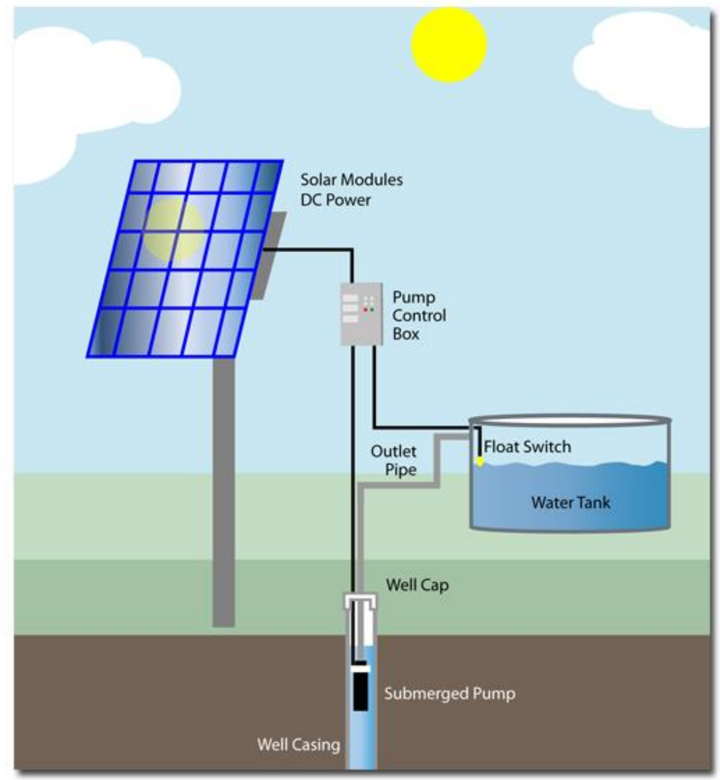
PV Systems IV

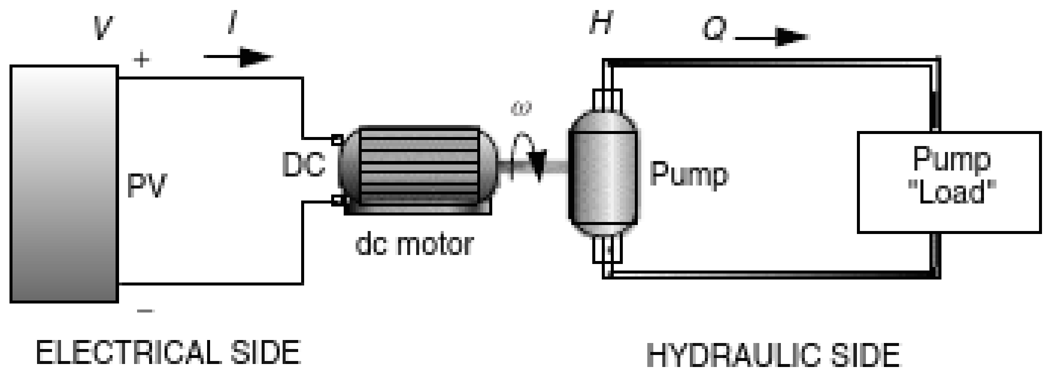
EE 446/646

PV-Powered water pumping

- One of the most economically viable photovoltaic applications today is water pumping in remote areas.
  - A simple PV system can raise water from a well or spring and store it in a tank, or it can circulate water through a solar water heater.
  - Water for irrigation, cattle watering, or village water supply can be critically important, and the value of a PV water-pumping system in these circumstances can far exceed its costs.
- Matching photovoltaics and pumps in such directly coupled systems, along with predicting their daily performance, is not a simple task.



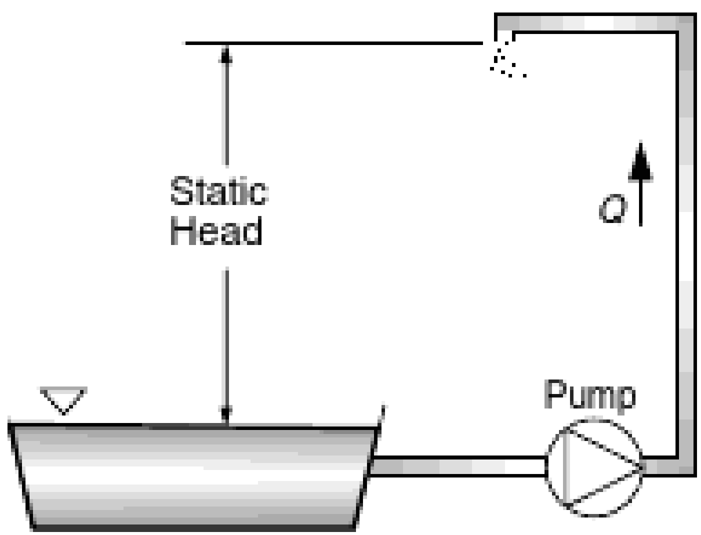
PV Pump System (closed or open)



- **Electrical side:** PVs create a voltage that drives current to a motor load. 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.
- **Hydraulic side:** A pump creates a pressure H (head) that drives water at some flow rate Q through pipes to some destination. H is analogous to voltage while Q is analogous to current. The role of H –Q curves in determining a hydraulic operating point is analogous to the role of I –V curves that determine the electrical operating point.

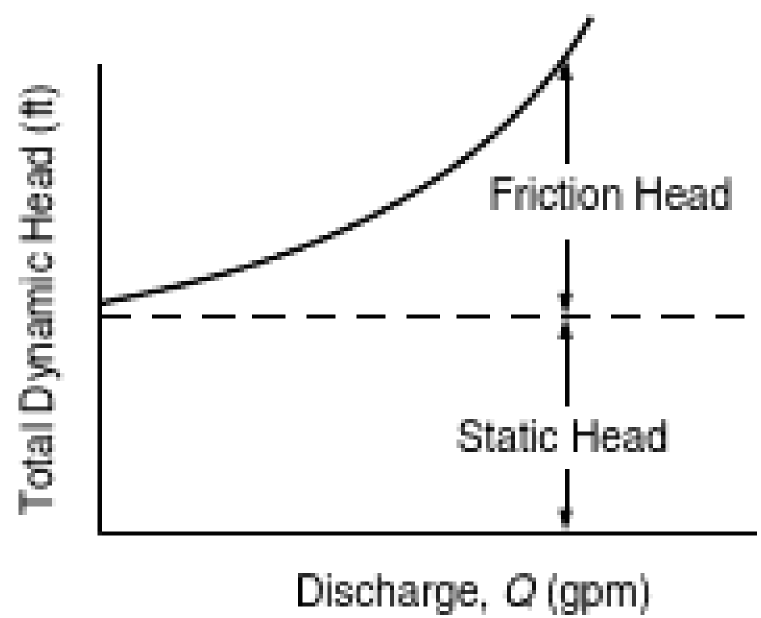
Static head

- **Open system:** water is to be raised from one level to the next.
  – 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). In the US, this is usually given in “feet of water.”
- Head can also be measured in units of pressure: The pressure that a 1-ft^3 of water weighing 62.4 lb. exerts 1 ft of head on its 144 in^2 of base. Hence, 1-ft of water = 62.4lb/144 in^2 = 0.433 psi. Conversely, 1 psi = 2.31 ft of water.



Dynamic Head (static + friction)

- If the pump supplies only enough pressure to the column of water to overcome the static head, the water would rise 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 losses rise roughly as the square of the flow velocity, and depend on the roughness of the inside of the pipe and on the numbers of bends and valves in the system.



Pressure loss due to friction

Pressure loss in plastic pipes (feet of water per 100 ft of tube)

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

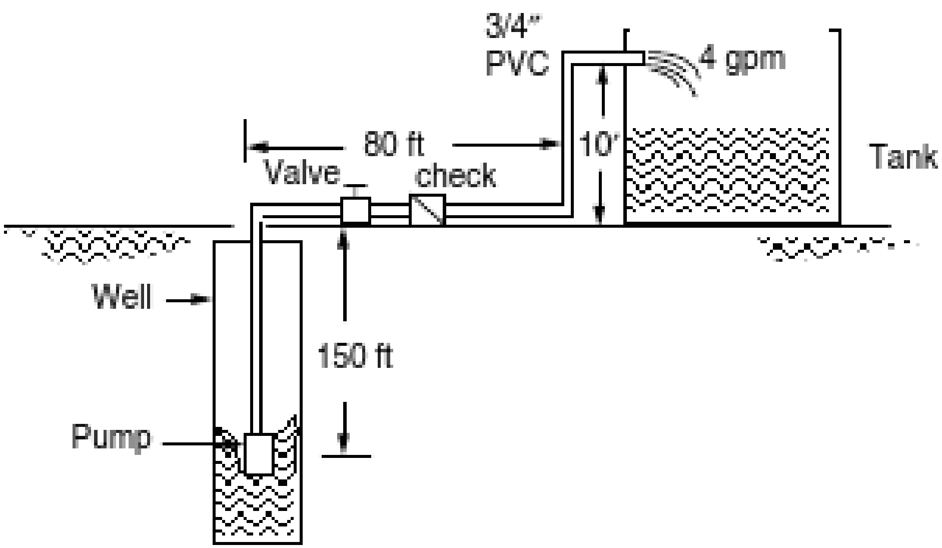
Pressure loss in valves and elbows (expressed in equivalent length of tube)

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

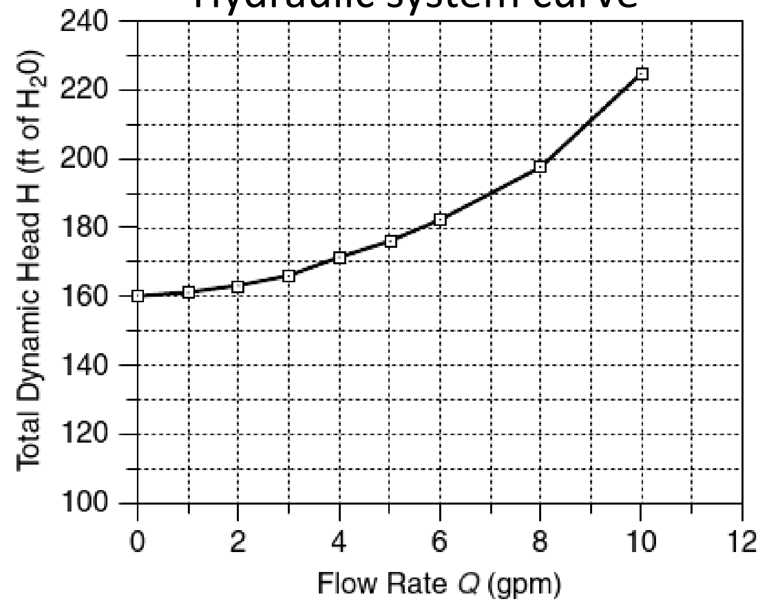
[a] Units are feet of pipe for various nominal pipe diameters.

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.
- *Answer: total pipe length: 240 f, the ells an valves add up to: 11.5 ft of pipe, total equivalent length of pipe: 251.5 ft, friction head requirement: 4.2x251.5/100= 10.5 ft of water, static head: 150+10=160 ft, dynamic head: 160+10.5 =170.5 ft of water pressure.*



Hydraulic system curve

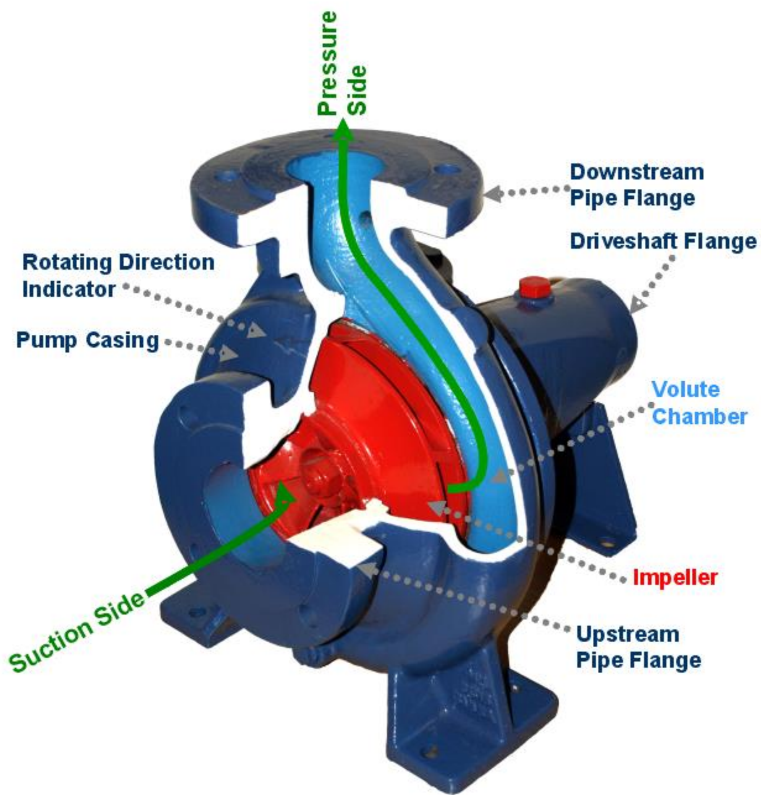


Centrifugal pumps

- To determine the actual flow that a given pump will provide, one needs the characteristics of the pump that will be used. Pumps suitable for PV-powered systems are either centrifugal and positive displacement pumps.

Centrifugal pumps have fast-spinning impellers that throw the water out of the pump, creating suction on the input side and pressure on the delivery side.

- When installed above the water, they are limited by the ability of atmospheric pressure to push water up into the suction side of the pump (theoretical maximum of 32 ft.)
- When installed below the water line, they can push water up hundreds of feet.
- Disadvantages: their speedy impellers are susceptible to abrasion and clogging by grit in the water. They are also sensitive to changes in solar intensity during the day.



Positive displacement pumps

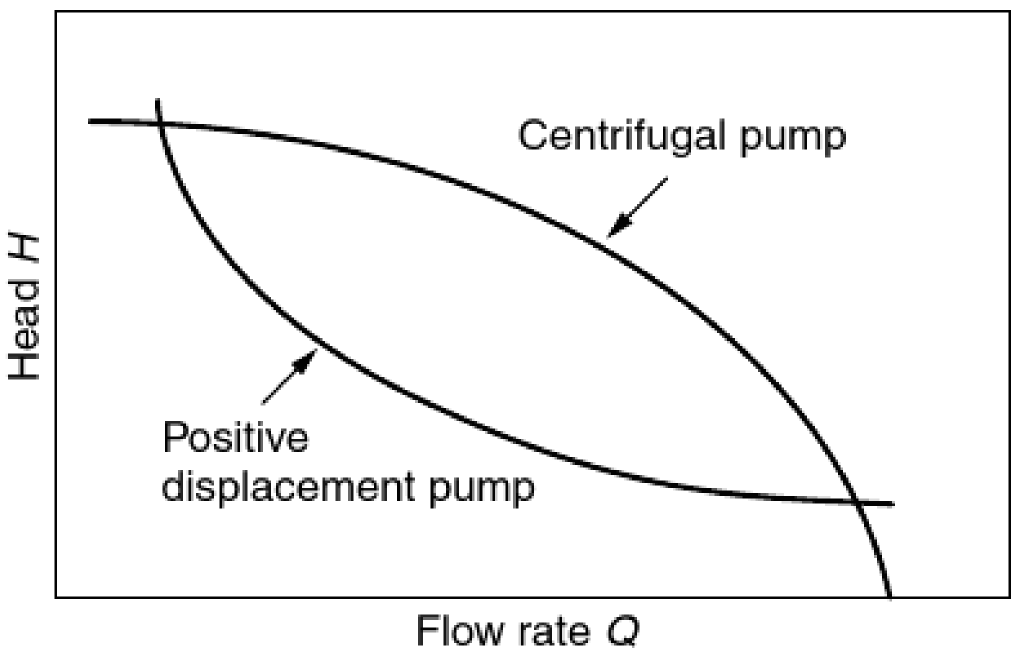
- Positive displacement pumps come in several types:
  - helical pumps, which use a rotating shaft to push water up a cavity,
  - jack pumps, which have an above-ground oscillating arm that pulls a long drive shaft up and down (like the classic oil-rig pumper),
  - diaphragm pumps, which use a rotating cam to open and close valves.
- Positive displacement pumps
  - pump at slower rates so they are most useful in low volume applications, but can handle high heads.
  - are much less susceptible to gritty water problems than centrifugal pumps, and are less sensitive to changes in solar intensity.

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

Hydraulic pump curve

- The graphical relationship between head and flow rate is called the hydraulic pump curve.
  - For a centrifugal pump, as the height of the water column above the pump increases, more and more of the pump's energy is devoted to simply holding up the water so flow rates rapidly diminish.
  - For positive displacement pump, it holds up the water column mechanically, so its flow rates are less affected by increasing head.



Power delivered by a pump

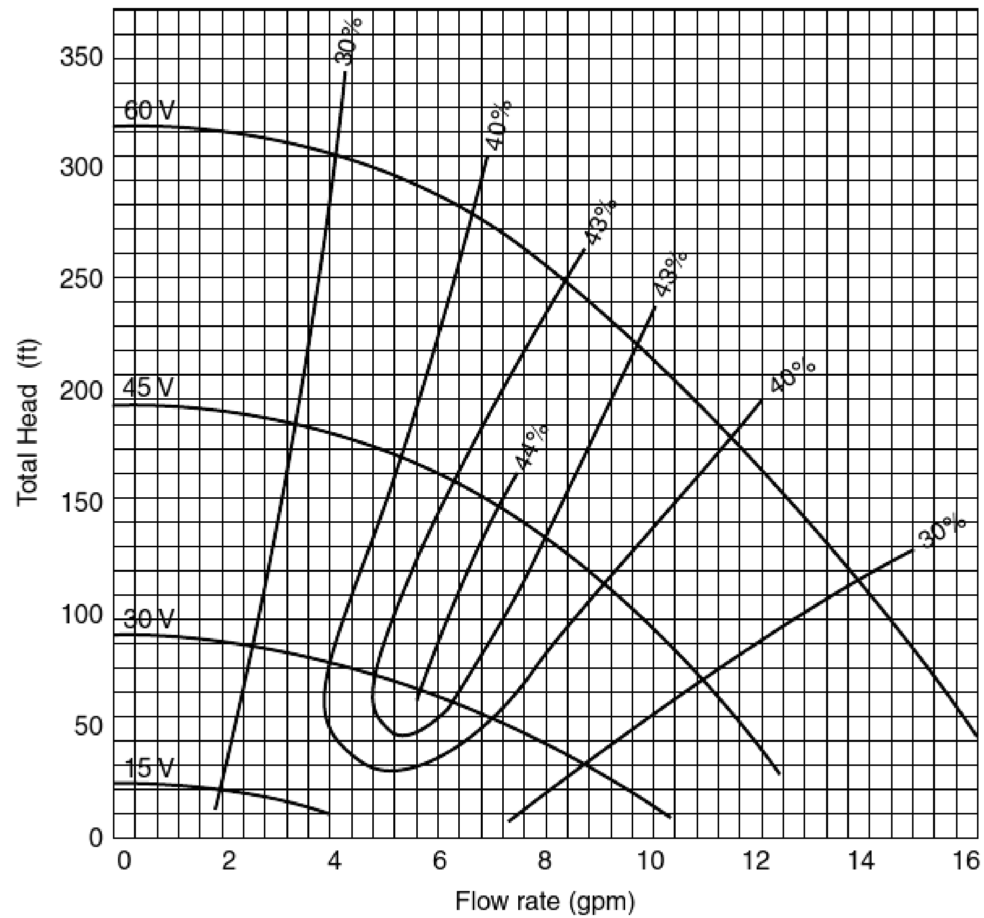
- The power delivered by the pump to the fluid with density ρ is given by

$$P = \rho H Q$$

- In American units, P(watts) = 8.34 lb/gal ×H(ft) × Q(gal/ min) × (1min /60 s) × 1.356 W/(ft-lb/s) = 0.1885 ×H(ft) × Q(gpm)
- In SI units, P(watts) = 9.81 ×H(m) × Q(L/s)
- When Q or H is zero, there is no power delivered to the fluid.
- 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.

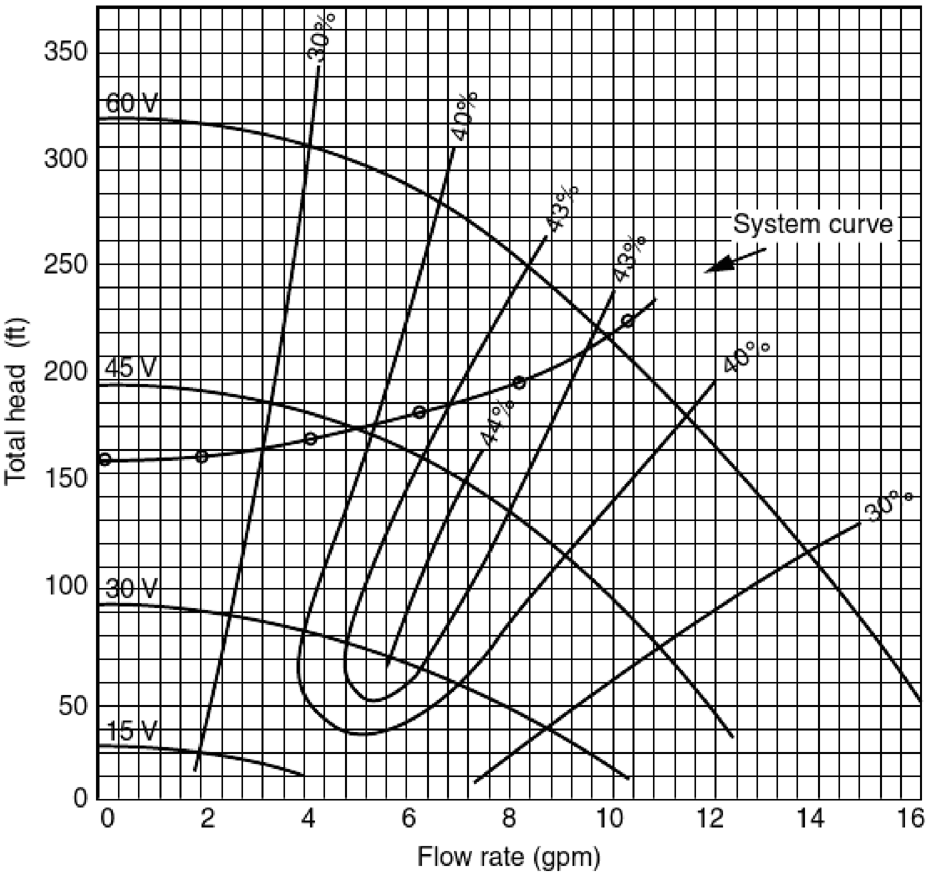
Pump curves for the Jacuzzi SJ1C11 dc centrifugal pump

- Individual curves are given for 15-V, 30-V, 45-V, 60-V inputs.
- A typical “12V” PV module operating near the knee of its I –V curve delivers about 15 V.
- The pump voltages are meant to correspond to 1, 2, 3, and 4, “12-V” PV modules wired in series.
- The efficiency of the pump as a function of flow rate and head are also shown.
- Notice that the peak in efficiency (44%) occurs along the knee of the pump curves - analogous to the PV I –V curve.



Hydraulic System Curve and Pump Curve Combined

- Just as an I –V curve for a PV load is superimposed onto the I –V curves, so is the Q– H system curve superimposed onto the Q– H pump curve to determine the hydraulic operating point.
- The figure tells us that 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 about 9.5 gpm.



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."
- 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 booster is included in the system to help start the pump in the morning and keep it running under conditions of low insolation.
- From pump power (W) and 1-sun PV power (W/module) we can determine the needed number of photovoltaic modules.

System sizing procedure

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

   Q(gpm) = Daily demand (gal/day)/{Insolation(h/day@1-sun)×60min/h}
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 and nominal voltage. Pump input power can also be estimated by dividing the power to fluid by pump efficiency η (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

   No. of modules in series = Pump voltage(V)/{15 V/mod}
6. The number of PV strings in parallel will be an integer number

   No. of strings = Pin/{no. of modules in series x 15 V/mod × IR (A) × de-rating}

   IR is the rated current at STC. A reasonable default value for de-rating is 0.80.
7. After having sized the system, the water pumped can be estimated by

Q(gal/day) = 15 V/mod × IR × η × (no. of mods) × (PSH) × 60 min/h × de-rating/ {0.1885 ×H(ft)}

Example 2: system sizing for 150-ft well in Santa Maria, CA

- Suppose that the goal is to pump at least 1200 gallons per day from the well described in Example 1 using the Jacuzzi SJ1C11 pump. Size the PV array based on Siemens SR100 modules with rated current 5.9 A, mounted at L -15^o tilt.
- Answer:
  - From Appendix E, the worst month is December with PSH =4.9
  - Q = 1200/(4.9x60)= 4.1 gpm
  - From the hydraulic pump and hydraulic system curves, the dynamic head is 170 ft and the pump efficiency is about 34%.
  - Estimated pump input power: P= 0.1885×170x4.1/.34 = 386 W
  - From the hydraulic curves, the pump voltage is a little under 45 V, hence, three 15 V modules in series should be sufficient.
  - Number of parallel strings = 386/{3x15x 5.9x0.80}= 1.8, so choose two parallel strings.
  - Estimated water delivery: Q ≈ 15× 5.9 × 6 x 4.9 x 60 x 0.80 × 0.34 /{0.1885 x 170} = 1325 gal/day

System Layout of Example 2.