CHAPTER 3

THEORY

3.1 Solar energy supply

The annual amount of solar energy incident on the surface of the earth is 795×10^{15} kWh. This solar radiation resource can be compared with the global primary energy consumption of 95.8×10^{12} kWh (1991). The solar energy supply is thus a factor of 8,300 greater than the global energy demand. If the land area of 149×10^{12} (29 % of the earth's surface) is taken as a basis, the incident solar energy is still 2400 times more than the energy demand.

The radiation intensity outside the earth's atmosphere is between 1300 and 1400 Wm^{-2}; this is called the extra-terrestrial radiation. Reflection, scattering and absorption by the atmosphere reduce this value by about 30 %, so that about 1000 Wm^{-2} is incident on the earth's surface at midday when the cloudless. The so - called global radiation consists of two components, the direct and the diffuse radiation. Direct (or beam) radiation comes directly from the sun, whereas diffuse radiation is incident from all sky directions; the sky thus appears to be equally bright in all directions. The diffuse component can be seen on sunny days as the blue sky. When the sky is completely overcast, only diffuse radiation reaches the surface of the earth.

The quality of the conversion from radiation to useful energy is described by The efficiency value η of the process:

$$\eta = \frac{useful\ energy}{radiation\ on the\ receiver\ are} \qquad \text{..........(3.1)}$$

This quality must take account of all losses occurring in the system. Often, inadequacies in the systems or devices used to process the energy decisively affect the performance of the whole system.

The conditions at the site of the receiver also play an important role for the energy yield. As the sun's position changes with the season and the time of day, the amount of radiation available for the conversion process depends on the receiver orientation. In general, an orientation toward the south is favorable (in the Northern Hemisphere), as then the radiation can be received equally well during the morning and the afternoon. Tilting the receiver has different effects on the collected direct and diffuse radiation. The usable diffuse fraction is smaller for a tilted receiver than for a horizontal one, as it then "sees" only part of the sky; the larger the tilt angle, the smaller is the diffuse fraction

Optimum use of direct radiation is only achieved when the receiver surface is always perpendicular to the incident radiation. The more oblique the incident angle, the smaller is the amount of useful energy. In Central Europe, as the sun is low in the sky in winter even at noon, a large tilt angle is advantageous, whereas in summer, a small tilt angle is better.

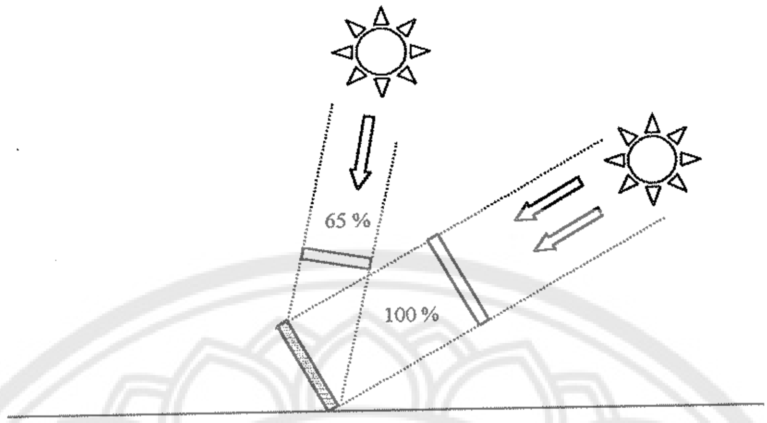

Figure 1 Direct radiation on a tilted receiver.

For stationary mounting of the receiver, the optimum tilt angle depends on the operating conditions of the system. The reliability of a solar energy system is determined not only by the radiation conditions and by the quality of technical system. Before a system is constructed, the energy demand should be carefully analyzed. It is not sensible to design the system before the results of this analysis are known. In many cases, it proves necessary first to reduce the consumer's energy demand by appropriate measures.

3.2 PV water pumping system

3.2.1. Energy for water pumping

The starting point for any assessment of water pumping is the relationship between energy and water requirements. The pumping (or hydraulic) energy to deliver a volume of water is given by the formula

$$E_H = \rho g V_W H_T \qquad \text{..........(3.2)}$$

Where E_H is hydraulic energy (Joules), ρ is density of water (1000 kg/m^3), g is acceleration due to gravity (9.81 m/s^2), V_W is the volume of water required to lift (m^3), H_T is total head (m).

The power required to lift a given quantity of water depends on the length of time that the pump is used. Power is the rate of energy supply, so the formula for hydraulic power is simply obtained from the formula for energy by replacing volume with flow rate (Q), in cubic meters per second.

$$P_H = \rho g Q H_T \qquad \text{..........(3.3)}$$

Energy is an important characteristic of water pumping since it is energy that has to be paid for in the form of diesel fuel, human labor, animal feedstock, or solar pump size. The equivalent power requirement only determines how quickly the required quantity of water, is delivered and the rate at which the energy is used.

3.2.2. Typical head in a water pumping system

The head has a proportional effect on the energy and power requirements with the result that it is cheaper to pump water through lower heads. It consists of two parts: the static head, or height through which the water must be lifted, and the dynamic head which is the pressure increase caused by friction through the pipe-work, expressed as an equivalent height of water. The static head can be easily determined by measurement and there are formulae for calculating the dynamic head. The latter depends on flow rate, pipe sizes and pipe materials. The smaller the pipes and the greater the flow rate, the higher the pressure required forcing the water though the pipes at the same rate. The diameter of the pipe should be such that if possible the frictional loss does not exceeds 10 percent of the total head.

The static head includes the static suction head and static discharge head. Static suction head is the vertical distance from the water level surface to the center of the pump. Static discharge is the vertical height from the center of the pump to the level of discharge. Both are in a static state. The head loss in the dynamic state occurs when water moves though in the pipe and encounters along the length of the pipe, bends, fittings, valves and changes in pipe diameter.

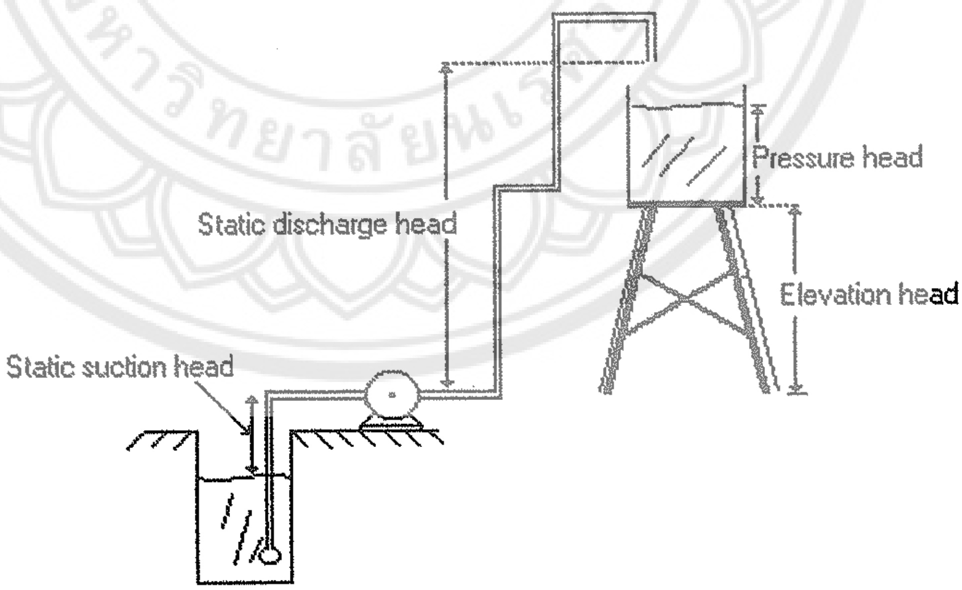

Figure 2 Typical head in water pumping system.

The sign of the static suction head depends on the water source position. It is a positive sign when the water source is above the pump and a negative sign when the water source is below the pump. The static discharge is not dependent on the delivery pipe form.

3.2.3. Electric motor

Electric motors used in solar water pumping systems are of three types:

- Brushed type permanent magnet DC motor
- Brushless permanent magnet DC motor
- Brushless permanent magnet AC motor (used with a DC to AC converter or inverter).

The obvious advantage of DC motors is that no converter is required. Brushed DC motors, in which the armature rotates in the field of a fixed permanent magnet, are traditional and reliable, but the brushes must be replaced after one or two years of operation. Brushless DC motors have a rotating permanent magnet that generates a current in electronically commuted field windings. They are a new development but are available on the commercial market and are likely to become the preferred option in small PV pumping systems. For large systems, AC may be used; the motor should be specially designed together with the converter for maximum efficiency to minimize the inherent power losses.

3.2.4. Water pumps

Pumps can be divided into two categories: centrifugal and positive displacement. They have inherently different characteristics.

Centrifugal pump

Centrifugal pumps are designed for a fixed head and their water output increases with rotational speed. They have an optimum efficiency at a specific design head and a specific design rotational speed. At heads and flows away from the design point their efficiency decreases. However, they offer the possibility of achieving a close natural impedance match with a PV array over a broad range of operating conditions. Centrifugal pumps are seldom used for suction lifts of more than 5 to 6 meters and are more reliably operated in submerged floating motor/pump sets. This is because they are not inherently self-priming and can easily lose their prime at higher suction heads.

The principle of a centrifugal pump is that the water is thrown out from the center of the pump because of the centrifugal force created as the impeller rotates. The water enters at the axis of the pump and is discharged at the perimeter.

Positive displacement pumps

Positive displacement pumps have a water output, which is almost independent of head but directly proportional to speed. This means that the efficiency of a piston type pump of fixed piston diameter increases with head and therefore for optimum efficiency pumps with different piston diameters need to be used for different heads. At high heads the frictional forces become small relative to the hydrostatic forces and consequently at high heads, positive displacement pumps can be more efficient than centrifugal pumps. At lower heads, below about 15m, the total hydrostatic forces are low in relation to the frictional forces and hence positive displacement pumps are less efficient and less likely to be used. The operating principle of a typical piston type positive displacement pump is that when the piston moves down, the foot valve closes and water passes to the chamber above the piston. On the upward stroke the upper valve closes, the foot valve opens and water is lifted to fill the chamber below the piston.

3.2.5 Irrigation Principles

Human dependence on irrigation can be traced to the earliest biblical references. Irrigation in very early times was practiced by the Egyptians, the Asians, and Native Americans. For the most part, water supplies were available to these people only during periods of heavy runoff. Current concepts of irrigation have been made possible only by the application of modern power sources to deep well pumps and by the storage of large quantities of water in reservoirs. Thus, by use of either underground or surface reservoirs it is now possible to bridge over the years and provide consistent water supplies.

Increasing demands for water, limited availability, and concerns about water quality make effective use of water essential. Because irrigation is a major water user, it is very important that irrigation systems be planned, designed and operated efficiently. This requires a thorough understanding of the relationships among plants, soils, water supply and system capabilities.

The water requirements and time of maximum demand vary with different crops. Although growing crops are continuously using water, the rate of evaporate transpiration depend on the kind of crop, the degree of maturity, and the atmospheric conditions, such as radiation, temperature, wind, and humidity. Where sufficient water is available, the soil water content should be maintained for optimum growth. The rate of growth at different soil water contents varies with different soils and crops. Some crops are able to begin growth with the water needs generally low but which increase rapidly during the maximum growing period to the fruiting stage. During the later stages of maturity water use decreases and irrigation is usually discontinued when the crop is ripening.

3.3 PV pumping analysis

This report will divide the time range into three parts which are:

- short term that will use data only each month
- middle term that will use data about four months or season
  - Winter (November – February)
  - Summer (March – June)
  - Rainy (July – October)
- long term that will use data all year (October 1997 – September 1998)

All data that was collected was used to find the efficiency of system, the performance and evaluation of system by a simulation method. And the efficiency of the system can be found by these below formulas.

3.3.1 PV system

For the PV system, that generated the electrical power for motor and pump can find the efficiency by usin this formula.

$$\eta_{PV} = \frac{I_{PV} \times V_{PV}}{G_{Tilt} \times A_{PV}} \qquad \text{..........(3.1)}$$

When,

η_{PV}	is efficiency of PV system
P_{PV}	is PV output power, W
I_{PV}	is PV output current, A
V_{PV}	is PV output voltage, V
G_{Tilt}	is tilt angle radiation, W/m^2
A_{PV}	is PV area, m^2

3.3.2 Motor and pump system

For the motor and pump system, which pumps water to tank by the use of electrical power from the PV system, we can find the efficiency by following these formulas.

$$P_M = \frac{2\pi \, T_O \, S}{60} \qquad \text{.........(3.2)}$$

When,

P_M	is the motor power, W
T_o	is the torque, Nm
S	is the speed of motor, rpm

To find the efficiency of the motor.

$$\eta_M = \frac{P_M}{P_{PV}} = \frac{2\pi T_O S}{60 \times I_{PV} \times V_{PV}} \qquad \text{..........(3.3)}$$

The hydraulic power can be found by this formula.

$$P_H = \rho g H_T Q \qquad \text{..........(3.4)}$$

When,

P_H is the hydraulic power,
ρ is the density of water (1,000 kg/m^3)
g is the gravitational acceleration (9.81 m/s^2)
H_T is the total head, m
Q is the flow rater, m^3/s

The total head loss determined from the pipe pressure P1, from the height difference of the supply pipe to actual water level and from additional friction losses in the pipe segment from the pump to measurement point P1. The fraction of kinetic head is very small. So, it can be neglected in this analysis method.

In addition, the height difference of the supply pipe to the actual water level and pressure P1 can find from the MODAS data logger in barr unit of pressure that we must change into meter units.

When,

1 barr = 100 kPa

So, the height we can find from this formula.

$$H_K = \frac{P}{\rho g} \qquad \text{..........(3.5)}$$

When,

H_K is the height of kinetic head, m.
P is the pressure, Pa
ρ is the density of water (1,000 kg/m^3)
g is the gravitational acceleration (9.81 m/s^2)

And, the friction loss we can find from the Hazen-Williams formula. This formula is used for calculating the head loss in very long pipe.

$$H_F = 10.666 L \frac{Q^{1.85}}{C^{1.85} D^{4.87}} \qquad \text{..........(3.6)}$$

When,

- H_F is the friction head or head loss, m.
- L is the length of pipeline, m.
- D is the inside dimension of pipe, m.
- Q is the velocity of water in pipeline, m^3/s
- C is the pipe coefficient (150 for PVC pipe)

And, we can find the efficiency of hydraulic power like this.

$$\eta_{MP} = \frac{P_H}{P_{PV}} = \frac{60\,\rho g H_T Q}{2\pi T_O S} \qquad \text{..........(3.7)}$$

Therefore, the efficiency of motor and pump we can find by using this formula.

$$\eta_{MP} = \frac{P_H}{P_{PV}} = \frac{\rho g H_T Q}{I_{PV} \times V_{PV}} \qquad \text{..........(3.8)}$$

Note: The efficiency is for the combined motor and pump subsystem, because there was no ability to measure torque and speed of the motor which is needed to calculate the power output of the motor. To compute the efficiency of the motor and pump subsystem, only measuring power input to the motor and the hydraulic power of output of the pump is needed.

3.3.3 Inverter system

The remaining component models of the pumping system are described on the basis of the electrical power measurements. The power losses caused by the inverter are determined by self-consumption, power losses linear to the output power (due to voltage drops in semi conductors) and power losses to the square of the output power (ohmic losses). Thus, the output power P_{AC} is achieved from

$$P_{AC} = P_{PV} - \sum_{i=0}^{2} a_i P^i{}_{AC} \qquad \text{..........(3.9)}$$

When,

- P_{PV} is input power from the PV array
- a_i is the coefficients that are determined to

a_0 = 7.32

a_1 = 9.727×10^{-3}

a_2 = 2.432×10^{-5}

3.3.4 Pipe system

The pipe system is one main point that effects the system. We can find the efficiency of this by using this formula.

$$H_T = H_S + H_F \qquad \text{.........(3.10)}$$

When,

H_T	is the total head, m
H_S	is the static head, m
H_F	is the friction loss in the pipe, m

3.3.5 System Efficiency

The average efficiency of the PV water pump system is defined as:

$$\eta_{PV} = \frac{\rho g H_T Q}{G_{Tilt} \times A_{PV}} \qquad \text{..........(3.11)}$$

When,

ρ	is the density of water (1,000 kg/m^3)
g	is the gravitational acceleration (9.81 m/s^2)
H_T	is the total head, m
Q	is the flow rater, m^3 / s
G_{Tilt}	is tilt angle radiation, W/m^2
A_{PV}	is PV area, m^2

3.3.6 Irradiation sum, H

The irradiation sum is defined as:

$$H = \int_{Period} G_T \, dt \qquad \text{..........(3.12)}$$

When,

H	is irradiation sum, kWh/m^2
G_T	is global radiation, kW/m^2
Period	is the time set, hour

3.3.7 Referents irradiation, H_{ref}

The referent irradiation is defined as:

$$H_{ref} = \frac{1}{G_{STC}} \int_{Period} G_T dt \qquad \text{.........(3.13)}$$

When,

H_{ref} is referent irradiation, h

G_{STC} is global radiation at standard testing condition = 1,000 W/m^2

3.3.8 Referents yield, RY

The referents yield is defined as:

$$RY = \frac{1}{n \times G_{STC}} H \qquad \text{..........(3.14)}$$

When,

RY is referents yield, h

n is amount of day, day

H is irradiation sum, kWh/m^2

G_{STC} is global radiation at standard testing condition = 1,000 W/m^2

3.3.9 Nominal Power

The nominal power is the value that uses for calculating the power of PV module. It can be found by this formula.

$$P_N = k \times P_{rate,\ module} \qquad \text{..........(3.15)}$$

When,

P_N is the nominal power, kWp

k is amount of module. Module

$P_{rate,\ module}$ is the module power that test at STC, kWp

3.3.10 PV module efficiency

The PV module efficiency can be found by

$$\eta_{STC,\ module} = \frac{P_{rate,\ module}}{A_{module} \times G_{STC}} \qquad \text{..........(3.16)}$$

When,

$\eta_{STC,\ module}$ is the PV module efficiency at STC

A_{module} is the module area, m^2

G_{STC} is the radiation at standard testing condition = 1000 W/m^2

3.3.11 Nominal Energy

The nominal energy is the value that is used to find the energy from a PV module. It can be found by this formula.

$$E_N = H_{Tilt} \times A_{module} \times k \times \eta_{STC,\,module} \qquad \text{..........(3.17)}$$

When, H_{Tilt} is the tilt angle radiation on the module, W/m^2

3.3.12 Utilizable PV Energy

In operation, the value of utilizable PV energy will be found from the energy that is uses or energy losses in the system. In this system, the energy that is used or energy losses is the power that the inverter uses. So, we can find the utilizable PV energy from this formula.

$$E_{PV,\,use} = \int_{period} P_{AC}\, dt \qquad \text{..........(3.18)}$$

When,

$E_{PV,\,use}$ is the value of utilizable PV energy, kWh

P_{AC} is the AC power and energy power, kWh

3.3.13 PV system performance number

Normally, the performance ratio will be calculated as a monthly or yearly value. The performance ratio will equal 1 when the system works at the standard condition and does not have an energy loss. In the long term, the value of the performance ratio is lower than 1, but in the short term the performance ratio is near 1. The performance ratio can found by this formula.

$$PR = \frac{E_{PV,\,use}}{H_{TILT} \times A_{module} \times k \times \eta_{STC,\,module}} \qquad \text{..........(3.19)}$$

3.3.14 Final yield

A daily rated operation time, final yield defined as reference yield that is.

$$FY = \frac{1}{n \times P_N} E_{PV,\,use} \qquad \text{..........(3.20)}$$