PHOTOVOLTAIC-POWERED WATER PUMPING SYSTEM

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*Abstract– **Photovoltaic (PV) is a well-established, proven technology with a substantial international industry network. And photovoltaic is increasingly more cost-effective compared with either extending the electrical grid or using generators in remote locations. Water pumping is one of the simplest and most appropriate uses for photovoltaic. From crop irrigation to domestic uses, photovoltaic-powered pumping systems meet a broad range of water needs. Most of these systems have the added advantage of storing water for use when the sun is not shining, eliminating the need for batteries, enhancing simplicity and reducing overall system costs. However, the high initial investment costs are still the main obstacle to application and dissemination of these systems. The aim of this paper is to explain the basic principles of photovoltaic-powered water pumping system, including the simple design of directly coupled photovoltaic-pump system***

Keywords– photovoltaic, water pumping, basic principles, design, main obstacle

1. Introduction

In many developing countries, the inadequate supply of drinking and irrigation water is a severe problem. In rural areas with no access to electrical grid, the villagers have to rely on hand pumps, diesel-driven pumps, or even lift directly the water without using the pumps. As a rule, hand-operated pumps are the least-cost option for low consumption rates and low pumping heads. If hand pumps can not satisfy the demand, diesel-driven pumps are commonly used for drinking and irrigation water supply.

However, there are some significant drawbacks by using diesel to power generators, including : (1) Fuel has to be transported to the generator’s location, which may quite a distance over some challenging roads and landscape ; (2) Their noise and fumes can disturb livestock ; (3) Fuel costs add up, and spills can contaminate the land ; and (4) Generators require a significant amount of maintenance and, like all mechanical systems, they break down and need replacement parts that are not always available.

Photovoltaic-powered water pumping systems offer numerous advantages over water supply systems utilizing conventional power, among others : (1) Photovoltaic-powered water pumping systems may be the only practical water supply solution in many regions where the logistics make it too expensive or even impossible to supply diesel generators with the required fuel ; (2) Photovoltaic-powered water pumping systems run automatically, require little maintenance and few repairs ; (3) In areas where photovoltaic-powered water pumps have entered into competition with diesel-driven pumps, their comparatively high initial cost is offset by the achieved savings on fuel and reduced maintenance expenditures ; and (4) The use of solar energy eliminates emissions and fuel spills.

2. PV-Powered Water Pumping System

The most common example of PV-powered water pumping systems consist of just a PV array connected directly to the dc motor running a pump/dc pump (Fig. 1).

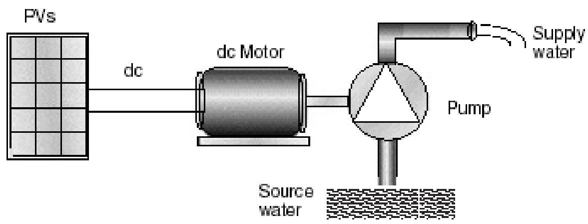


Figure 1. Conceptual diagram of a PV-powered water pumping system

When the sun shines, water is pumped. Water that has been pumped may be used at that time or stored in a tank for use later, so the disadvantages of battery storage can be avoided. The result can be a system that combines simplicity, low cost, and reliability. Matching photovoltaics and pumps in such directly coupled systems (without battery storage), along with predicting their daily performance, is actually a quite challenging task. More complex systems may include a battery and inverter to run a conventional ac pump, along with a *Linear Current Booster* (LCB) to improve performance in low-light conditions.

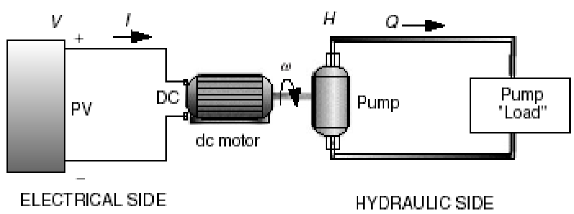


Figure 2. The electrical characteristics of the PV– motor combination need to be matched to the hydraulic characteristics of the pump and its load.

As shown in Fig. 2, a simple, directly coupled PV–pump system has (a) an electrical side in which PVs create a voltage V that drives current I through wires to a motor load and (b) a hydraulic side in which a pump creates a pressure H (for *head*) that drives water at some flow rate Q through pipes to some destination. The figure shows that the hydraulic side is a *closed* loop with water circulating back to the pump, but it may also be an *open* system in which water is raised from one level to the next and then released. On the electrical side of the system, the voltage and current delivered at any instant are determined by the intersection of the PV I - V curve and the motor I - V curve. In the hydraulic system, H is analogous to voltage while Q is analogous to current; as we shall see, the role of H - Q curves in determining a hydraulic operating point is exactly analogous to the role of I - V curves that determine the electrical operating point.

3. Photovoltaic *I – V* Curve

Photovoltaic (PV) is the technical name for a technology in which radiant energy from the sun is converted to direct current (dc) electrical energy. PV cells are connected electrically to form PV modules, which are the building blocks of PV systems. The modules (sometimes called ”panels”) can be connected into PV arrays for powering a wide variety of electrical equipment (Fig. 3).

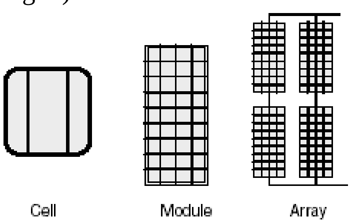


Figure 3. Photovoltaic cells, modules, and arrays

There is widespread international agreement that the performance of PV cells and modules should be measured under a set of standard test conditions (STC). These specify that the temperature of the cell or module should be 25°C and that solar radiation incident on the cell should have a total power density of 1000 watts per square metre (W/m^2) with a spectral power distribution known as Air Mass 1.5 (AM 1.5).

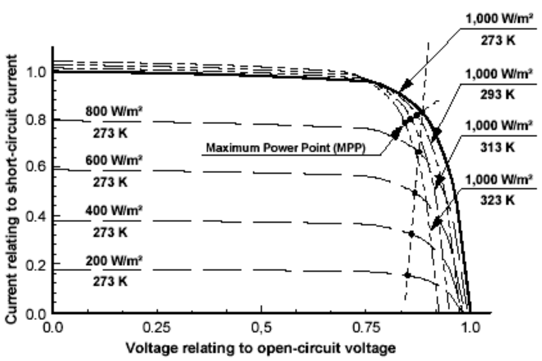


Figure 4. Influence of insolation (*incident solar radiation*) and temperature on the characteristic I - V curve

Fig. 4 shows the typical shape of PV I - V curve for various operating modes.

I_{sc} increases slightly with temperature, but this is so small and normally ignored. However, a more significant effect is the temperature dependence of voltage which decreases with increasing temperature. I_{sc} is directly proportional to the insolation, so that if insolation halves so does I_{sc} . The voltage variation is very small and usually ignored.

4. DC Motor *I – V* Curve

DC motors are often used in PV water pumping systems. Most are permanent magnet dc motors which can be modeled as shown in Fig. 5.

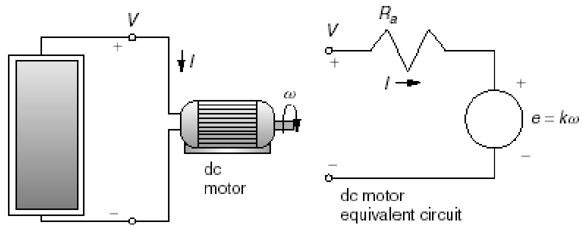


Figure 5. Electrical model of a permanent magnet dc motor

Notice that as the motor spins, it develops a *back electromotive force* (e), which is a voltage proportional to the speed of the motor (ω) that opposes the voltage supplied by the photovoltaic. From the equivalent circuit, the voltage–current relationship for the dc motor is simply

$$V = IR_a + k\omega \qquad (1)$$

where back emf e = $k\omega$ and R_a is the armature resistance.

Based on (1), the electrical characteristic curve of a dc motor will appear to be something like the one shown in Fig. 6.

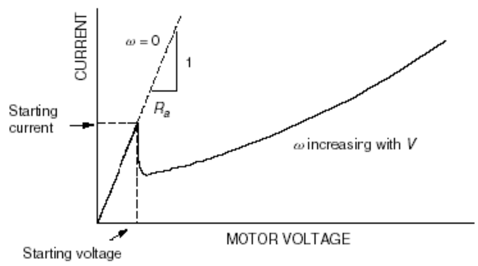


Figure 6. Electrical characteristics of a permanent-magnet dc motor

Notice that at start-up, while **ω = 0,** the current rises rapidly with increasing voltage until current is sufficient to create enough starting torque to break the motor loose from static friction. Once the motor starts to spin, back emf drops the current and thereafter I rises more slowly with increasing voltage.

5. Combination of DC Motor *I – V* Curve and Photovoltaic *I – V* Curves

A dc motor I –V curve is superimposed on a set of photovoltaic I – V curves in Fig. 7. The mismatch of operating points with the ideal MPP is apparent. Notice in this somewhat exaggerated example that the motor doesn't have enough current to overcome static friction until insolation reaches at least 400 W/m^2. Once it starts spinning, however, it only needs about 200 W/m^2 to keep running.

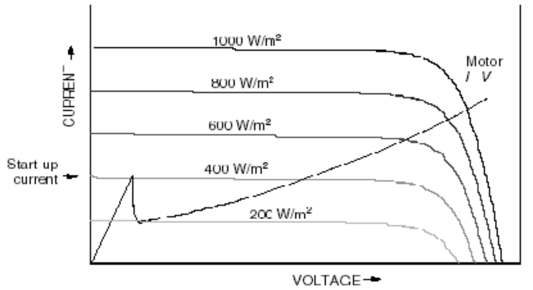


Figure 7. DC motor *I - V* curve on photovoltaic *I - V* curves for varying insolation.
In this example (somewhat exaggerated), the motor won't start spinning until insolation
reaches 400 W/m^2, but after that it only needs 200 W/m^2 to keep running

There is a device, called a LCB, that is designed to help overcome this loss of potentially usable insolation when current delivered to the motor is insufficient to overcome friction (Fig. 8).

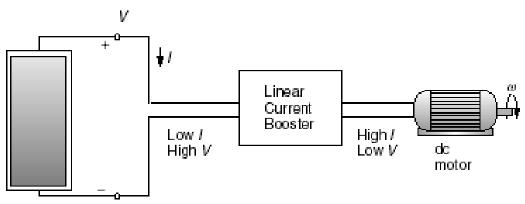


Figure 8. A linear current booster (LCB) increases current to help start or keep the motor running in low sunlight

What an LCB does is to shift this relationship around. By converting low-current, high-voltage power into high-current, low-voltage power, they can get the motor started earlier in the morning. The lower voltage, however, means that the motor will spin at a slower rate, but at least it is working. In addition, the motor with an LCB will not stall as early in the afternoon, though it will slow down. So there are additional gains.

6. Hydraulic System Curves

Figure 9*a* shows an open system in which water is to be raised from one level to the next.

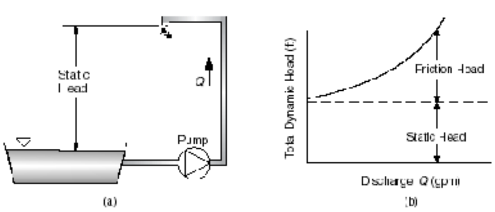


Figure 9. An "open" system and the resulting "system curve" showing the static and friction head components

The vertical distance between the lower water surface and the elevation of the discharge point is referred to as the *static head* (or gravity head), and in the United States it is usually given in "feet of water." Head can also be measured in units of pressure, such as pounds per square inch (psi) or pascals (1 psi = 6895 Pa). To convert between these two equivalent approaches to units, just picture the pressure that a cube of water exerts on its base. For example, the pressure that a 1-ft cube weighing 62.4 lb would exert on its 144 square inches of base would be

$$1 \text{ ft of head} = 62.4 \text{ lb}/144 \text{ in.}^2 = 0.433 \text{ psi} \qquad (2)$$

Conversely, 1 psi = 2.31 ft of water. Typical city water pressure is about 60 psi which corresponds to a column of water roughly 140 ft high.

If the pump is capable of supplying only enough pressure to the column of water to overcome the static head, the water would rise in the pipe and just make it to the discharge point and then stop. In order to create flow, the pump must provide an extra amount of head to overcome friction losses in the piping system. These friction losses rise roughly as the square of the flow velocity (as is suggested in Fig. 9); they depend on roughness of the inside of the pipe and on the numbers of bends and valves in the system. For example, the pressure drop per 100 ft of plastic water pipe for various flow rates and diameters is presented in Table 1. In keeping with U.S. tradition, flow rates are given in gallons per minute (gpm), pipe diameters in inches, and head in feet of water.

Table 2 gives pressure drop of various plumbing fittings expressed as equivalent lengths of pipe.

Table 1. Pressure Loss Due to Friction in Plastic Pipe, Feet of Water per 100 ft of Tube for Various Nominal Tube Diameters

gpm	0.5 in.	0.75 in.	1 in.	1.5 in.	2 in.	3 in.
1	1.4	0.4	0.1	0.0	0.0	0.0
2	4.8	1.2	0.4	0.0	0.0	0.0
3	10.0	2.5	0.8	0.1	0.0	0.0
4	17.1	4.2	1.3	0.2	0.0	0.0
5	25.8	6.3	1.9	0.2	0.0	0.0
6	36.3	8.8	2.7	0.3	0.1	0.0
8	63.7	15.2	4.6	0.6	0.2	0.0
10	97.5	26.0	6.9	0.8	0.3	0.0
15		49.7	14.6	1.7	0.5	0.0
20		86.9	25.1	2.9	0.9	0.1

Table 2. Friction Loss in Valves and Elbows Expressed as Equivalent Lengths of Tube *)

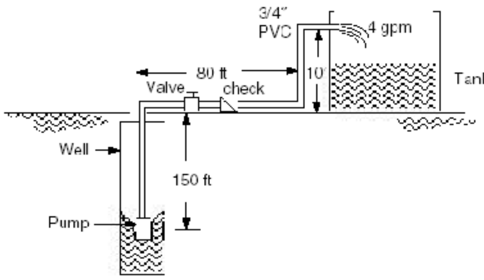
Fitting	0.5 in.	0.75 in.	1 in.	1.5 in.	2 in.	3 in.
90-degree ell	1.5	2.0	2.7	4.3	5.5	8.0
45-degree ell	0.8	1.0	1.3	2.0	2.5	3.8
Long sweep ell	1.0	1.4	1.7	2.7	3.5	5.2
Close return bend	3.6	5.0	6.0	10.0	13.0	18.0
Tee—straight run	1.0	2.0	2.0	3.0	4.0	
Tee—side inlet or outlet	3.3	4.5	5.7	9.0	12.0	17.0
Globe valve, open	17.0	22.0	27.0	43.0	55.0	82.0
Gate valve, open	0.4	0.5	0.6	1.0	1.2	1.7
Check valve, swing	4.0	5.0	7.0	11.0	13.0	20.0

*) Unit are feet of pipe for various nominal pipe diameters.

For example, each **3/4" 90^o** elbow in a plumbing run adds to the pressure drop the same amount as would 2.0 ft of straight pipe. So we can add up all the bends and

valves in a pipe run and find what equivalent length of straight pipe would have the same pressure drop.
The sum of the friction head and the static head is known as the *total dynamic head (H)*.

Example 1. *Total Dynamic Head for a Well.* What pumping head would be required to deliver 4 gpm from a depth of 150 ft. The well is 80 ft from the storage tank, and the delivery pipe rises another 10 ft. The piping is 3/4-in. diameter plastic, and there are three **90°** elbows, one swing-type check valve, and one gate valve in the line.



Solution :
The total length of pipe is 150 + 80 + 10 = 240 ft. From Table 2, the three ells add the equivalent of 3 × 2.0 = 6 ft of pipe; the check valve adds the equivalent of 5.0 ft of pipe; the gate valve (assuming it is totally open) adds the equivalent of 0.5 ft of pipe. The total equivalent length of pipe is therefore 240 + 6 + 5 + 0.5 = 251.5 ft.
From Table 1, 100 ft of 3/4-in. pipe at 4 gpm has a pressure drop of **4.2 feet/100'** of tube. Our friction-head requirement is therefore 4.2 × 251.5/100 = 10.5 ft of water.

The water must be lifted 150 + 10 = 160 ft (static head). Total head requirement is the sum of static and friction heads, or 160 + 10.5 = 170.5 ft of water pressure.

If the process followed in Example 1 is repeated for varying flow rates, a plot of total dynamic head *H* (static plus friction) versus flow rate, called the *hydraulic system curve*, can be derived. The hydraulic system curve for Example 1 is given in Fig. 10.

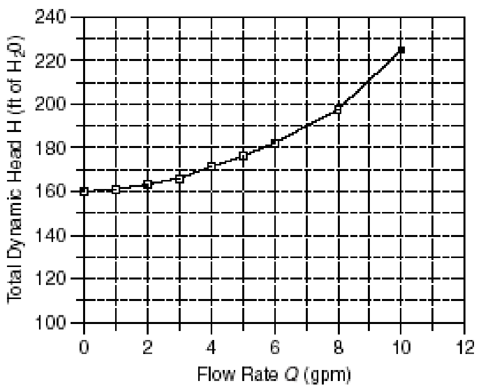


Figure 10. The hydraulic system curve for Example 1

6.1. Hydraulic Pump Curves

The hydraulic system curve tells us the amount of head that the pump must provide to supply a given flow rate *Q*. To determine the actual flow that a given pump will provide, we need to know something about the characteristics of the pump that will be used. Pumps suitable for PV-powered systems generally fall into one of two categories: *centrifugal* and *positive displacement* pumps. A brief comparison of the two types of pumps is presented in Table 3.

Table 3. A Comparison Between Centrifugal and Positive-Displacement Pumps

Centrifugal	Positive Displacement
High-speed impellers	Volumetric movement
Large flow rates	Lower flow rates
Loss of flow with higher heads	Flow rate less affected by head
Low irradiance reduces ability to achieve head	Low irradiance has little effect on head
Potential grit abrasion	Unaffected by grit

The graphical relationship between head and flow is called the *hydraulic pump curve*, two examples of which are shown in Fig. 11.

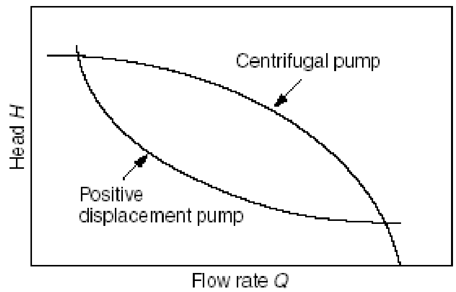


Figure 11. The pump curves for positive displacement pumps and centrifugal pumps have quite different shapes

6.2. Electrical *I –V* Curves and Hydraulic *Q – H* Curves

Electrical *I –V* curves and hydraulic *Q – H* curves share many similar features. For example, recall that the electrical power delivered by a PV is the product of *I* times *V* and the maximum power point is at the knee of the *I –V* curve. For the hydraulic side, the power delivered by the pump to the fluid is given by

$$P = \rho HQ \qquad (3)$$

Where ρ is fluid density. In American units,

P(watts)= 8.34 lb/gal × H(ft) x Q(gal/min) x (1min/60s) x1.356 W/(ft-lb/s)

$$P \text{ (watts)} = 0.1885 \times H \text{ (ft)} \times Q \text{ (gpm)} \qquad (4)$$

In SI units,

$$P \text{ (watts)} = 9.81 \times H \text{ (m)} \times Q \text{ (L/s)} \qquad (5)$$

To complicated matters, for directly coupled PV-to-pump systems the voltage delivered to the pump will vary as insolation changes. In turn, the pump curve will shift as the pump voltage changes, which means that the *pump curves vary with insolation*. Many manufacturers of pumps intended for solar applications will supply pump curves for voltages corresponding to nominal 12-V module voltages. Figure 12 shows an example of a set of pump curves for the Jacuzzi SJ1C11 dc centrifugal pump, which is intended for use with photovoltaics.

Individual curves have been given for 15-V, 30-V, 45-V, and 60-V inputs. A typical "12-V" PV module operating near the knee of its *I –V* curve delivers about 15 V, so these pump voltages are meant to correspond to 1, 2, 3, and 4, typical "12-V" PV modules wired in series. Also shown are indications of the efficiency of the pump as a function of flow rate and head. Notice that peak efficiency (about 44%) occurs along the knee of the pump curves, which is exactly analogous to the case for a PV *I –V* curve.

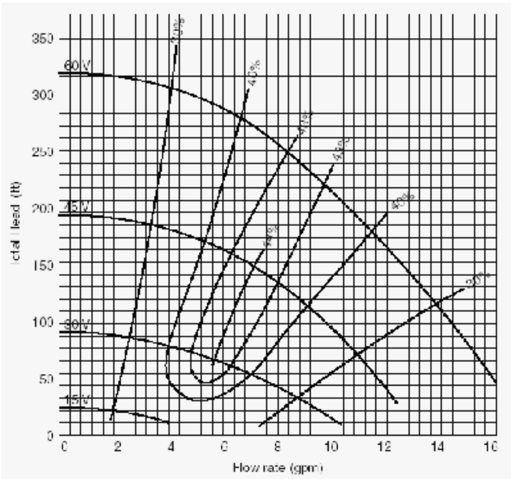


Figure 12. Pump curves for the Jacuzzi SJ1C11 pump showing pump efficiency for various input voltages. Pump efficiencies are also shown, with the peak along the knee of the curves.

6.3. Combination of Hydraulic System Curve and Pump Curve

Just as an *I – V* curve for a PV load is superimposed onto the *I – V* curves for the PV, so is the *Q – H* system curve superimposed onto the *Q – H* pump curve to determine the hydraulic operating point. For example, superimposing the system curve of Fig. 10 onto the pump curves in Fig. 12 gives us Fig. 13.

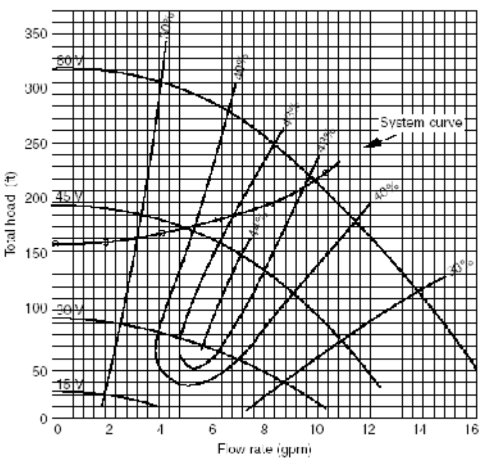


Figure 13. The system curve for the example, superimposed onto the pump curves for the Jacuzzi SJ1C11. No flow occurs until pump voltage exceeds about 36 V

A glance at the figure tells us a lot. For example, this pump will not deliver any water unless the voltage applied to the pump is at least about 36 V. At 45 V, about 5 gpm would be pumped, while at 60 V the flow would be nearly 10 gpm.

7. A Simple Directly Coupled PV – Pump Design Approach

The easiest approach to estimating average performance of directly coupled PV–pump systems is based on the familiar concept of "peak sun hours." That is, insolation expressed as kWh/m^2-day is treated as if it is numerically equivalent to "peak hours" at 1-sun. This lets us base the analysis of PV performance on its 1-sun rated voltage, current, and power. And it lets us assume that the flow rates on a pump curve are deliverable for the number of peak sun hours per day.

This procedure assumes that a linear current booster (LCB) is included in the system to help start the pump in the morning and keep it running under conditions of low insolation. Starting a pump requires high current at low voltage, but under low-light conditions the maximum power point on the PV *I –V* curve has just the opposite characteristic. An LCB is the clever dc-to-dc converter that enables the PVs to operate at their highest efficiency in low light—that is, at low current and relatively high voltage—while providing the pump with what it needs to start or keep running—that is, high current and low voltage.

Usually manufacturers provide a nominal voltage and power for their pump curves. From pump power (W) and 1-sun PV power (W/module) we can determine the needed number of photovoltaic modules. If pump voltage and efficiency are given, as is the case with the pump curves in Fig. 13, pump power can be determined using (4).

$$P_{in}\text{ (W) to pump} = \frac{\text{Power to fluid}}{\text{Pump efficiency}} = \frac{0.1885 \times H\text{ (ft)} \times Q\text{ (gpm)}}{\eta_p} \quad (6)$$

The sizing procedure is based on the following simple steps (Thomas, 1987) :

1. Determine the water production goal (gallons/day) in the design month (highest water need and lowest insolation).
2. Use design-month insolation (hours @ 1-sun) as the hours of pumping to find the pumping rate :

$$Q\text{(gpm)} = \frac{\text{Daily demand (gal/day)}}{\text{Insolation (h/day @ 1-sun)} \times 60 \text{ min/h}} \quad (7)$$

3. Find the total dynamic head *H* @ *Q* (gpm). As a default, the friction head may be assumed to be 5% of the static head.
4. Find a pump capable of delivering the desired head *H* and flow *Q*. Note its input power P_{in} and nominal voltage. Pump input power can also be estimated from (6) along with estimated pump efficiency η_p (defaults : suction pumps 25 % ; submersible pumps 35 %).
5. The number of PV modules in series (assuming that modules will operate at about 15 V) is an integer number based on

$$\text{Module in series} = \frac{\text{Pump voltage (V)}}{15\ \text{V / module}} \quad (8)$$

6. The number of PV strings in parallel will be an integer number based on

$$\#\,\text{strings} = \frac{\text{Pump input power } P_{in}\ \text{(W)}}{\#\ \text{modules in series} \times 15\ \text{V / module} \times I_R(\text{A}) \times \text{de-rating}} \quad (9)$$

Where I_R is the PV rated current at STC. The de-rating factor takes into account dirt and temperature effects. A reasonable default value is 0.80.

7. After having sized the system, the water pumped can be estimated by rearranging (6) and adding in the de-rating factor:

$$Q(\text{gal/day}) = 15\ \text{V/module} \times I_R(\text{A}) \times (\#\ \text{modules}) \times (\text{Peak h/day}) \times 60\ \text{min/h} \times \text{de-rating} \times \eta_p / [0.1885 \times H\ (\text{ft})] \quad (10)$$

Example 2. Sizing an Array for a 150-ft Well. Suppose that the goal is to pump at least 1200 gallons per day from the 150-ft well described in Example 1 using the Jacuzzi SJ1C11 pump. If December is the worst month in that location, with an insolation of 4.9 kWh/m^2-day, find :

a) The size of PV array based on the modules with rated current 5.9 A.

b) The water production in January with an insolation of 5.1 kWh/ m^2-day according to the size of PV array above.

Solution :

(a) The worst month is December with an insolation of 4.9 kWh/m^2-day. From (7) :

$$Q = \frac{1200\ \text{gal/day}}{4.9\ (\text{h/day @ 1-sun}) \times 60\ \text{min/h}} = 4.1\ \text{gpm}$$

From Fig. 13, at 4.1 gpm the total dynamic head is about 170 ft and the pump efficiency is about 34 %. From (6), the estimated pump input power is

$$P_{in}(\text{W}) = \frac{0.1885 \times H\ (\text{ft}) \times Q\ (\text{gpm})}{\text{Pump efficiency}} = \frac{0.1885 \times 170 \times 4.1}{0.34} = 386\ \text{W}$$

From Fig. 13, at 4.1 gpm and 170 ft of head, the pump voltage is a little under 45 V, which means that at 15 V per module, three modules in series should be sufficient.

Using (9), we can decide upon the number of parallel strings of modules :

$$\#\ \text{strings} = \frac{386\ \text{W}}{3\ \text{modules string} \times 15\ \text{V/module} \times 5.9\ \text{A} \times 0.80} = 1.8$$

so choose two parallel strings.

b) From (10), estimated delivery in January with two strings of three modules would be

$$Q = \frac{15\ \text{V} \times 5.9\ \text{A} \times 6\ \text{modules} \times 5.1\ \text{h/day} \times 60\ \text{min/h} \times 0.80 \times 0.34}{0.1885 \times 170\ \text{ft}} = 1379\ \text{gal/day}$$

A system diagram is shown in Fig. 14.

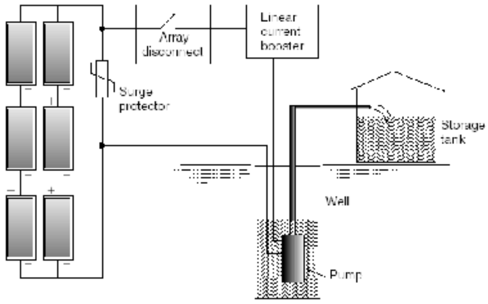


Figure 14. PV water pumping system for Example 2

8. CONCLUSION

One of the most economically viable photovoltaic applications nowadays is for water pumping in remote areas. For an off-grid home, a simple photovoltaic system can raise water from a well or spring and store it in a tank, or it can circulate water through a solar water heating system. Water for irrigation, cattle watering, or village water supply—especially in developing countries—can be critically important, and the value of a photovoltaic-powered water pumping system in these circumstances can far exceed its costs.

Photovoltaic--powered water pumping systems are technically fit for use, beneficial for the environment and are able to yield cost advantages over diesel-driven pumps, as long as certain site-specific conditions apply. However, the high initial investments costs are still the main obstacle to application and dissemination of photovoltaic pumps. Therefore it is necessary to compensate for the high investment costs by providing loans on favourable terms via development banks or through other suitable financing models.

Photovoltaic power is cost-competitive with traditional energy sources for small, remote applications, if the total system design and utilization timing is carefully considered and organized to use the solar energy as efficiently as possible. In the future, when the prices of fossil fuels rise and the economic advantages of mass production reduce the peak watt cost of the photovoltaic cell, photovoltaic power will become more cost-competitive and more common.

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