Pumping Water with Solar Cells*

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ABSTRACT

A short overview of the different types of photovoltaic solar pumps is presented, as well as a rule of thumb to calculate their output and an example of the commercial options for a practical pumping problem.

INTRODUCTION

In a preceding article on solar pumps† the conclusion was drawn that thermal solar pumps with concentrating collectors did hold a good promise for the future (because of their high efficiency) and that it would be a hard job to make the other two available types economical: photovoltaic solar pumps and thermal solar pumps with flat plate collectors.

Since 1980, not much has been heard of the concentrating type of solar pump. Philips Laboratories even completely stopped the development of its very promising solar pump, based on a Sterling engine, powering a linear generator. Solar pumps with flat plate collectors on the other hand probably will remain uneconomical for decades to come, due to their inherent low Carnot efficiency. Water pumping with solar cells is not economical yet, as we will see, but the fact that more and more firms appear on the market with solar pumps and also the promise they hold for the future justify a closer look at their configurations, characteristics and economics.

In this article we will not discuss solar cells as such, because they are described in many articles and textbooks [1-3]. Recently an excellent overview was published in a special issue on solar photovoltaics of the ISES publication "SUNWORLD" [4]. A list of installed photovoltaic solar pumps could not be traced by the authors. Most manufacturers seem to have one or more prototypes, both near the factory and on locations in countries where their governments happen to have aid programs. For example [4], French groups have set up fifteen solar pumps in Senegal, Mali, Nigeria, Upper Volta, Rwanda, Cameroon, Saudi-Arabia, Abu Dhabi and Corsica. The largest solar pump up to now has been built in the U.S.A. – a 25 kW pump in Nebraska.

SYSTEMS CONFIGURATIONS

Basically in each solar pump the electricity produced by one or more solar panels (each consisting of a number of solar cells) is used to run an electric motor that drives a pump. Two main

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groups of systems exist: those *with* and those *without* storage batteries. Pumps with battery storage have the advantage that even at low light intensities, in the early morning or during very cloudy wheather, some energy is stored for pumping. In some situations it can also be advantageous to possess charged batteries to use for other applications. The disadvantages are the high costs of the batteries, their relatively short lifetime, the need for maintenance (except with more expensive maintenance-free batteries, e.g. lead-calcium batteries), the extra efficiency losses of the system as a whole, and the need to build a protecting housing for the batteries.

Pumps without battery storage have the advantage of a simple and therefore reliable systems layout, requiring little maintenance. If storage is required a water tank is provided, although its cost and maintenance obviously have to be balanced against those of the battery option. A disadvantage could be that the solar panels can only be used for water pumping. A separate installation for other applications is often simpler in operation than one large installation. In each particular situation a decision has to be made whether or not batteries will be used. It seems clear, however, that in pure pumping situations, pumps without batteries are more attractive.

Looking into detail, more variations in types of solar pumps can be found: one can use submersible AC motors or DC motors at ground level, the latter requiring a mechanical or hydraulic transmission to the pump, the former requiring a DC/AC converter. Also the types of pump can differ: most often centrifugal pumps are used, but piston pumps are found sometimes. An overview of five different systems configurations is given in Fig. 1. Not shown in this figure are the controls to operate the pump satisfactorily. For example, if the well runs dry or the reservoir is full the pump must be switched off automatically.

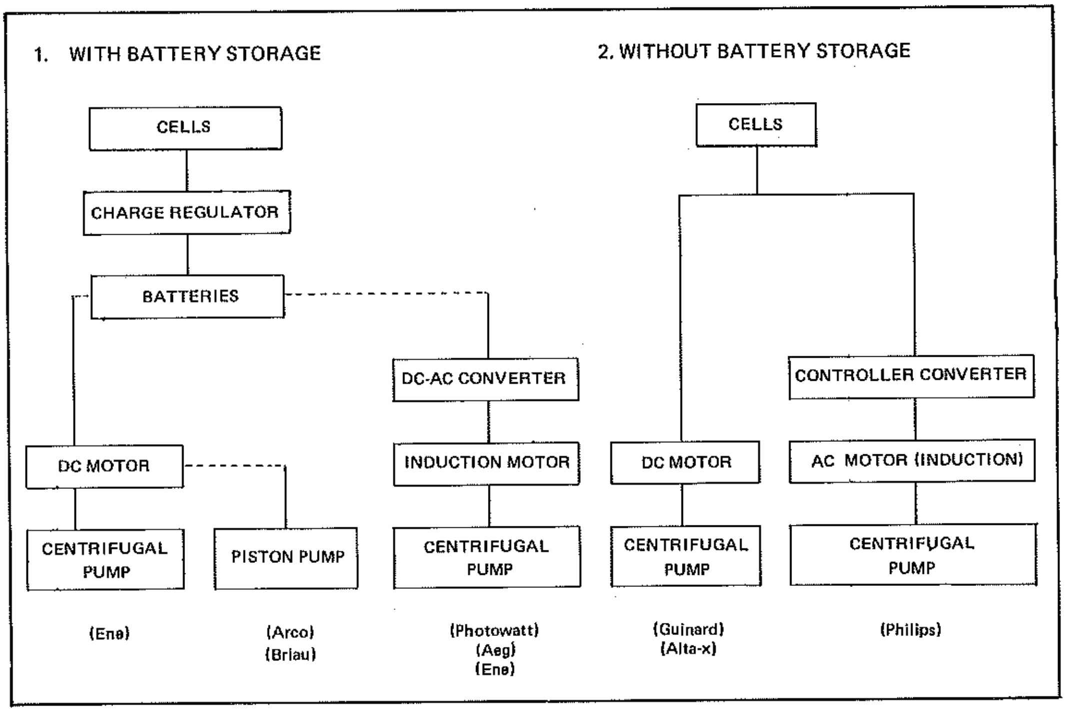

Fig. 1 Possible photovoltaic pumping system (based on manufacturer's information).

CALCULATION OF THE WATER OUTPUT

To estimate the amount of electrical energy that has to be delivered by a solar panel to pump 1 m^3 of water over a head, H, the following formula can be used:

$$\frac{E}{Q} = \frac{\rho g H}{3{,}600\,\eta} = 2.725\,\frac{H}{\eta} \quad (\mathrm{Wh/m^3})$$

in which: E: electrical energy (Wh)
Q: quantity of water (m^3)
ρ: density of water (1000 kg/m^3)
g: gravity constant (9.8 m/s^2)
H: total head (m)
η: total efficiency of the system (motor and pump, eventually battery and converter as well)

For example: in a system in which the solar panel is directly coupled to a motor that drives a pump, with efficiencies of 75% and 50% respectively, the formula becomes:

$$\frac{E}{Q} = 2.725\,\frac{H}{0.75 \times 0.5} = 7.3 \times H \quad (\mathrm{Wh/m^3})$$

In other words, when this installation operates at a total head of 10 m^3 then each m^3 of water requires 73 Wh of electrical energy.

Now we want to calculate the capacity of the solar panel that is required to pump a given amount per day or per year. It is customary to express the peak power of a solar cell or a solar panel in the number of peak watts it can produce at maximum in full sunshine, i.e. 1,000 W/m^2.

The electrical energy output of the panel depends on the solar radiation received in a given location per day or per year: E_{loc} In most cases this quantity is expressed in joules/m^2 per period, but in our case we will use the unit kWh/m^2 day. It must be remembered that these kilowatt hours are *thermal* kilowatt hours, falling upon a horizontal measuring surface.

Knowing that full sunshine is equal to 1 kW/m^2, we can make a useful conversion [5]: if a given location receives for example 6 kWh/m^2 per day, this is equivalent to saying that it receives the full sunshine of 1 kW/m^2 during 6 hours per day. This in turn is the same as saying that it receives 6 kWh/kW per day. Since the efficiency of a solar cell hardly changes at lower radiation intensities, we can conclude that the same ratio also applies at the electrical side of the solar cell: each peak watt installed can produce 6 Wh per day. So the following expression is valid:

$$E_{loc}\,(\mathrm{kWh/m^2\ day}) = E_{loc} \quad (\mathrm{Wh/Wp\ day})$$

This is the maximum amount of energy produced by a solar panel in a horizontal position at that location.

Finally we can calculate the amount of water that will be pumped over a head of one meter by a solar cell of one peak watt capacity in a location receiving E_{loc} kWh/m^2 day. We will call this the specific output, Q_{spec} :

$$Q_{spec} = \frac{\eta}{2.725} E_{loc} \text{ (m}^3\text{/m day Wp)}$$

Knowing that the system efficiency will be in the order of 20% to 30% and that E_{loc} in most tropical areas will be between 5 and 7 kWh/m^2 day, the value for Q_{spec} will lay between 0.35 and 0.75 m^3/m day Wp. A reasonable value for "rule of thumb" calculations thus emerges:

$$Q_{spec} = 0.5 \text{ m}^3\text{/m day Wp}$$

As 0.5 m^3/m day represents a continuous power (over 24 hours) of 0.057 W, the rule of thumb is equivalent to saying that each peak watt of solar panel delivers a net continuous power of 0.057 W to lift water, or each watt of continuous pumping power needs 17.5 Wp of solar cells. Obviously, this "rule" should be handled with care: as soon as more information about the solar pump and the solar regime is available, a better calculation has to be made, if possible with angle corrections for titled panels, start/stop losses and extra losses at high heads.

COMMERCIAL OPTIONS FOR A PRACTICAL PUMPING PROBLEM

A community in Barahona (the Dominican Republic) recently expressed the wish to install a solar pumping system for a daily water supply of 20 m^3/day from a depth of 60 to 70 m. As the well and the pump already existed, the solar system should be able to drive the existing induction motor. As a first step, quotations were asked from different manufacturers with the request that they specify their systems layout for this situation. Table 1 gives an overview of the different solutions as proposed by the manufacturers. The prices date from early 1980.

The table shows a remarkable difference in total installation costs. Possible explanations are:

- the large range of peak-watt prices of the solar cells;
- the differences between the technical options;
- the differences in power rating chosen by the manufacturers.

A remarkable coherence on the other hand can be found in the total costs per peak watt (except ARCO and Solar Power): about US$35/Wp.

ECONOMICS

The photovoltaic pumps as described in the previous section require investments of the order of US$35/Wp. With an annuity of 15% (loan costs, plus operation and maintenance) the annual costs become US$5.25/Wp. This is based on a lifetime of 30 years. This peak watt can pump roughly 0.5 m^3/day as we have seen in in the calculation of the water output; so with 200 effective pumping days (two crops of 100 days each) this means 100 m^3/m year. The resulting water costs are:

current costs of water: US$0.05 per m^3/m

In the future the cost of solar cells is expected to decrease. At the moment roughly 60% to 80% of the total cost of a photovoltaic solar pump can be attributed to the cost of the cells. If the cell costs come down by a factor of (say) ten, then the future costs of solar pumps will probably be somewhere between US$5 and US$10/Wp. Under identical conditions as the calculation above the future water costs will be:

Table 1: Commercially available solar pumping systems

		ARCO SOLAR	GUINARD (1)	GUINARD (2)	ENE (1)	ENE (2)	AEG	SOLAR POWER	OCLI (1)	OCLI (2)	PHOTO WATT
SOLAR CELLS type		ASI 16 – 2000/7	ALTA X 2600/60 fpa 36 V	ALTA X 1800/60 fpa 36 V	PSP 8700-12	PSP 8700-12	MQ 40/0	G12-3039-12	60-3039-12	60-3039-12	41 F51 GC
total power	W	1150	2560	1760	3000-4000	3000-4000	3967	1740	(2200)	(4400)	2288
power per module	W	33			17	17	11.6		(20)	(20)	26
total voltage	V	90							12	12	
voltage per module	V	12			15	15	15				16
daily energy production	Wh/day								8200	13600	
number of modules		35	128	88			342	64	110	220	88
PUMP motor: voltage	V	90	120	60			Submersible pump type CORA A 219				not specified
power	W	736	1590	1110							
type		DC	DC	DC	AC	DC					
pump: capacity			6			17 m^3/h					
type		Jensen 50 W	Centrifugal	ALTA	Centrifugal						
head	m	60	60	60	60	60					
min. daily capacity	m^3/day		25	20	20	20					
BATTERIES total, capacity	Ah	735			not specified	not specified	250	5700			2000
number of modules		7					1				32
total voltage	V	84					110	24	12	12	32
voltage/battery	V	12					110		2	2	2
type		lead-calcium (Delco)					lead acid		lcpsa 21	lcpsa 21	VS-260 Hydro
CONTROLS		ARCO	level contactor	level contactor	level contactors voltage regulator	level contactors	charge regulator 25A	voltage regulator	voltage regulator	voltage regulator	charge regulator
INVERTER	DCV/ ACV	–			48 V/DC 220 V/AC		110 DC/220AC 3kW				
SUPPORT STRUCTURES		5 with 8 modules			–	–	19 with 18 modules	–	8 with ± 14 modules	16 with ± 14 modules	
COSTS cells	$	11550							48730	94160	37400
motorpump	$	3550							–	–	8750
batteries	$	770							13662	27324	9075
support structures	$	845							6992	13984	
controls + accessories	$	925							4144	8288	
TOTAL	$	17935	86970	63255	100000	90000	153067	34766	73528	143756	69250
installation	$	295	2800	1867							
COST/Wp	S/Wp	15.6	34.0	35.9	33.3	30	38.6	(20.)	(33.4)	(32.7)	30.3
DELIVERY		60 days	6 weeks	6 weeks			12 months	16-20 weeks	–	–	4 months
GUARANTEE		cells: 5 years pump: 2 years									

future water costs: US\$0.0075 to US\$0.05 per m^3/m

With an acceptable cost of irrigation water, based on the average farmer income of US\$0.01 to US\$0.02 per m^3, these costs indicate again that photovoltaic solar pumps for these farmers may only be competetive in the case of low head pumping. If higher water costs are acceptable, the solar pump also becomes attractive for deep-well pumping. With the current costs, however, we do not expect to see a widespread use of solar pumps in this decade.

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