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Pumping Water for Irrigation Using Solar Energy[1]

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This publication discusses photovoltaic technology and the cost of photovoltaic power for water pumping. The information presented includes:

- an overview of how electricity is generated from solar radiation using photovoltaic cells,
- a description of a demonstrational photovoltaic powered water pumping system, and
- a discussion of the present day price of such a system and the potential future effects of current trends which continue to decrease the cost of photovoltaic power.

FROM SUNSHINE TO ELECTRICAL CURRENT

Photovoltaic cells are able to turn the energy in solar radiation into electricity due to an energy transfer that occurs at the sub-atomic level. Solar energy comes in small packages called photons. These photons hit the outer level electrons in the photovoltaic cells like the flappers hit the metal ball in the pin ball machine. The dislocated electrons form the electrical current.

Silicon is one of the elements used as a base material for the production of photovoltaic cells. A silicon atom has four valence electrons which are shared with adjacent silicon atoms in covalent bonding (Figure 1a). To produce the positive-charged side of a photovoltaic cell, boron atoms which have only three valence electrons are introduced into the lattice structure of pure silicon. The boron atoms occupy a lattice position within the silicon structure, and a positive-charged hole forms in place of the missing fourth electron (Figure 1b). Silicon material with boron impurities is called a positive or p-type semiconductor. To produce the negative-charged side of a photovoltaic cell, phosphorus atoms which have five valence electrons are introduced into the pure silicon structure. The phosphorus atoms occupy a lattice position within the silicon structure and form a negative or n-type semiconductor (Figure 1c). Photovoltaic cells are made by putting a layer of n-type and a layer of p-type semiconductor material together. When the photons in solar radiation strike a photovoltaic cell, the kinetic energy of the photons is transferred to the valence level of electrons. The freed electrons and positive-charged holes attract each other and create positive-negative pairs. The formation of these pairs creates electricity (Garg, 1987).

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A photovoltaic cell is analyzed by its open circuit voltage and short circuit current capabilities (Figure 2a). Open circuit voltage is the voltage output from a photovoltaic cell when no current is flowing through the circuit. It is the maximum possible voltage that a photovoltaic cell can produce in sunlight. Short circuit current is the current flowing freely from a photovoltaic cell through an external circuit that has no load or resistance. It is the maximum possible current that the photovoltaic cell can produce at a given level of irradiance[2] (Florida Solar Energy Center, 1988).

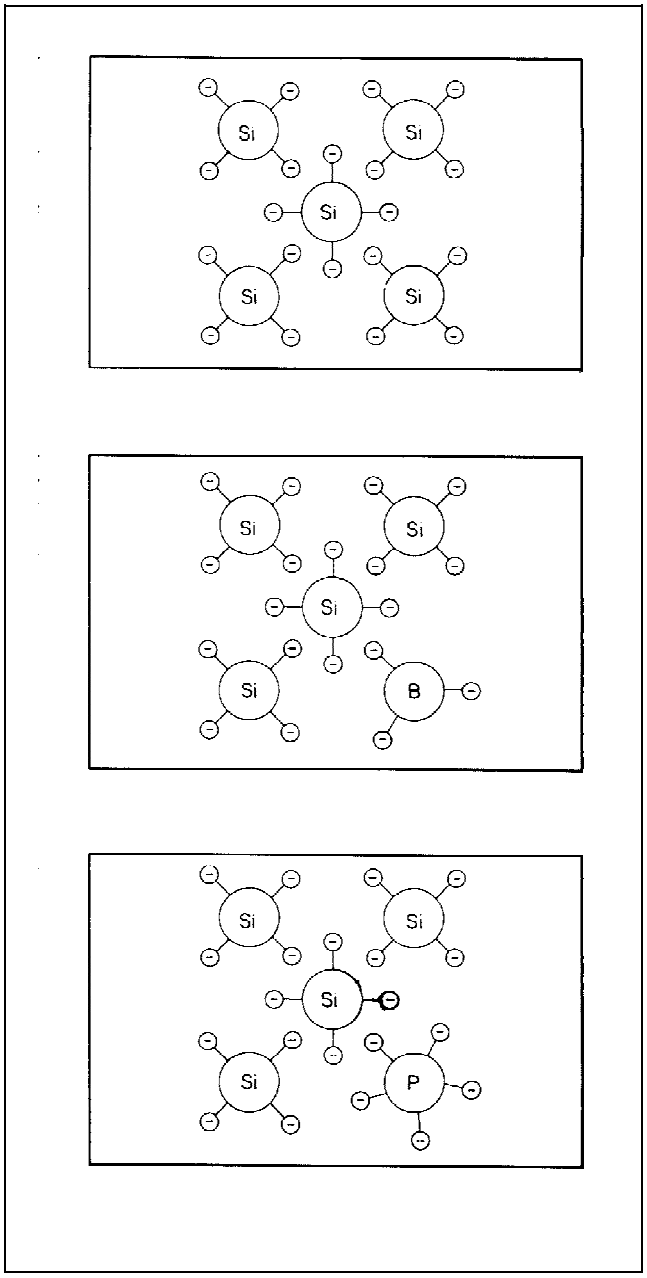

Figure 1. Silicon lattice schematic with 4 valence electrons (top); with boron impurities (center); with phosphorous impurity, the extra electron gives a negative charge (bottom)

To increase voltage output, photovoltaic cells are wired in series; to increase amperage output, photovoltaic cells are wired in parallel. A photovoltaic module is a combination of photovoltaic cells wired together in series and parallel with the purpose of generating a specific current and voltage at a given level of irradiance. A photovoltaic array is composed of two or more photovoltaic modules.

The maximum power point is the point on a given photovoltaic I-V graph which gives the highest amperage and voltage product at a given level of irradiance (Figure 2b). This is the desired point of operation for a photovoltaic array.

The direct current (DC) power received by an electrical load from a photovoltaic array is mainly controlled by two parameters[3]: the solar irradiance available to the module, and the current-and-voltage demand of the load. The voltage production of a photovoltaic cell remains practically constant under all levels of irradiance, but the current produced is directly proportional to the level of irradiance available at any given point in time. Since the power produced by a photovoltaic cell is the product of the current and voltage being produced at any given time, photovoltaic power is directly proportional to the level of irradiance available at any given time (Figure 2c).

The current-and-voltage components of a DC electrical load form a straight line on an I-V graph, after the initial start-up power surge, which rises at a constant current-to-voltage ratio (Figure 3a). In comparison, the representative I-V graph of a photovoltaic power supply shows a constant amperage while the voltage increases until the amperage falls sharply to zero at the open circuit voltage. If a photovoltaic array is designed to produce 24 volts but the load only requires 12 volts, the load will only draw from the photovoltaic array the power which corresponds to 12 volts on the I-V curve even though the photovoltaic array is able to produce more power. Figure 3a shows an electric load line and a photovoltaic power supply line which are not properly matched.

In addition to the difference in I-V curve formation between an electric load and a photovoltaic electric supply, there is a continual variation in the amperage level of the photovoltaic power supply due to changes in the level of irradiance available throughout the day. Amperage fluctuations continually change the location of the maximum power point on the I-V graph and

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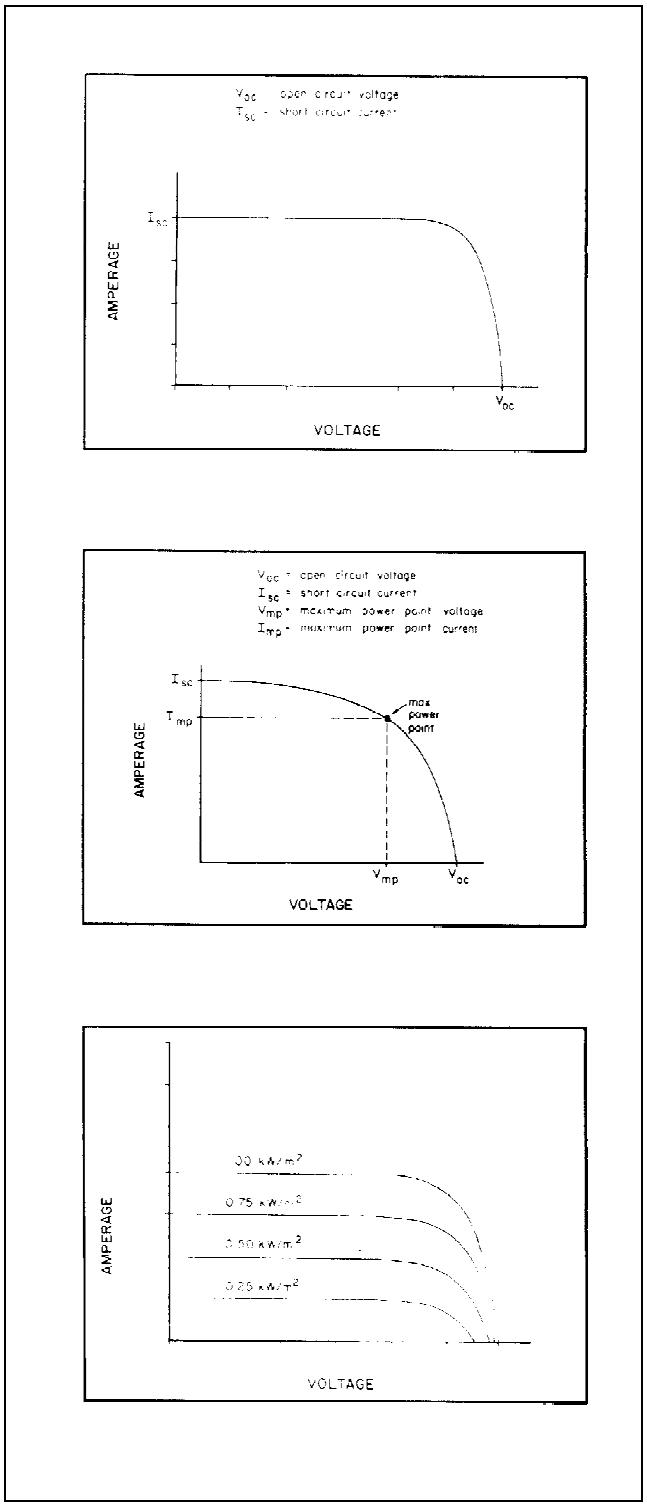

Figure 2. Amperage-voltage (I-V) curve for photovoltaic module (top); I-V curve showing maximum power point (center); I-V curve showing various levels of solar irradiance (bottom).

hinder the matching of the maximum power points of a photovoltaic module to points along the straight load line of the DC electric load (Figure 3b). Care must be taken when designing a photovoltaic system to match the I-V load curve and maximum power points over the widest possible range to create a system with high overall efficiency.

SYSTEM DESCRIPTION

A photovoltaic array comprised of two units of three modules each was used to power the water pumping system used in this demonstration (Figure 3c). The six photovoltaic modules had a photon responsive surface area of 3.17 m^2. The three modules of each unit were connected end-to-end and reflectors, constructed from sheet metal and aluminum foil tape, were attached to the two long sides of each unit. The reflectors doubled the area of the array structure normal to the sun and increased the short circuit amperage of the units up to 33 percent overall.

The photovoltaic array was attached to a one-axis tracking mechanism. This system enabled the array to remain essentially normal to the sun throughout the day so that the photovoltaic modules were able to utilize a larger portion of the available sunlight. The tracking mechanism was powered and controlled by two, small photovoltaic modules which functioned independently from the six primary modules (Dinh, 1988).

Photovoltaic cells have minimal current resistance when exposed to light, but when they are shaded, all current flow through them is blocked. The tracking-control photovoltaic modules on the photovoltaic system used in this demonstration were placed on the east and west sides of the array. When both tracking modules were in equal sunlight, the electricity produced by them flowed between the two modules and the array remained stationary. When one of the modules was shaded, the electricity produced by the module remaining in sunlight flowed to the tracking motor which turned the array until both tracking modules were again in equal sunlight (Figure 4a).

To match the maximum power points of the photovoltaic array with the I-V load line of the DC electric motor, the photovoltaic system used in this demonstration included an electronic array reconfiguration controller (EARC) (Salameh et al., 1989). An EARC is an electronically controlled circuit which monitors the amperage being generated by a module and connects the modules in series or parallel to match the maximum power points of a photovoltaic system to the I-V curve of the connected load over the widest possible range. To describe the

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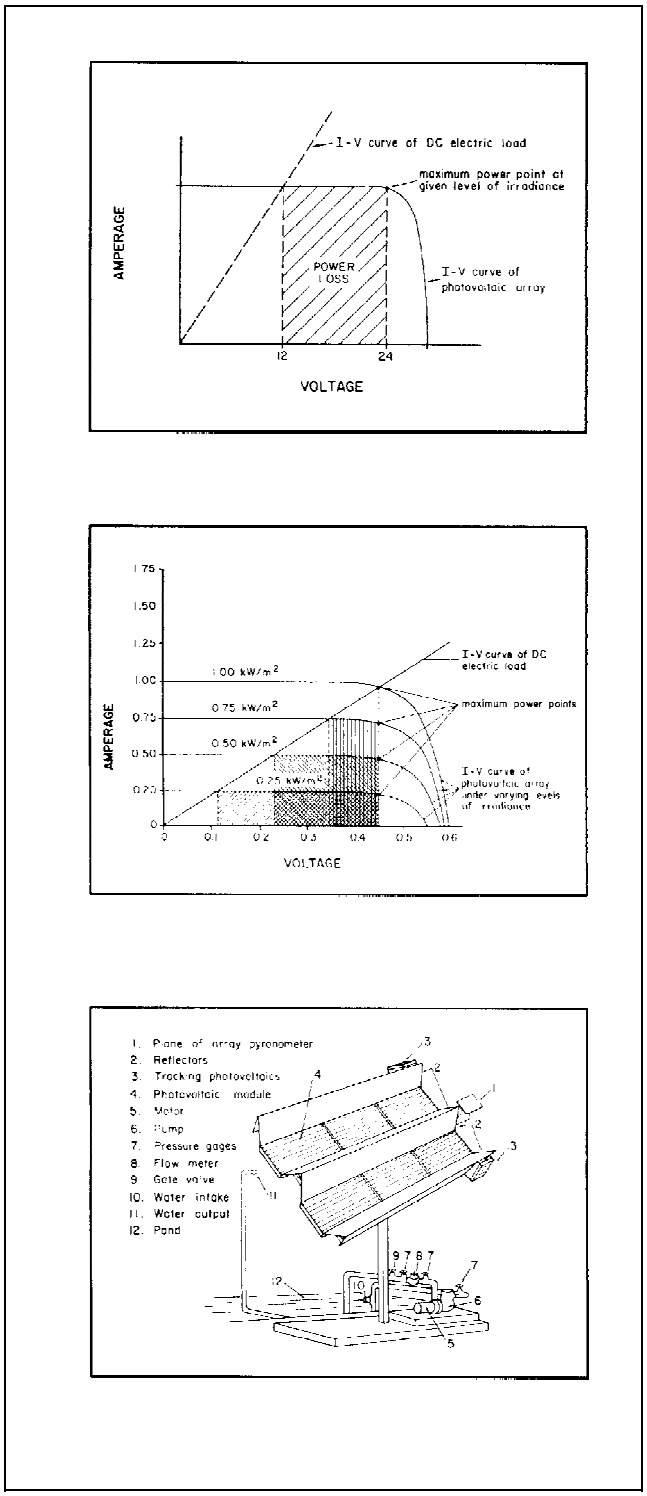

Figure 3. Graph showing I-V curve of array at given level of irradiance and a resistive load (top); variances in amperage component (center); photovoltaic-powered water pumping system used in here (bottom).

function of the EARC, assume a photovoltaic module of seven, 10 cm^2 photovoltaic cells wired together in parallel so that at maximum sunlight (1000 W/m^2) the short circuit current equals 1.00 amp and the open circuit voltage is 0.6 volts. At lower levels of irradiance, the amperage falls proportionally, but the voltage remains practically constant. If two, seven-cell modules are connected permanently in parallel, their maximum power point at low irradiance values will match the DC motor load line at low operational voltages (Figure 4b). In the same manner, if these two modules are connected permanently in series, the maximum power point at high irradiance values will match the load line at high operational voltages (Figure 4c).

The EARC used in this demonstration system alternated the configuration of the two units of the photovoltaic array between parallel and series in reference to the irradiance level. When the irradiance level was low, the two units were electronically connected in parallel to maintain an adequate amperage level for continued operation of the motor at a low voltage. When the irradiance level was high, the two units were electronically connected in series which increased the voltage output of the array and produced an amperage and voltage power supply which closely matched the amperage and voltage power demand of the attached load at the higher level. In this manner, as the irradiance level varied, the motor utilized the power available from the photovoltaic array more efficiently than if the two units had been statically configured in a parallel or series connection.

The pumping system used in this demonstration included a 0.5 Hp, DC, permanent magnet motor and a single-stage centrifugal pump. The water was pumped from a surface pond through 5-cm (2-in) diameter PVC pipe and discharged at a height of 2.44m (8 ft). The photovoltaic system had an average SOC[4] peak watt (W_p)[5] rating of 374 watts at the solar irradiance level of 1000 watts/m^2.[6]

SUBSYSTEM EFFICIENCIES

The photovoltaic system used in this demonstration was mathematically analyzed as three separate subsystems: 1) the photovoltaic modules with the reflectors, 2) the EARC, and 3) the motor and pump subsystem. The individual efficiencies of these subsystems were 11 percent, 96 percent, and 44 percent respectively. Figure 5 shows the flow of energy converted from solar radiation to fluid power. The overall efficiency of the entire system was 4.6 percent.

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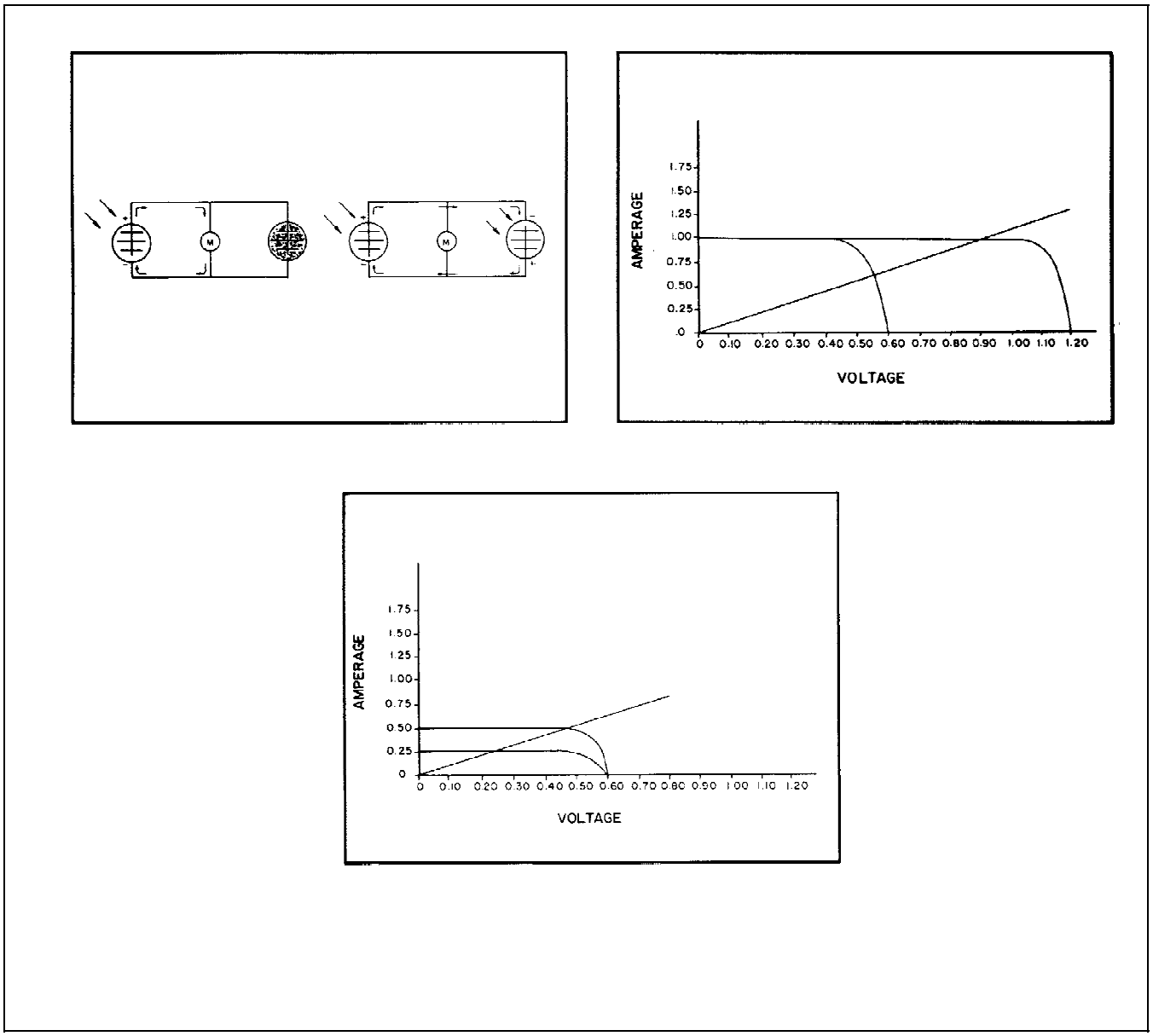

Figure 4. 2 photovoltaic modules, one cell shaded (*l*), both in full sun (*r*) (top l.); 2 7-cell modules - irradiance level .25 kw/m2 (bottom); 2 7-cell modules - irradiance level .10 kw/m2 (top r.)

WATER VOLUMES PUMPED PER DAY

The volume of water which a photovoltaic-powered pump is able to produce is related to the irradiance level which it receives throughout the day. On October 7, 1989, high levels of irradiance were available throughout the entire day and the photovoltaic system pumped 20,180 gallons of water against a static head of 2.44m (8ft) (Figure 6). On January 6, 1990, clouds blocked the sun's rays over a large part of the day, and the system pumped only 1,655 gallons of water (Figure 7).

An advantage of using direct solar radiation as a power source for irrigation is that it is available at the site of application without the employment of a distribution system (Halcrow and Partners, 1981). Plant water demand and the quantity of water pumped by a photovoltaic powered water pumping system are both directly correlated to daily solar insolation.[7]

To ascertain the area for which the system used in this demonstration could replace daily potential evapotranspiration (ET_p), ten years of historical weather data were used to calculate the theoretical daily fluid power output of the system and the daily

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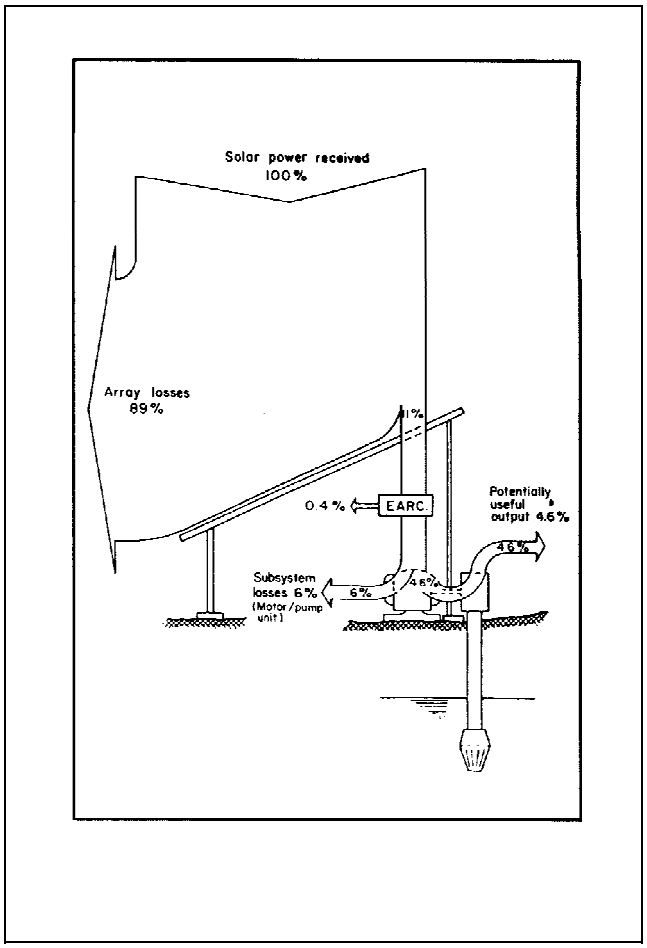

Figure 5. The photovoltaic system and its points of power loss. The photovoltaic array with reflectors converted only 11% of the solar energy it received into electrical energy.

ET_p (Smajstrla et al., 1984). The volume of water which could be pumped through an irrigation system with a total dynamic head of 5m (16ft) using the fluid power generated by the photovoltaic system was divided by the daily ET_p. These calculations showed that the photovoltaic system used in this demonstration could replace the daily ET_p through the winter vegetable growing season between September and May for 1.42 hectares (3.5 acres) on a soil able to store a seven-day volume of daily ET_p at an 80 percent[8] probability of success.

COMPARATIVE ECONOMIC ANALYSIS

A comparison was made of the net present value of the costs of irrigation power over a 20-year period using different power sources. The five power sources studied were:

1. 0.3-horsepower electric motor powered by electric grid with a mainline available,

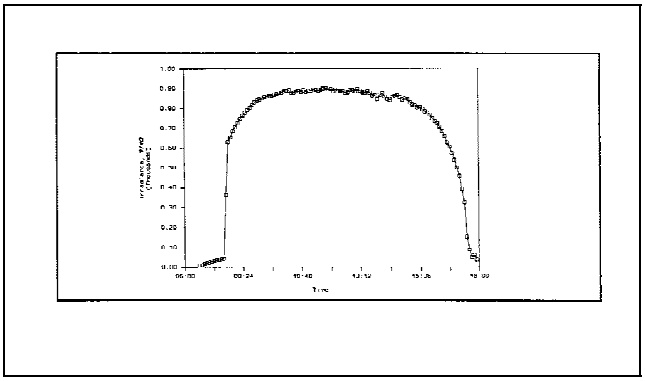

Figure 6. On an almost cloudless day, the array received almost 900 watt/m2 for 7 straight hours. The system pumped 20,180 gallons of water to a height of 2.44 m (8 ft.).

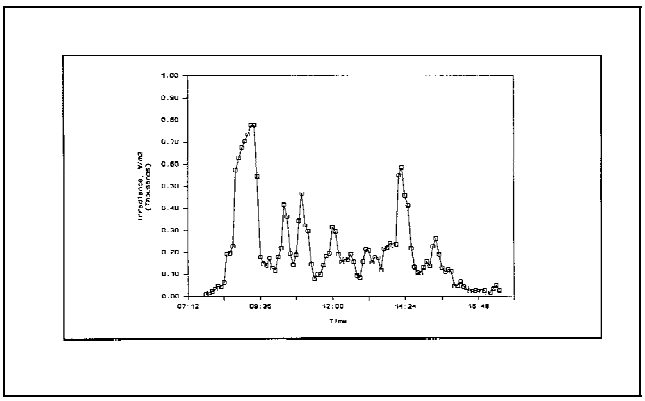

Figure 7.A very cloudy day in which the system pumped only 1,655 gallons of water.

2. 0.3-horsepower electric motor powered by electric grid when a 2-mile mainline must be installed,

3. 3-horsepower gasoline engine (smallest available),

4. 5-horsepower diesel engine (smallest available),

5. 0.5-horsepower photovoltaic power system.

Figure 8a is a graphical representation of the change in the 20-year net present cost of each power supply as the size of the irrigated land area increases. It shows that at 1989 prices, photovoltaic power is competitive for irrigated land areas of less than 1.5 ha (3.7 ac) with diesel power and electric grid power when mainline installation is required of more than two miles to reach the site of energy application. For irrigated land areas greater than this, the current cost of photovoltaic power is prohibitive.

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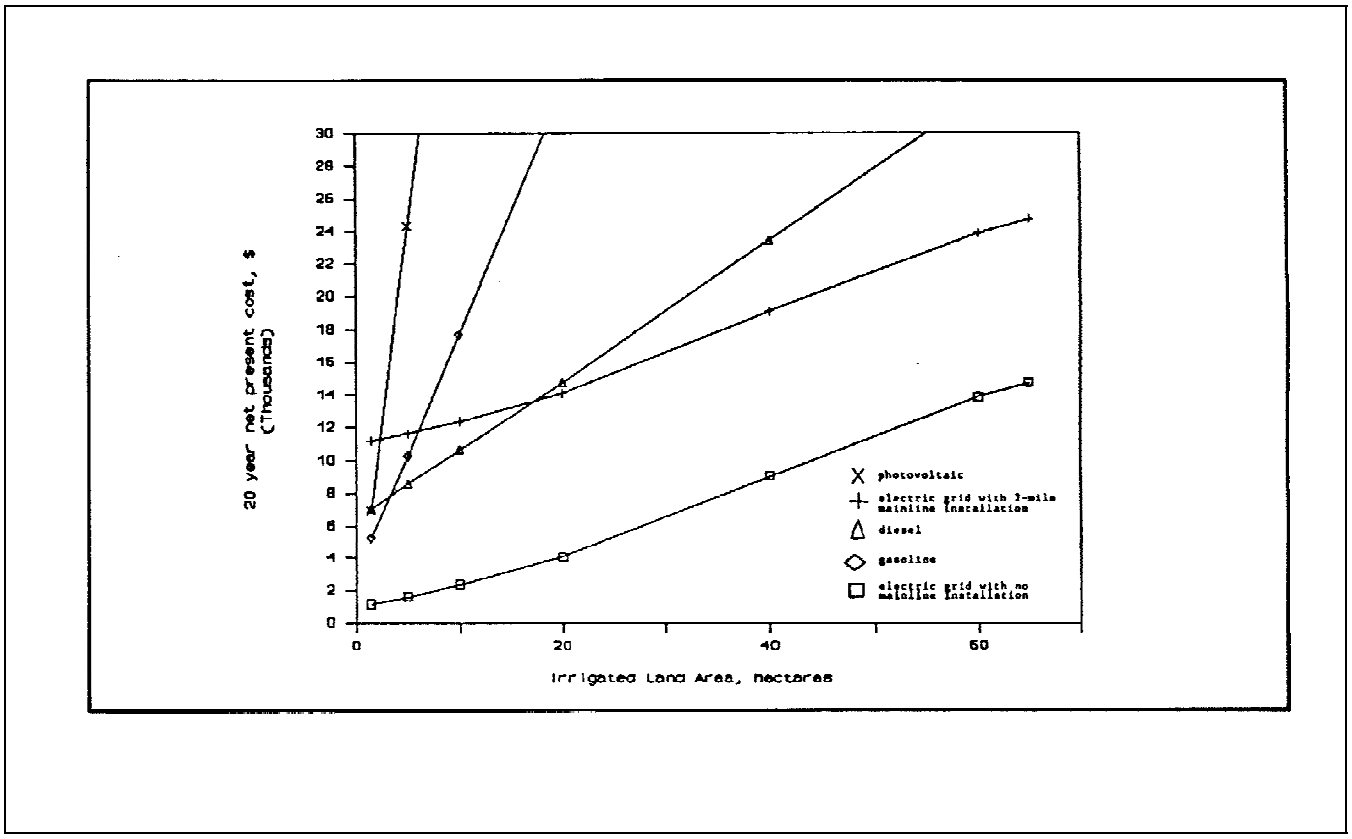

Figure 8a. Net cost comparison for irrigation power sources as size of land to be irrigated increases. The system at 1989 prices is competitive for irrigated land area of 1.5 ha or less.

ECONOMICS AND THE FUTURE

The cost of photovoltaic-powered water pumping systems is decreasing. The cot of photovoltaic modules has fallen 400 percent in the last 30 years and this trend continues. Photovoltaic technology also continues to improve the power conversion efficiency of the photovoltaic cell. Increases in photovoltaic cell efficiency decrease the cost of photovoltaic power, because fewer modules are required to produce the same amount of power.

While the cost of photovoltaic power is decreasing, the cost of power derived from fossil fuels is increasing. In an effort to understand the combined effect of these trends on the economic viability of photovoltaic power for irrigation, a theoretical scenario of future power costs was developed. Figure 8b shows the results of these calculations.

At the present time (1989), the cost of a semi-crystalline silicon module is $\$9.00/W_p$.[9] Figure 8b shows the net present cost of a photovoltaic power supply for an irrigated land area of 5 ha (12.4 ac) at a module cost of $\$7.00/W_p$, $\$3.00/W_p$, and $\$1.00/W_p$. It also shows the effect of increases in fuel cost on the net present cost of the diesel system, gasoline system, and electric grid with two-mile mainline installation system.

- The $\$7.00/W_p$ photovoltaic system became competitive with the gasoline system for an irrigated land area of 5 ha (12.4 ac) at a gasoline fuel price of $2.70/gallon which was 170 percent higher than the 1989 price.

- The $\$3.00/W_p$ photovoltaic system became competitive with the gasoline system at a fuel price of $1.90/gallon which was 90 percent higher than the 1989 price.

- The $\$1.00/W_p$ price made the photovoltaic system competitive with gasoline with an increase in the gasoline fuel price of 50 percent, to $1.50/gallon.

- The $\$3.00/W_p$ photovoltaic system was competitive with an electric grid system (with two-mile mainline installation) when the cost of electricity was increased by 300 percent from the current price of $0.80/kWh to $0.32/kWh.

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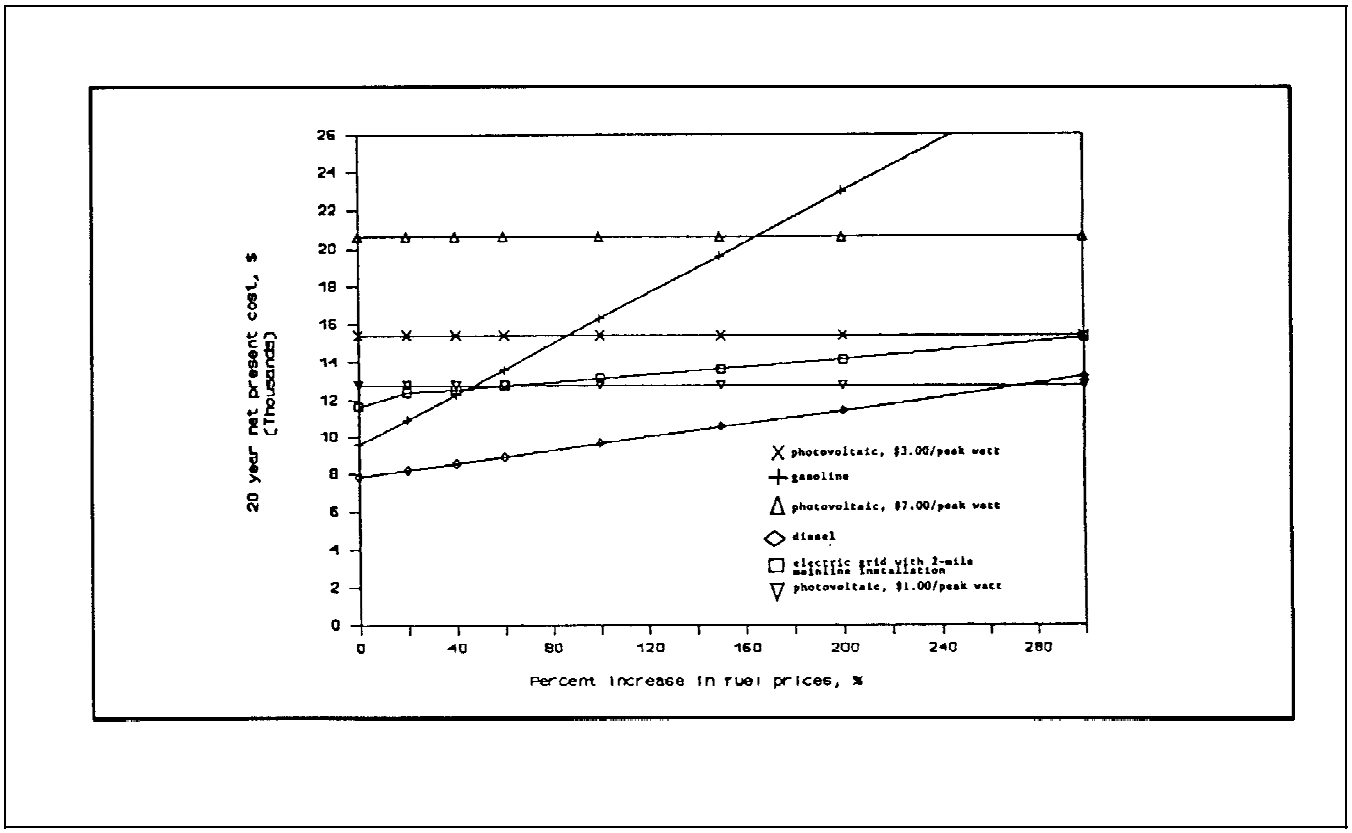

Figure 8b. Net present cost comparison for power sources for irrigation for land area of 5 ha (12.4 ac) as price of photovoltaic system is decreased and price of fuels is increased.

- The $\$1.00/W_p$ photovoltaic system was competitive with a diesel system at a 270 percent increase of the 1989 price of diesel to $4.63/gallon.

CLOSING REMARKS

The use of photovoltaic power for irrigation is a well-matched application of solar energy supply to energy need, because both the plant water needed and the availability of water supplied by a photovoltaic system depend upon the solar irradiance available. Complete utilization of all of the solar power available, however, without an energy (battery) or fluid power (elevated water storage tank) storage unit is impossible for two reasons: 1) Solar energy will be available on days when no additional water is required by the plants, i.e., a sunny day after a rainstorm. 2) Since the ratio of ET_p to fluid power is greater in the summer months than the winter months in Florida, the photovoltaic system must be oversized for the winter months to guarantee an adequate water supply for the crop during the summer months.

The vegetable winter growing season of Florida (September - May) was used for the irrigated area example in this paper. The efficient application of photovoltaic power to an irrigation system requires that the solar power availability pattern at the application site match the annual crop water need closely and that the crop growing season be lengthy to utilize the photovoltaic system as much as possible throughout the year.

Since the increase in price per increase in unit power output of a photovoltaic system is greater than that for a diesel, gasoline, or electric system, photovoltaic power is more cost competitive when the irrigation system with which it operates has a low total dynamic head. For this reason, photovoltaic power is more cost competitive when used to power a micro-irrigation system as compared to an overhead-sprinkler system.

In conclusion, photovoltaic power for irrigation 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,

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photovoltaic power will become more cost competitive and more common.

ENDNOTES

2. Irradiance: Solar power per unit area.

3. Cell temperature and cell type also influence power output.

4. Standard operating conditions (SOC): Irradiance - 1000 watts/m^2, Cell temperature - 45 degrees C.

5. Peak watt (W_p): Maximum power output of photovoltaic system at SOC.

6. 1000 watts/m^2 is considered to be the practical maximum amount of solar irradiance which can reach the earth's surface after passing through the atmosphere.

7. Insolation: Solar energy received during a specific time interval.

8. An 80 percent chance of success means that on any given day the chance that the power supply will be unable to replace the daily water loss through evapotranspiration is 20 percent. Eighty percent is considered to be an appropriate success percentage for irrigation system design by the Florida Water Management Districts.

9. Price of module divided by the actual wattage output of the module under 1000 watts/m^2 of solar irradiance as tested in the field.

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