	57.11	68.50	72.45	70.92
Direct radiation (mWh/cm^2)		CL	CL	5.15	28.15	38.20
Global+Direct (mWh/cm^2)		30.81	57.11	73.65	100.60	109.12
Temperature ($^\circ C$)		NR	39.40	42.90	42.20	41.80

Date: 10/8/82
Number of hours using solar array for pumping: 2
Number of hours using battery for pumping: Nil
Volume of water pumped: 732 L
Average volume of water pumped: 366 L/h
Average irradiance: 80.5 mWh/cm^2

Table 3.7 Measured data and calculated values of case I set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)	7.60	8.13	8.27	7.00	5.01	8.70
DC current (A)	11.60	12.81	13.00	11.04	9.34	11.93
Input power (W)	88.40	104.18	107.51	77.30	46.81	103.79
AC voltage (V)	100.00	120.00	117.86	98.57	63.57	113.75
AC current (A)	0.69	0.74	0.76	0.65	0.56	0.69
Output power (W)	69.00	88.80	89.41	63.79	35.60	78.20
Output power/Input power	0.78	0.85	0.83	0.83	0.76	0.75
Irradiance (mWh/cm^2) side	94.70	76.01	66.38	48.65	46.21	65.86
Irradiance (mWh/cm^2) centre	82.60	67.51	62.22	48.60	44.71	60.10
Irradiance (mWh/cm^2) side	80.73	66.36	59.61	46.93	43.11	56.91
Average irradiance (mWh/cm^2)	86.01	69.96	62.74	48.25	44.68	60.97
Global radiation (mWh/cm^2)	54.61	72.17	57.50	59.28	44.81	57.17
Direct radiation (mWh/cm^2)	38.41	40.25	10.13	CL	CL	CL
Global+Direct (mWh/cm^2)	90.10	112.42	67.63	59.28	44.81	57.17
Temperature (°C)	43.80	49.40	42.90	43.30	40.40	

Date: 12/8/82
Number of hours using solar array for pumping: 1.5
Number of hours using battery for pumping: Nil
Volume of water pumped: 366 L
Average volume of water pumped: 244 L/h
Average irradiance: 62.1 mWh/cm^2

Table 3.8 Measured data and calculated values of case I set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)		5.94	6.49	10.17	10.17	10.33
DC current (A)		11.16	11.01	14.07	14.77	14.06
Input power (W)		66.29	71.45	141.69	158.20	145.20
AC voltage (V)		76.14	88.14	156.71	166.43	159.14
AC current (A)		0.67	0.64	0.80	0.83	0.78
Output power (W)		51.01	56.58	125.14	138.85	124.84
Output power/Input power		0.77	0.79	0.88	0.88	0.86
Irradiance (mWh/cm^2) side		62.67	63.33	128.18	120.13	103.72
Irradiance (mWh/cm^2) centre		56.84	58.55	102.77	93.87	82.38
Irradiance (mWh/cm^2) side		55.19	57.19	104.41	93.43	83.09
Average irradiance (mWh/cm^2)		58.23	59.69	111.78	102.48	89.73
Global radiation (mWh/cm^2)		54.64	54.06	89.72	84.31	76.73
Direct radiation (mWh/cm^2)		CL	CL	60.77	65.22	49.51
Global+Direct (mWh/cm^2)		54.64	54.06	150.49	149.53	126.24
Temperature (°C)		32.90	34.10	42.16	45.00	43.20

Date: 13/8/82
Number of hours using solar array for pumping: 3.16
Number of hours using battery for pumping: Nil
Volume of water pumped: 1881 L
Average volume of water pumped: 595.0 L/h
Average irradiance: 84.4 mWh/cm^2

Table 3.9 Measured data and calculated values of case I set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)		10.73	11.51	11.16	10.37	9.97
DC current (A)		14.53	14.97	14.99	14.76	14.09
Input power (W)		155.89	172.32	173.88	153.03	140.43
AC voltage (V)		169.29	185.43	182.86	164.29	145.00
AC current (A)		0.81	0.82	0.84	0.83	0.79
Output power (W)		136.64	152.05	153.34	137.06	113.93
Output power/Input power		0.88	0.88	0.88	0.89	0.81
Irradiance (mWh/cm^2) side		112.81	122.48	127.65	113.71	99.95
Irradiance (mWh/cm^2) centre		86.24	98.16	104.40	90.35	81.50
Irradiance (mWh/cm^2) side		86.14	96.65	100.90	90.43	80.33
Average irradiance (mWh/cm^2)		95.06	105.76	110.98	98.16	87.26
Global radiation (mWh/cm^2)		74.31	83.00	86.73	83.39	73.56
Direct radiation (mWh/cm^2)		66.12	65.61	69.91	61.47	53.56
Global+Direct (mWh/cm^2)		140.43	148.61	156.64	144.86	127.12
Temperature ($^\circ C$)		45.90	48.10	50.30	51.40	48.10

Date: 14/8/82
Number of hours using solar array for pumping: 5
Number of hours using battery for pumping: Nil
Volume of water pumped: 2299 L
Average volume of water pumped: 490.0 L/h
Average irradiance: 99.4 mWh/cm^2

Table 3.10 Measured data and calculated values of case I set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)		9.15	3.24	6.16	4.94	2.94
DC current (A)		12.87	5.53	9.16	8.09	4.57
Input power (W)		117.77	17.91	56.41	39.96	13.44
AC voltage (V)		146.67	28.75	83.57	62.14	10.00
AC current (A)		0.72	0.33	0.52	0.45	0.26
Output power (W)		105.60	9.49	43.81	28.22	2.63
Output power/Input power		0.89	0.53	0.78	0.71	0.20
Irradiance (mWh/cm^2) side		100.38	44.82	62.92	47.29	21.64
Irradiance (mWh/cm^2) centre		82.40	39.22	60.81	43.82	21.93
Irradiance (mWh/cm^2) side		78.40	39.31	58.06	43.72	21.61
Average irradiance (mWh/cm^2)		87.06	41.14	60.60	44.94	21.73
Global radiation (mWh/cm^2)		47.31	32.83	63.69	44.42	23.81
Direct radiation (mWh/cm^2)		CL	CL	CL	CL	CL
Global+Direct (mWh/cm^2)		47.31	32.83	63.69	44.42	23.81
Temperature ($^\circ C$)		37.80	32.70	39.40	34.10	30.70

Date: 15/8/82
Number of hours using solar array for pumping: 1.67
Number of hours using battery for pumping: Nil
Volume of water pumped: 627 L
Average volume of water pumped: 375 L/h
Average irradiance: 51.1 mWh/cm^2

Table 3.11 Measured data and calculated values of case I set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)	7.00	10.09	8.79	NR	RA	RA
DC current (A)	13.63	14.73	12.36	NR	RA	RA
Input power (W)	95.38	148.61	108.62	NR	RA	RA
AC voltage (V)	96.25	154.29	122.86	NR	RA	RA
AC current (A)	0.83	0.83	0.68	NR	RA	RA
Output power (W)	79.89	127.40	84.07	NR	RA	RA
Output power/Input power	0.86	0.86	0.77	NR	RA	RA
Irradiance (mWh/cm^2) side	76.66	99.93	78.76	2.84	RA	RA
Irradiance (mWh/cm^2) centre	69.69	87.86	78.69	2.98	RA	RA
Irradiance (mWh/cm^2) side	74.35	96.67	63.32	2.90	RA	RA
Average irradiance (mWh/cm^2)	73.57	94.82	73.59	2.91	RA	
Global radiation (mWh/cm^2)	61.50	75.67	70.03	9.89	41.86	67.92
Direct radiation (mWh/cm^2)	54.63	56.44	29.14	CL	RA	19.24
Global+Direct (mWh/cm^2)	116.13	132.11	99.17	9.89	41.86	87.16
Temperature ($^\circ C$)	39.10	40.40	42.90	NR	NR	NR

Date: 19/8/82
Number of hours using solar array for pumping: 1.83
Number of hours using battery for pumping: Nil
Volume of water pumped: 627 L
Average volume of water pumped: 342 L/h
Average irradiance: 61.2 mWh/cm^2

Table 3.12 Measured data and calculated values of case I set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)	5.20	6.91	8.36	8.36	3.70	5.34
DC current (A)	10.18	12.71	13.30	12.17	8.64	9.79
Input power (W)	52.91	87.86	111.19	101.75	31.96	52.26
AC voltage (V)	67.50	88.86	126.43	126.43	62.50	66.43
AC current (A)	0.62	0.76	0.77	0.69	0.37	0.58
Output power (W)	42.02	67.66	96.99	87.59	23.39	38.62
Output power/Input power	0.79	0.77	0.87	0.86	0.73	0.74
Irradiance (mWh/cm^2) side	59.83	58.86	71.40	79.72	31.44	53.00
Irradiance (mWh/cm^2) centre	54.59	60.20	76.01	83.67	34.10	49.83
Irradiance (mWh/cm^2) side	5.74	56.84	68.33	75.14	33.02	49.75
Average irradiance (mWh/cm^2)	55.39	58.63	71.91	79.51	32.85	50.86
Global radiation (mWh/cm^2)	47.08	61.09	66.14	65.56	35.17	46.25
Direct radiation (mWh/cm^2)	20.59	22.64	20.27	12.05	3.02	9.06
Global+Direct (mWh/cm^2)	67.67	83.73	86.41	77.61	38.19	55.31
Temperature ($^\circ C$)	NR	NR	NR	NR	NR	NR

Date: 20/8/82
Number of hours using solar array for pumping: 1.60
Number of hours using battery for pumping: Nil
Volume of water pumped: 940 L
Average volume of water pumped: 588.0 L/h
Average irradiance: 58.2 mWh/cm^2

Table 3.13 Measured data and calculated values of case I set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)	5.65	10.27	11.86	8.97	6.03	4.67
DC current (A)	10.90	14.44	15.00	12.84	10.81	8.97
Input power (W)	61.59	148.33	177.90	115.20	65.18	41.90
AC voltage (V)	52.50	154.29	188.57	133.57	92.86	51.43
AC current (A)	0.65	0.82	0.83	0.73	0.62	0.52
Output power (W)	34.13	127.17	156.51	97.51	57.57	26.60
Output power/Input power	0.55	0.86	0.88	0.85	0.88	0.63
Irradiance (mWh/cm^2) side	65.28	97.81	122.93	82.82	59.03	46.53
Irradiance (mWh/cm^2) centre	63.04	94.23	113.12	77.09	53.55	45.36
Irradiance (mWh/cm^2) side	58.86	86.36	101.19	72.76	54.97	43.78
Average irradiance (mWh/cm^2)	62.31	92.80	112.41	77.56	55.85	45.25
Global radiation (mWh/cm^2)	42.39	77.78	83.17	66.56	51.39	43.06
Direct radiation (mWh/cm^2)	29.94	44.95	71.98	CL	9.46	7.32
Global+Direct (mWh/cm^2)	72.33	122.73	155.15	66.56	60.85	50.38
Temperature ($^\circ C$)	42.90	43.40	40.60	39.00	35.50	34.40

Date: 21/8/82
Number of hours using solar array for pumping: 3
Number of hours using battery for pumping: Nil
Volume of water pumped: 1463 L
Average volume of water pumped: 487 L/h
Average irradiance: 74.4 mWh/cm^2

Table 3.14 Measured data and calculated values of case I set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)	8.10	10.43	10.74	11.10	8.41	6.93
DC current (A)	12.70	14.26	14.27	14.45	12.29	11.34
Input power (W)	102.87	148.70	153.28	160.68	103.32	78.61
AC voltage (V)	115.00	162.71	168.57	175.43	124.43	92.57
AC current (A)	0.72	0.80	0.81	0.80	0.69	0.65
Output power (W)	82.80	130.63	136.54	139.59	85.86	60.17
Output power/Input power	0.80	0.88	0.89	0.87	0.83	0.77
Irradiance (mWh/cm^2) side	76.70	121.20	131.15	136.55	93.49	78.82
Irradiance (mWh/cm^2) centre	76.03	98.75	111.56	135.91	91.31	72.79
Irradiance (mWh/cm^2) side	69.88	88.65	110.81	110.04	77.87	65.26
Average irradiance (mWh/cm^2)	74.20	102.86	117.84	127.50	87.56	72.29
Global radiation (mWh/cm^2)	59.98	75.92	90.00	96.19	68.03	60.97
Direct radiation (mWh/cm^2)	51.12	61.08	77.74	74.32	31.24	37.01
Global+Direct (mWh/cm^2)	101.10	137.00	167.74	170.51	99.27	97.98
Temperature ($^\circ C$)	42.70	44.70	47.40	48.70	43.80	43.60

Date: 22/8/82
Number of hours using solar array for pumping: 4
Number of hours using battery for pumping: Nil
Volume of water pumped: 2195 L
Average volume of water pumped: 548 L/h
Average irradiance: 97.0 mWh/cm^2

Table 3.15 Measured data and calculated values of case I set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)	8.68	9.84	10.67	11.24	10.62	8.76
DC current (A)	13.43	13.71	14.67	14.46	14.00	13.11
Input power (W)	116.53	134.95	156.53	162.49	148.68	114.88
AC voltage (V)	127.50	150.71	170.00	181.86	164.71	141.67
AC current (A)	0.78	0.75	0.79	0.78	0.77	0.73
Output power (W)	99.77	113.68	134.79	141.07	127.53	103.82
Output power/Input power	0.86	0.84	0.86	0.87	0.86	0.89
Irradiance (mWh/cm^2) side	88.93	111.98	129.43	136.60	124.34	108.00
Irradiance (mWh/cm^2) centre	89.64	106.20	116.63	122.40	123.83	98.29
Irradiance (mWh/cm^2) side	87.09	92.46	105.45	108.33	106.77	80.03
Average irradiance (mWh/cm^2)	88.55	103.55	117.17	122.44	118.31	95.44
Global radiation (mWh/cm^2)	64.67	76.33	87.78	91.33	86.81	70.69
Direct radiation (mWh/cm^2)	60.47	63.31	77.41	77.69	68.78	52.69
Global+Direct (mWh/cm^2)	125.14	139.64	165.19	169.02	155.59	123.38
Temperature (°C)	43.20	45.40	49.20	50.90	49.60	43.80

Date: 23/8/82
Number of hours using solar array for pumping: 5
Number of hours using battery for pumping: Nil
Volume of water pumped: 2090 L
Average volume of water pumped: 418 L/h
Average irradiance: 107.6 mWh/cm^2

Table 3.16 Measured data and calculated values of case I set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)	6.40	8.37	9.90	10.89	10.54	8.56
DC current (A)	12.35	12.87	14.63	14.40	14.35	13.11
Input power (W)	79.04	107.73	144.82	156.82	151.25	112.26
AC voltage (V)	7.50	126.43	157.86	170.00	166.43	129.29
AC current (A)	0.69	0.71	0.76	0.80	0.79	0.74
Output power (W)	51.93	90.31	120.65	136.00	132.19	96.04
Output power/Input power	0.66	0.84	0.83	0.87	0.87	0.86
Irradiance (mWh/cm^2) side	88.21	89.21	115.89	158.45	125.91	104.11
Irradiance (mWh/cm^2) centre	80.00	86.49	110.05	135.58	125.81	99.88
Irradiance (mWh/cm^2) side	78.00	80.20	96.69	109.54	100.25	87.62
Average irradiance (mWh/cm^2)	82.07	85.30	107.54	134.52	117.32	97.20
Global radiation (mWh/cm^2)	58.78	75.03	82.64	80.50	64.78	50.13
Direct radiation (mWh/cm^2)	53.08	50.76	46.06	77.86	73.01	58.76
Global+Direct (mWh/cm^2)	111.86	125.79	128.70	158.36	137.79	108.89
Temperature (°C)	40.90	43.40	43.80	44.10	43.50	39.40

Date: 26/8/82
Number of hours using solar array for pumping: 4
Number of hours using battery for pumping: Nil
Volume of water pumped: 1881 L
Average volume of water pumped: 470 L/h
Average irradiance: 104.0 mWh/cm^2

Table 3.17 Measured data and calculated values of case I set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)	6.13	8.84	10.41	9.90	6.93	5.06
DC current (A)	11.28	13.36	14.08	14.00	12.26	7.44
Input power (W)	69.12	118.08	146.63	138.60	84.94	37.64
AC voltage (V)	75.50	131.71	164.50	151.43	90.71	42.86
AC current (A)	0.70	0.79	0.78	0.75	0.71	0.54
Output power (W)	52.85	104.05	128.78	113.57	64.02	23.32
Output power/Input power	0.76	0.88	0.88	0.82	0.75	0.62
Irradiance (mWh/cm^2) side	70.36	99.82	112.03	106.61	74.00	52.73
Irradiance (mWh/cm^2) centre	68.57	93.43	93.43	104.50	73.10	51.52
Irradiance (mWh/cm^2) side	62.14	92.80	93.17	90.97	68.59	49.53
Average irradiance (mWh/cm^2)	67.02	95.35	99.54	100.69	71.90	51.26
Global radiation (mWh/cm^2)	57.20	74.28	75.11	91.33	86.14	74.06
Direct radiation (mWh/cm^2)	48.55	53.32	55.80	51.29	23.09	9.18
Global+Direct (mWh/cm^2)	105.75	127.60	130.91	142.62	109.23	83.24
Temperature ($^\circ C$)	37.50	42.20	41.80	42.60	36.50	35.80

Date: 27/8/82
Number of hours using solar array for pumping: 2.83
Number of hours using battery for pumping: Nil
Volume of water pumped: 1045 L
Average volume of water pumped: 369 L/h
Average irradiance: 81.0 mWh/cm^2

Table 3.18 Measured data and calculated values of case I set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)		5.12	4.77	5.77	5.94	6.39
DC current (A)		9.57	8.84	10.33	10.56	11.54
Input power (W)		49.00	42.18	50.60	62.71	73.76
AC voltage (V)		62.57	59.29	72.86	74.29	80.71
AC current (A)		0.56	0.51	0.61	0.62	0.67
Output power (W)		34.86	30.49	44.44	46.06	53.85
Output power/Input power		0.71	0.72	0.75	0.73	0.73
Irradiance (mWh/cm^2) side		59.72	47.87	57.80	59.63	62.58
Irradiance (mWh/cm^2) centre		59.93	47.44	57.38	59.40	61.60
Irradiance (mWh/cm^2) side		56.03	46.90	56.28	56.73	59.97
Average irradiance (mWh/cm^2)		58.57	47.40	57.15	58.59	61.38
Global radiation (mWh/cm^2)		52.58	46.58	55.33	57.17	48.89
Direct radiation (mWh/cm^2)		CL	CL	CL	CL	CL
Global+Direct (mWh/cm^2)		52.58	46.58	55.33	57.17	48.89
Temperature ($^\circ C$)		42.60	42.50	43.80	45.90	46.30

Date: 29/8/82
Number of hours using solar array for pumping: Nil
Number of hours using battery for pumping: Nil
*Volume of water pumped: 0
Average irradiance: 56.6 mWh/cm^2

*Pump malfunction

Table 3.19 Measured data and calculated values of case I set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)	3.68	7.11	6.17	6.67	5.09	4.77
DC current (A)	6.53	11.57	10.63	9.80	8.24	8.30
Input power (W)	24.04	82.27	65.58	65.37	41.96	39.59
AC voltage (V)	32.50	98.57	72.14	93.29	54.43	47.50
AC current (A)	0.40	0.67	0.60	0.61	0.53	0.48
Output power (W)	13.00	66.89	43.28	57.04	28.85	22.87
Output power/Input power	0.54	0.81	0.66	0.87	0.69	0.58
Irradiance (mWh/cm^2) side	39.64	83.86	71.83	55.97	46.65	53.05
Irradiance (mWh/cm^2) centre	39.46	79.67	60.50	51.17	46.23	51.17
Irradiance (mWh/cm^2) side	38.75	72.12	57.34	51.76	42.48	48.06
Average irradiance (mWh/cm^2)	39.28	78.55	63.22	52.95	45.13	50.87
Global radiation (mWh/cm^2)	41.81	71.58	65.19	55.83	48.53	46.89
Direct radiation (mWh/cm^2)	CL	22.76	13.45	CL	4.40	CL
Global+Direct (mWh/cm^2)	41.81	94.34	78.64	55.83	52.93	46.89
Temperature (°C)	32.90	36.50	36.50	36.00	34.80	35.30

Date: 30/8/82
Number of hours using solar array for pumping: Nil
Number of hours using battery for pumping: Nil
*Volume of water pumped: 10 L
Average irradiance: 55.0 mWh/cm^2

*Pump malfunction

Table 3.20 Measured data and calculated values of case I set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)		5.04	6.14	6.35	4.76	RA
DC current (A)		8.89	10.20	9.27	7.45	RA
Input power (W)		44.78	62.63	58.87	35.46	RA
AC voltage (V)		60.71	87.57	82.29	45.00	RA
AC current (A)		0.57	0.61	0.53	0.42	RA
Output power (W)		34.86	53.29	43.62	18.81	RA
Output power/Input power		0.78	0.85	0.74	0.53	RA
Irradiance (mWh/cm^2) side		50.37	67.27	76.47	47.87	RA
Irradiance (mWh/cm^2) centre		47.51	64.44	75.78	47.96	RA
Irradiance (mWh/cm^2) side		46.15	58.96	65.22	42.51	RA
Average irradiance (mWh/cm^2)		48.01	63.56	72.49	46.11	RA
Global radiation (mWh/cm^2)		53.11	49.69	54.53	34.81	RA
Direct radiation (mWh/cm^2)		12.17	14.56	35.14	19.29	RA
Global+Direct (mWh/cm^2)		65.28	64.25	89.67	54.10	RA
Temperature (°C)		42.50	43.80	45.10	34.80	RA

Date: 31/8/82
Number of hours using solar array for pumping: 0.83
Number of hours using battery for pumping: Nil
*Volume of water pumped: 123 L
Average volume of water pumped: 148 L/h
Average irradiance: 57.5 mWh/cm^2

*Pump malfunction

Table 3.21 Measured data and calculated values of case II set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)		12.67	13.42	12.52	12.01	10.85
DC current (A)		13.28	15.28	14.41	15.38	11.61
Input power (W)		168.26	205.10	180.50	203.38	125.96
AC voltage (V)		162.16	185.16	176.67	192.21	143.21
AC current (A)		0.82	0.94	0.89	0.91	0.73
Output power (W)		132.84	178.56	158.75	174.91	104.54
Output power/Input power		0.79	0.87	0.87	0.86	0.84
Irradiance (mWh/cm^2) side		82.78	83.21	80.71	79.29	54.29
Irradiance (mWh/cm^2) centre		90.24	95.00	90.71	89.52	56.84
Irradiance (mWh/cm^2) side		96.19	97.45	90.73	90.48	60.59
Average irradiance (mWh/cm^2)		89.80	91.89	87.38	86.43	57.24
Global radiation (mWh/cm^2)		75.95	74.06	75.48	70.14	51.70
Direct radiation (mWh/cm^2)		51.46	39.22	39.51	37.81	25.96
Global+Direct (mWh/cm^2)		127.41	113.28	114.99	107.95	77.66
Temperature ($^\circ C$)		50.50	52.50	49.70	49.40	43.60

Date: 23/4/83
Number of hours using solar array for pumping: 2.15
Number of hours using battery for pumping: 3.85
Volume of water pumped: 3156 L
Average volume of water pumped: 632 L/h
Average irradiance: 82.6 mWh/cm^2

Table 3.22 Measured data and calculated values of case II set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)		9.94	3.41	3.19	3.90	3.72
DC current (A)		11.08	5.83	5.70	7.24	5.28
Input power (W)		110.16	19.88	18.18	28.24	19.64
AC voltage (V)		121.58	31.21	28.75	30.17	16.21
AC current (A)		0.68	0.42	0.36	0.39	0.26
Output power (W)		82.67	13.11	10.35	11.76	4.21
Output power/Input power		0.75	0.66	0.57	0.42	0.22
Irradiance (mWh/cm^2) side		57.96	24.49	29.64	37.55	26.33
Irradiance (mWh/cm^2) centre		58.49	24.89	29.49	37.24	27.14
Irradiance (mWh/cm^2) side		58.78	24.49	29.49	37.59	26.73
Average irradiance (mWh/cm^2)		58.41	24.62	29.54	37.46	26.73
Global radiation (mWh/cm^2)		55.87	26.64	27.31	43.72	31.97
Direct radiation (mWh/cm^2)		CL	CL	CL	CL	CL
Global+Direct (mWh/cm^2)		55.87	26.64	27.31	43.72	31.97
Temperature ($^\circ C$)		43.60	40.40	41.80	45.20	41.30

Date: 24/4/83
Number of hours using solar array for pumping: Nil
Number of hours using battery for pumping: 6
Volume of water pumped: 2980 L
Average volume of water pumped: 496 L/h
Average irradiance: 35.4 mWh/cm^2

Table 3.23 Measured data and calculated values of case II set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)		9.21	6.98	9.08	6.28	4.92
DC current (A)		13.50	10.63	12.79	10.00	7.78
Input power (W)		124.31	74.16	116.21	62.73	38.29
AC voltage (V)		133.16	100.56	146.67	79.53	61.79
AC current (A)		0.69	0.59	0.71	0.56	0.40
Output power (W)		91.88	59.33	104.13	44.54	27.19
Output power/Input power		0.74	0.80	0.89	0.71	0.71
Irradiance (mWh/cm^2) side		67.38	56.07	58.88	51.53	43.47
Irradiance (mWh/cm^2) centre		70.12	57.86	62.55	54.59	45.20
Irradiance (mWh/cm^2) side		72.38	57.14	62.24	53.06	45.92
Average irradiance (mWh/cm^2)		69.96	57.02	61.22	53.06	44.86
Global radiation (mWh/cm^2)		61.47	57.03	57.34	51.36	42.06
Direct radiation (mWh/cm^2)		25.02	20.40	30.76	11.42	20.10
Global+Direct (mWh/cm^2)		86.49	77.43	88.10	62.78	62.16
Temperature ($^{\circ}C$)		50.00	49.52	47.90	47.21	44.70

Date: 25/4/83
Number of hours using solar array for pumping: 0.17
Number of hours using battery for pumping: 5.83
Volume of water pumped: 2710 L
Average volume of water pumped: 451 L/h
Average irradiance: 57.2 mWh/cm^2

Table 3.24 Measured data and calculated values of case II set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)		5.02	8.56	13.50	13.00	8.22
DC current (A)		9.00	12.08	16.00	15.63	13.08
Input power (W)		45.19	103.41	216.00	203.13	107.51
AC voltage (V)		61.33	85.99	180.12	173.46	113.56
AC current (A)		0.56	0.90	0.93	0.89	0.71
Output power (W)		34.34	77.39	167.25	154.38	80.63
Output power/Input power		0.76	0.75	0.77	0.76	0.75
Irradiance (mWh/cm^2) side		47.96	65.71	82.04	77.05	64.29
Irradiance (mWh/cm^2) centre		46.23	69.50	93.06	86.03	69.05
Irradiance (mWh/cm^2) side		46.18	70.51	93.78	89.59	74.29
Average irradiance (mWh/cm^2)		46.79	68.57	89.63	84.22	69.21
Global radiation (mWh/cm^2)		47.11	60.11	74.67	70.70	58.92
Direct radiation (mWh/cm^2)		26.19	16.95	35.93	39.69	30.29
Global+Direct (mWh/cm^2)		73.30	77.06	110.60	110.39	89.21
Temperature ($^{\circ}C$)		43.60	47.60	56.80	53.40	52.30

Date: 26/4/83
Number of hours using solar array for pumping: 2
Number of hours using battery for pumping: 4
Volume of water pumped: 2930 L
Average volume of water pumped: 488 L/h
Average irradiance: 65.7 mWh/cm^2

Table 3.25 Measured data and calculated values of case II set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)		13.65	15.34	15.17	14.01	13.81
DC current (A)		16.34	17.11	17.08	14.52	14.96
Input power (W)		223.08	262.53	259.10	203.38	206.68
AC voltage (V)		189.17	210.00	208.57	196.67	181.21
AC current (A)		0.98	1.00	1.00	0.98	0.95
Output power (W)		185.39	210.00	208.57	193.39	172.15
Output power/Input power		0.83	0.80	0.80	0.95	0.83
Irradiance (mWh/cm^2) side		90.71	103.37	100.92	92.45	84.28
Irradiance (mWh/cm^2) centre		92.24	110.31	111.33	96.63	85.00
Irradiance (mWh/cm^2) side		113.06	132.14	130.10	119.64	89.29
Average irradiance (mWh/cm^2)		98.67	115.27	114.12	102.91	86.19
Global radiation (mWh/cm^2)		79.20	89.23	87.53	83.34	69.12
Direct radiation (mWh/cm^2)		73.99	77.40	76.33	76.32	71.25
Global+Direct (mWh/cm^2)		153.19	166.63	163.86	159.66	140.37
Temperature (°C)		46.70	48.70	52.10	60.00	53.60

Date: 29/4/83
Number of hours using solar array for pumping: 4.21
Number of hours using battery for pumping: 1.79
Volume of water pumped: 3206 L
Average volume of water pumped: 534 L/h
Average irradiance: 103.4 mWh/cm^2

Table 3.26 Measured data and calculated values of case II set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)		14.75	14.67	14.84	14.30	10.33
DC current (A)		15.75	17.00	17.02	16.70	12.90
Input power (W)		232.31	249.39	252.58	238.81	133.26
AC voltage (V)		195.00	200.00	203.86	195.00	127.14
AC current (A)		0.94	1.00	1.00	0.98	0.74
Output power (W)		183.30	200.00	203.86	192.21	95.17
Output power/Input power		0.79	0.80	0.81	0.80	0.71
Irradiance (mWh/cm^2) side		79.39	104.29	102.65	93.67	72.96
Irradiance (mWh/cm^2) centre		79.59	107.86	103.37	94.50	73.27
Irradiance (mWh/cm^2) side		88.67	126.73	133.06	123.47	81.01
Average irradiance (mWh/cm^2)		82.55	112.96	113.03	103.98	75.75
Global radiation (mWh/cm^2)		60.70	87.39	90.42	84.42	71.92
Direct radiation (mWh/cm^2)		11.37	74.30	77.60	76.89	73.69
Global+Direct (mWh/cm^2)		72.07	161.69	168.02	161.31	145.61
Temperature (°C)		56.40	58.40	58.00	58.40	53.80

Date: 30/4/83
Number of hours using solar array for pumping: 4.18
Number of hours using battery for pumping: 1.82
Volume of water pumped: 3239 L
Average volume of water pumped: 540 L/h
Average irradiance: 97.7 mWh/cm^2

Table 3.27 Measured data and calculated values of case II set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)	RA	13.29	8.75	12.98	13.53	12.75
DC current (A)	RA	13.77	4.21	12.92	14.90	12.12
Input power (W)	RA	183.00	36.84	167.70	201.60	154.53
AC voltage (V)	RA	113.00	29.58	150.17	196.25	160.42
AC current (A)	RA	0.71	0.46	1.00	0.91	0.77
Output power (W)	RA	79.67	13.80	150.17	178.26	122.98
Output power/Input power	RA	0.44	0.37	0.89	0.88	0.80
Irradiance (mWh/cm^2) side	RA	74.05	23.27	75.89	80.77	75.59
Irradiance (mWh/cm^2) centre	RA	74.46	23.21	76.55	81.07	75.24
Irradiance (mWh/cm^2) side	RA	82.38	20.42	91.07	100.42	91.67
Average irradiance (mWh/cm^2)	RA	76.96	22.30	81.17	87.42	80.83
Global radiation (mWh/cm^2)	RA	39.93	17.14	29.11	25.06	26.39
Direct radiation (mWh/cm^2)	RA	NR	NR	NR	NR	NR
Global+Direct (mWh/cm^2)	RA	39.92	17.14	29.11	25.06	26.39
Temperature ($^{\circ}C$)	RA	52.10	36.50	42.90	50.30	51.40

Date: 2/5/83
Number of hours using solar array for pumping: 1.96
Number of hours using battery for pumping: 4.04
Volume of water pumped: 3037 L
Average volume of water pumped: 506 L/h
Average irradiance: 70.0 mWh/cm^2

Table 3.28 Measured data and calculated values of case II set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)	9.81	11.28	14.34	14.52	13.58	11.30
DC current (A)	11.79	14.37	16.73	17.00	16.62	14.75
Input power (W)	115.17	162.09	239.94	246.78	225.62	166.68
AC voltage (V)	126.06	155.45	196.67	200.00	186.25	135.27
AC current (A)	0.75	0.91	0.99	1.00	0.97	0.77
Output power (W)	94.55	141.46	195.03	200.00	180.66	104.16
Output power/Input power	0.82	0.87	0.81	0.81	0.80	0.62
Irradiance (mWh/cm^2) side	65.53	76.31	116.49	104.58	92.44	73.99
Irradiance (mWh/cm^2) centre	64.94	79.11	116.96	110.59	93.04	73.33
Irradiance (mWh/cm^2) side	76.67	81.30	132.38	138.75	122.50	98.45
Average irradiance (mWh/cm^2)	69.05	78.91	121.94	117.97	102.66	81.92
Global radiation (mWh/cm^2)	62.13	56.96	89.11	89.23	76.28	71.32
Direct radiation (mWh/cm^2)	59.45	65.66	73.60	85.07	72.92	67.15
Global+Direct (mWh/cm^2)	121.58	122.62	162.71	174.30	149.20	138.47
Temperature ($^{\circ}C$)	43.20	48.10	51.40	57.30	60.50	55.40

Date: 3/5/83
Number of hours using solar array for pumping: 4.57
Number of hours using battery for pumping: 1.43
Volume of water pumped: 3373 L
Average volume of water pumped: 562 L/h
Average irradiance: 95.4 mWh/cm^2

Table 3.29 Measured data and calculated values of case III set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)	12.00	12.18	10.31	6.93	3.86	8.73
DC current (A)	15.67	16.03	13.37	9.93	7.38	10.30
Input power (W)	187.99	195.18	137.81	68.78	28.47	89.92
AC voltage (V)	200.00	200.50	158.75	101.92	47.33	118.00
AC current (A)	0.94	0.95	0.79	0.59	0.50	0.68
Output power (W)	187.00	190.81	126.31	60.11	23.74	79.65
Output power/Input power	0.99	0.98	0.92	0.87	0.83	0.89
Irradiance (mWh/cm^2) side	95.95	113.10	101.85	66.36	30.29	50.12
Irradiance (mWh/cm^2) centre	97.38	113.93	102.32	66.43	30.60	51.73
Irradiance (mWh/cm^2) side	97.38	113.10	103.90	65.95	30.04	50.00
Average irradiance (mWh/cm^2)	96.79	113.38	102.90	66.25	30.32	50.62
Global radiation (mWh/cm^2)	58.14	66.23	64.25	48.19	21.67	31.68
Direct radiation (mWh/cm^2)	50.83	64.35	64.35	48.00	14.68	36.27
Global+Direct (mWh/cm^2)	108.97	128.58	128.58	96.17	35.36	67.95
Temperature (°C)	56.60	64.40	64.40	48.10	37.80	37.30

Date: 3/9/83
Number of hours using solar array for pumping: 2
Number of hours using battery for pumping: 4
Volume of water pumped: 2925 L
Average volume of water pumped: 488 L/h
Average irradiance: 76.7 mWh/cm^2

Table 3.30 Measured data and calculated values of case III set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)	11.78	11.61	12.80	12.05	12.33	4.90
DC current (A)	15.35	16.26	15.97	15.38	15.30	7.85
Input power (W)	180.82	188.76	204.37	185.27	185.29	38.47
AC voltage (V)	195.17	207.42	211.25	194.50	204.25	61.25
AC current (A)	0.91	0.90	0.96	0.91	0.91	0.51
Output power (W)	178.09	186.68	202.62	177.48	184.85	31.14
Output power/Input power	0.98	0.98	0.99	0.96	0.99	0.81
Irradiance (mWh/cm^2) side	88.21	118.10	131.17	92.86	92.50	35.24
Irradiance (mWh/cm^2) centre	89.39	119.05	131.85	92.33	93.20	35.54
Irradiance (mWh/cm^2) side	89.39	118.10	131.54	93.04	92.80	35.12
Average irradiance (mWh/cm^2)	88.55	118.43	131.52	93.08	92.83	35.30
Global radiation (mWh/cm^2)	53.13	69.16	71.23	54.12	55.15	26.16
Direct radiation (mWh/cm^2)	56.63	56.67	62.87	50.66	54.82	33.17
Global+Direct (mWh/cm^2)	109.76	125.83	134.10	104.78	109.97	59.33
Temperature (°C)	65.60	66.00	67.80	55.40	51.90	39.20

Date: 4/9/83
Number of hours using solar array for pumping: 4.75
Number of hours using battery for pumping: 1.25
Volume of water pumped: 3380 L
Average volume of water pumped: 563 L/h
Average irradiance: 93.3 mWh/cm^2

Table 3.31 Measured data and calculated values of case III set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)	12.16	12.88	14.11	13.48	11.90	7.91
DC current (A)	13.67	14.58	14.92	14.58	14.26	9.25
Input power (W)	166.19	187.76	210.47	196.47	169.67	73.17
AC voltage (V)	170.00	187.42	203.00	208.33	169.50	118.50
AC current (A)	0.87	0.89	0.89	0.88	0.80	0.61
Output power (W)	148.18	167.58	182.02	183.33	135.32	72.29
Output power/Input power	0.89	0.89	0.86	0.93	0.80	0.99
Irradiance (mWh/cm^2) side	86.84	85.53	131.19	117.74	105.00	64.11
Irradiance (mWh/cm^2) centre	87.56	86.73	132.14	118.63	105.48	64.58
Irradiance (mWh/cm^2) side	87.32	86.49	130.95	117.74	104.88	64.23
Average irradiance (mWh/cm^2)	87.24	86.25	131.43	118.08	105.12	64.31
Global radiation (mWh/cm^2)	76.12	82.19	79.69	79.69	83.13	66.36
Direct radiation (mWh/cm^2)	60.35	64.38	74.12	74.12	62.31	52.56
Global+Direct (mWh/cm^2)	136.47	146.57	153.81	153.18	145.44	118.92
Temperature (°C)	57.40	57.40	59.90	59.90	49.90	44.90

Date: 11/9/83
Number of hours using solar array for pumping: 4.0
Number of hours using battery for pumping: 1.80
Volume of water pumped: 3313 L
Average volume of water pumped: 571 L/h
Average irradiance: 98.7 mWh/cm^2

Table 3.32 Measured data and calculated values of case III set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)	14.15	14.50	10.71	5.76	4.48	5.93
DC current (A)	15.77	15.70	11.63	6.77	7.16	7.83
Input power (W)	223.09	227.65	124.50	38.98	32.10	46.40
AC voltage (V)	205.00	214.58	161.25	87.08	70.42	96.25
AC current (A)	0.95	1.04	0.74	0.42	0.31	0.46
Output power (W)	194.75	222.36	119.59	36.57	21.83	44.28
Output power/Input power	0.87	0.98	0.96	0.94	0.68	0.95
Irradiance (mWh/cm^2) side	109.41	132.92	97.98	75.71	65.89	84.52
Irradiance (mWh/cm^2) centre	112.14	133.75	98.87	76.67	66.96	85.26
Irradiance (mWh/cm^2) side	113.33	132.98	97.98	75.95	65.77	84.40
Average irradiance (mWh/cm^2)	111.63	133.22	98.28	76.11	66.21	84.76
Global radiation (mWh/cm^2)	67.28	79.23	61.02	46.12	32.62	39.12
Direct radiation (mWh/cm^2)	66.27	74.37	44.15	17.48	21.16	46.05
Global+Direct (mWh/cm^2)	133.55	153.60	105.17	63.60	53.78	85.47
Temperature (°C)	62.10	61.40	56.20	50.50	44.90	42.70

Date: 16/9/83
Number of hours using solar array for pumping: 3.90
Number of hours using battery for pumping: 2.10
Volume of water pumped: 3220 L
Average volume of water pumped: 537 L/h
Average irradiance: 95.0 mWh/cm^2

Table 3.33 Measured data and calculated values of case III set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)	11.38	9.64	8.80	11.21	13.48	10.83
DC current (A)	13.87	11.47	10.49	12.86	15.48	12.38
Input power (W)	157.80	110.54	92.33	144.14	208.67	134.12
AC voltage (V)	172.65	146.35	127.30	150.25	225.25	156.76
AC current (A)	0.85	0.71	0.66	0.66	0.91	0.77
Output power (W)	146.75	103.91	84.02	98.54	204.24	120.71
Output power/Input power	0.93	0.94	0.91	0.68	0.98	0.90
Irradiance (mWh/cm^2) side	94.88	104.82	111.79	124.04	133.10	108.57
Irradiance (mWh/cm^2) centre	95.18	105.77	112.50	124.94	133.10	109.23
Irradiance (mWh/cm^2) side	94.64	104.34	112.08	124.40	132.68	108.75
Average irradiance (mWh/cm^2)	94.90	104.98	112.12	124.46	132.96	108.85
Global radiation (mWh/cm^2)	59.29	64.41	69.28	71.22	76.31	58.26
Direct radiation (mWh/cm^2)	36.99	45.54	53.08	58.86	56.75	42.16
Global+Direct (mWh/cm^2)	96.28	109.97	122.37	130.08	132.96	100.42
Temperature (°C)	58.60	55.00	50.90	50.00	49.90	45.20

Date: 17/9/83
Number of hours using solar array for pumping: 5
Number of hours using battery for pumping: 1
Volume of water pumped: 3643 L
Average volume of water pumped: 607 L/h
Average irradiance: 113.1 mWh/cm^2

Table 3.34 Measured data and calculated values of case III set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)	5.33	6.46	6.98	8.18	8.30	7.22
DC current (A)	10.47	10.45	11.00	11.19	12.51	10.54
Input power (W)	55.79	67.51	76.78	91.53	103.82	76.11
AC voltage (V)	71.67	92.92	119.58	125.92	127.92	107.17
AC current (A)	0.64	0.60	0.62	0.63	0.64	0.59
Output power (W)	45.75	56.06	74.14	79.01	81.22	63.59
Output power/Input power	0.82	0.83	0.97	0.86	0.78	0.84
Irradiance (mWh/cm^2) side	51.67	88.48	99.23	102.21	95.28	81.29
Irradiance (mWh/cm^2) centre	56.55	100.21	117.55	119.92	109.62	90.19
Irradiance (mWh/cm^2) side	61.67	95.11	116.70	119.53	109.27	88.96
Average irradiance (mWh/cm^2)	56.63	94.60	111.16	113.89	104.72	86.81
Global radiation (mWh/cm^2)	63.92	79.21	82.12	82.64	72.16	71.09
Direct radiation (mWh/cm^2)	58.31	53.83	59.90	59.46	67.24	52.14
Global+Direct (mWh/cm^2)	122.23	142.02	142.02	142.10	139.40	123.23
Temperature (°C)	32.70	50.00	50.00	52.80	44.10	41.30

Date: 19/9/83
Number of hours using solar array for pumping: 3.50
Number of hours using battery for pumping: 2.50
Volume of water pumped: 3178 L
Average volume of water pumped: 530 L/h
Average irradiance: 94.6 mWh/cm^2

Table 3.35 Measured data and calculated values of case III set-up

Parameter	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
DC voltage (V)	3.18	7.18	10.29	10.23	6.84	6.07
DC current (A)	5.28	10.97	14.13	14.88	12.48	11.18
Input power (W)	16.80	78.74	145.35	152.26	85.23	67.88
AC voltage (V)	54.67	108.58	166.67	147.17	71.50	60.83
AC current (A)	0.30	0.62	0.82	0.85	0.73	0.66
Output power (W)	16.40	67.05	136.81	125.09	52.37	39.99
Output power/Input power	0.98	0.85	0.94	0.82	0.61	0.59
Irradiance (mWh/cm^2) side	38.48	60.14	83.03	85.33	68.77	63.26
Irradiance (mWh/cm^2) centre	39.32	72.63	105.42	97.95	79.62	69.84
Irradiance (mWh/cm^2) side	36.73	69.23	108.79	109.99	79.75	69.60
Average irradiance (mWh/cm^2)	38.18	67.33	99.08	97.76	76.05	67.57
Global radiation (mWh/cm^2)	32.13	62.13	82.19	72.94	68.81	52.32
Direct radiation (mWh/cm^2)	25.12	39.15	58.28	58.24	43.54	54.03
Global+Direct (mWh/cm^2)	57.25	101.28	140.47	131.18	112.35	106.35
Temperature ($^{\circ}C$)	31.70	33.20	42.50	41.30	38.20	37.50

Date: 22/9/83
Number of hours using solar array for pumping: 1.67
Number of hours using battery for pumping: 4.33
Volume of water pumped: 2922 L
Average volume of water pumped: 487 L/h
Average irradiance: 74.3 mWh/cm^2

COMPARISON OF PERFORMANCE WITH FORECAST

The performance of the water pumping system under different weather conditions and the three set-ups was compared with respect to the forecast hourly mean solar radiation discussed in Part I, page 22[1]. The forecast hourly mean solar radiation from 1000 hours to 1600 hours for the twelve months were obtained from the graphs of Fig. 1 to Fig. 12 (Part I) and are shown in Table 3.36.

Table 3.36 Forecast hourly mean solar radiation in mWh/cm^2

Month	Time					
	10-11	11-12	12-13	13-14	14-15	15-16
January	97.25	119.88	127.55	127.88	116.60	89.68
February	92.04	110.58	121.18	122.05	110.49	88.70
March	95.73	111.19	118.62	123.71	114.25	88.80
April	94.49	110.42	122.10	124.98	115.67	91.88
May	82.59	89.94	98.47	101.08	89.41	72.60
June	79.71	90.12	97.56	98.54	88.12	71.29
July	78.01	96.11	105.63	102.85	94.40	75.45
August	75.04	88.93	98.68	97.72	86.93	67.95
September	76.72	87.64	93.60	94.38	84.15	65.84
October	82.29	94.15	99.63	94.20	80.43	61.20
November	91.91	104.45	109.11	102.00	83.99	62.89
December	89.76	106.28	111.83	107.56	94.90	69.81

Comparison of estimated solar radiation and measured solar radiation

Figures 3.1 to 3.3 show a plot of some of the estimated total concentrated solar radiation obtained by adding the global solar radiation to the direct solar radiation to give a concentration factor of two (discussed in Part I)[1] and the measured average total concentrated solar radiation for the time period from 1000 hours to 1600 hours for the various weather conditions and set-ups. The forecast solar radiation for the relevant month is also included in each group.

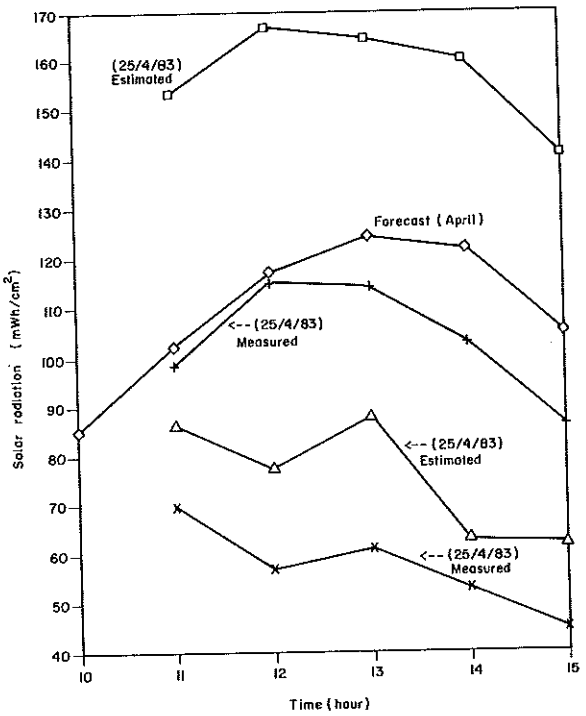

Fig. 3.1 Solar radiation performance for Case II set-up

From the plots of solar radiation versus the time, it can be seen that generally, the estimated total concentrated solar radiation obtained by adding the global solar radiation and the direct solar radiation is greater than the actual measured total concentrated solar radiation in the early hours and in the later hours of the day, mainly due to the low altitude of the sun at these times.

However, they seem to be quite close during noon time. One trend that can also be seen is that the measured total concentrated solar radiation is closer to the forecast solar radiation compared to the estimated total concentrated solar radiation. This appears to be due to the measured total concentrated solar radiation being measured in a horizontal plane and a shadowing effect caused by the structural set-up of the concentrating mirrors.

Referring to Fig. 3.3, the estimated and measured data are quite close. However they are higher than the forecast data for high solar radiation but less than the forecast data when the average of the high and the low solar radiation is considered.

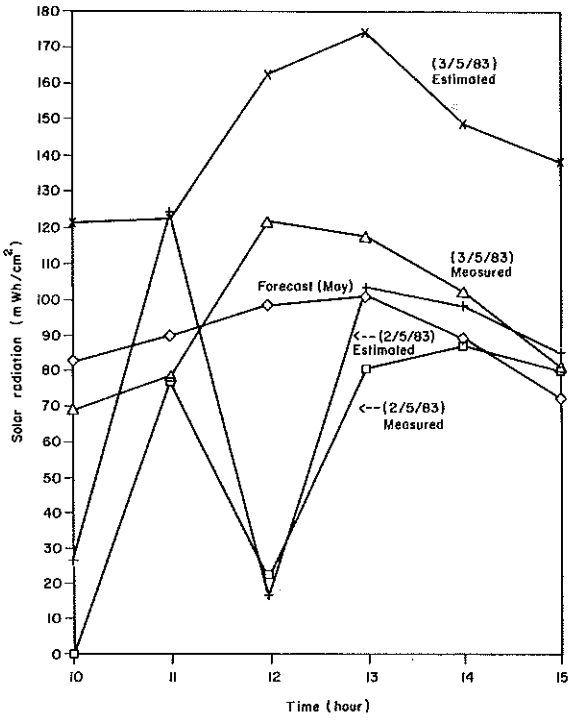

Fig. 3.2 Solar radiation forecast performance for Case II set-up

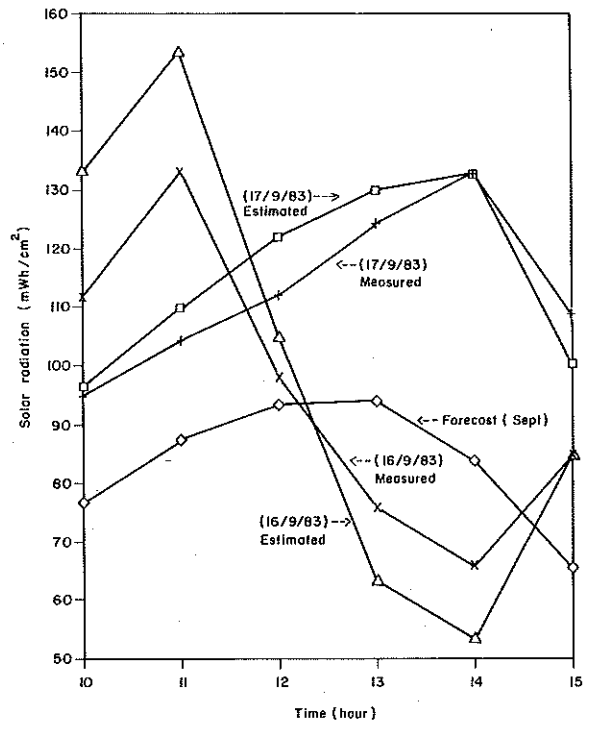

Fig. 3.3 Solar radiation forecast performance for Case III set-up.

Comparing Fig. 3.3 which shows the performance for one-axis tracking system to Fig. 3.2 which shows the performance for non-tracking system, it can be seen that the estimated and measured solar radiations are quite close. This indicates that the one-axis tracking improves the performance of the photovoltaic water-pumping system in terms of the concentrated solar radiation.

Comparison of system performance for the three set-ups

The performance of the water pumping system under the three set-ups can be compared with respect to the average volume of water collected per hour. Tables 3.37 to 3.39 show the average volume of water obtained per hour against the average solar irradiance received by the photovoltaic modules for the three set-ups.

Table 3.37 (Case I) — Comparison of average solar irradiance with average volume of water (L/h) during pumping

Date	Average irradiance* (mWh/cm^2)	Total volume of water (litre)
5/8/82	91.5	422.0
6/8/82	113.3	438.0
7/8/82	92.1	483.0
8/8/82	66.0	314.0
10/8/82	58.4	470.0
11/8/82	80.5	366.0
12/8/82	62.1	244.0
13/8/82	84.4	595.0
14/8/82	99.4	490.0
15/8/82	51.2	375.0
19/8/82	61.2	342.0
20/8/82	58.2	588.0
21/8/82	74.4	487.0
22/8/82	97.0	548.0
23/8/82	107.6	418.0
26/8/82	104.0	470.0
27/8/82	81.0	369.0
29/8/82	56.6	0+
30/8/82	55.0	10+
31/8/82	57.5	148+

*Average irradiance on photovoltaic modules.
+Pump malfunction.

From Table 3.37 it can be seen that the average volume of water pumped per hour using a manually controlled (or a microprocessor controlled) photovoltaic water pump is limited during low average solar irradiance. However, for days of high average solar irradiance (about 70 mWh/cm^2), the average volume of water obtained is around 462.0 L/h.

Table 3.37, Table 3.38 and Table 3.39 clearly show that the back-up battery increases the total volume of water collected for a magnitude of about the same solar radiation.

Another feature which can be seen by comparing Table 3.38 and Table 3.39 is the performance with and without one-axis tracking. The data on the average solar irradiance for 3/5/83 and 16/9/83, show that the average solar irradiance is about the same (95.0 mWh/cm^2) but the

Table 3.38 (Case II) — Comparison of average solar irradiance with average volume of water (L/h) during pumping

Date	Average irradiance (mWh/cm^2)	Average volume of water (L/h)	Comment
23/4/83	82.6	631	*
24/4/83	35.4	496	*
25/4/83	57.2	451	*
26/4/83	65.7	488	*
29/4/83	103.4	534	+
30/4/83	97.7	540	+
2/5/83	70.0	506	*
3/5/83	95.4	562	+

*Implies pumping using most energy from battery.
+Implies pumping using significant part of solar energy.

Table 3.39 (Case III) — Comparison of average solar irradiance with average volume of water (L/h) during pumping

Date	Average irradiance (mWh/cm^2)	Average volume of water (L/h)	Comment
3/9/83	76.7	488	*
4/9/83	93.3	563	+
11/9/83	98.7	571	+
16/9/83	95.0	537	+
17/9/83	113.1	607	+
19/9/83	94.6	530	+
22/9/83	74.3	487	*

*Implies pumping using most energy from battery.
+Implies pumping using significant part of solar energy.

pumping time for about the same average volume of water pumped per hour using solar energy is less for the one-axis tracking. Similar results can be seen for solar radiation in the average range of 70-98.0 mWh/cm^2. Therefore, one-axis tracking increases solar radiation and thus the rate of pumping.

Efficiency per day

The efficiency of the water-pumping system for a day can be taken to be the potential energy stored in terms of the total volume of water collected during the pumping period divided by the total solar energy obtained for the same period.

$$\eta = \frac{\text{Potential energy of water}}{\text{Solar radiation input}} \times 100\%$$

$$= \frac{mgh}{Q \times A_{eff}} \times 100\% \qquad (1)$$

where m = mass of water in Kg

g = gravitational constant

h = height in meter

Q = solar radiation in Wh/cm^2

A_{eff} = Effective area of solar cells in cm^2

Using equation (1) the efficiency of the water-pumping system for the three set-ups is calculated and tabulated in Table 3.40 to Table 3.42. Here, h is equal to 4.42m and A_{eff} is 69.78 cm^2.

Table 3.40 Efficiency per day for Case I set-up

Date	Volume of water (litre)	Number of hours of solar energy	Efficiency per day (%)
5/8/82	1900	4.50	.73
6/8/82	2332	5.33	.84
7/8/82	2090	4.33	.80
8/8/82	314	1.00	.28
10/8/82	732	1.00	.54
11/8/82	470	2.00	.63
12/8/82	366	1.50	.23
13/8/82	1881	3.16	.79
14/8/82	2299	5.00	.82
15/8/82	627	1.67	.43
19/8/82	627	1.83	.65
20/8/82	940	1.16	.57
21/8/82	1463	3.00	.80
22/8/82	2195	4.00	.76
23/8/82	2090	5.00	.66
26/8/82	1881	4.00	.61
27/8/82	1045	2.83	.44
29/8/82	0	0.00	6.2×10^{-3}
30/8/82	10	0.00	6.1×10^{-3}
31/8/82	123	0.83	.09

Table 3.41 Efficiency per day for Case II set-up

Date	Volume of water (litre)	Number of hours of solar energy	Efficiency per day (%)
23/4/83	3156	2.15	1.35
24/4/83	2980	0.00	2.98
25/4/83	2710	0.17	1.68
26/4/83	2930	2.00	1.45
29/4/83	3206	4.21	1.10
30/4/83	3239	4.18	1.17
2/5/83	3037	4.57	0.94
3/5/83	3373	1.96	1.71

Table 3.42 Efficiency per day for Case III set-up

Date	Volume of water (litre)	Number of hours of solar energy	Efficiency per day (%)
3/9/83	2925	2.00	1.13
4/9/83	3380	4.75	1.07
11/9/83	3313	3.90	1.00
16/9/83	3220	3.90	1.27
17/9/83	3643	5.00	0.95
19/9/83	3178	3.50	0.99
22/9/83	2922	1.67	1.16

Comparing the efficiency per day in Case I with that in Case II or Case III, it can be seen that in Case I, the efficiency per day is lower than that of Case II or Case III for about the same quantity of total solar radiation. This can be attributed to the fact that in Case I there is no battery back-up sub-system whereas in Case II or Case III, the battery back-up sub-system is performing the work whenever the solar radiation is insufficient. It can also be seen by comparing Table 3.41 and Table 3.42 that the efficiency per day of the non-tracking system is higher than that of the one-axis tracking system. However, a closer look at Table 3.41 reveals that the cases of relatively higher efficiency per day (on 24/4/83, 25/4/83 and 3/5/83) are due to longer duration of water-pumping using battery, that is, the total volume of water collected over the day is not due to the amount of total solar radiation falling on the solar array as equation (1) suggests.

Referring to Table 3.42, it can be deduced that the efficiency per day for the one-axis tracking system is quite consistent, in the range of 0.95 to 1.27. This may be due to the improvement of the amount of solar radiation collected using one-axis tracking system as can be observed in Table 3.39.

Another reason for the increase in efficiency per day in Case II and Case III is the usage of a microprocessor control. The microprocessor is constantly keeping track of the availability of the solar array current and the condition of the battery, thus providing proper and efficient management of the two sources of energy.

Comparison of System Efficiency

Theoretically, the instantaneous efficiency of the water pumping system can be deduced as

$$\eta_{sys} = \eta_{pv} \times \eta_{inv} \times \eta_{pump} \qquad (2)$$

where η_{sys} = photovoltaic conversion efficiency

η_{inv} = invertor efficiency

η_{pump} = pump efficiency

Referring to Part I[1] and taking the optimum efficiency of photovoltaic module as 7.35% at 45°C with concentration factor of two and taking the efficiency of invertor and pump to be 90% and 45% respectively, the system efficiency of the water pumping system is approximately 3%. This is quite close to the results of Privdo[2] who obtained an instantaneous system efficiency of 2.5% for a photovoltaic water pumping system using an AC motor.

SYSTEM LOSSES

DC line losses seem to be the major concern regarding the system performance. Referring to Table 3.40, the set-up using wire of small cross-sectional area and thus bigger resistance results in lower efficiency even during periods of high solar radiation.

The next significant loss is due to the effect of temperature. This can be clearly seen in Table 3.39 and Table 3.42 where the efficiency is lowest when the solar radiation is highest (on 4/9/83, 17/9/83 and 19/9/83). A closer look at the temperatures from Table 3.30, Table 3.33 and Table 3.34 indicates that the temperature is well above the suggested temperature of 45°C discussed in Part I[1].

They range from around 50°C to a maximum of about 68°C. The higher temperatures increase the series resistance of the solar cells and thus reduce the efficiency. Further, the standard reference condition operating at a temperature of 25°C under the solar irradiance of 100 mWh/cm^2 gives a disadvantage in the calculation of the efficiency of the water pumping system.

RELIABILITY OF THE SYSTEM

The microprocessor-controlled water pumping system was operated from July 1982 to September 1983 with intermittent breaks for modifications and improvements. There was no major breakdown and the only problem encountered was the collection of dirt in the pump which reduced the efficiency of the pump tremendously. Constant servicing of the pump was necessary.

CONCLUSION

From the data obtained and discussed in the section "Efficiency per day," it can be seen that the one-axis microprocessor-controlled water pumping system with battery back-up is operated to a significant extent by solar energy. This is made possible because tracking results in a more consistent amount of solar irradiance falling on the solar modules.

The AC pump is operated continuously by the microprocessor control sub-system which consistently monitors the operating conditions of both the solar array and the battery back-up. The microprocessor also provides efficient energy management in terms of the availability of the solar energy at any one time and the state of the battery.

It can also be seen that concentration using mirrors increases the amount of solar irradiance falling on the solar modules thus enabling a reduction in the number of photovoltaic modules used.

SUGGESTIONS FOR FURTHER WORK

A further improvement could be made by having a two-axis tracking system to eleminate the possible loss of performance due to shadowing effect in the early and late hours of the day. A two-axis tracking system would enable better reception of the sun's rays onto the mirrors.

To reduce the adverse effect of temperature, passive cooling fins could be incorporated to

the base of the photovoltaic modules to optimise the efficiency at about the optimum operating temperature of 45°C.

REFERENCES

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2. R. Privdo-CNES (1977), *Water Pumping System using Solar Power from Photovoltaic Source, Proceedings of the International Conference,* Luxemburg, 27-30 Sept 1977.