July 2004 • NREL/SR-500-30481

Subcontractor Report

Renewable Energy Water Pumping Systems Handbook

Period of Performance: April 1–September 1, 2001

Neway Argaw
Denver, Colorado

National Renewable Energy Laboratory
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Operated for the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
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Contract No. DE-AC36-99-GO10337

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NREL Technical Monitor: L. Flowers

Prepared under Subcontract No. RAM-1-31224-01

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This publication received minimal editorial review at NREL

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

Contents

1. Introduction

1.1 Background

Water is the source of life, and the availability of water has become more crucial than ever before. The demand for water grows along with the world's population. The need for water to irrigate land, which will then produce more food, as well as clean water for drinking purposes, is crucial in coping with the world's population growth.

A source of energy to pump water is also a big problem in many developing countries. Developing a grid system is often too expensive because rural villages are frequently located too far away from existing grid lines. Depending on an imported fuel supply is difficult and risky; foreign exchange rates fluctuate and the economy of many developing countries can then plummet. Even if fuel is available within the country, transporting that fuel to remote, rural villages can be difficult. There are no roads or supporting infrastructure in many remote villages where transportation by animals is still common. Transportation by animals limits load capacities, and some loads, diesel generators, for example, may be impossible to bring to such locations.

The use of renewable energy is attractive for water pumping applications in rural areas of many developing countries. Transportation of renewable energy systems, such as wind machines and photovoltaic (PV) pumps, is much easier than other types because they can be transported in pieces and reassembled on site.

Traditional windmills have been used to pump water in the Great Plains of the United States and many developing countries for the last century. These wind pumps are used for irrigation, livestock watering, and domestic water supplies. This technology, with little modification, is still attractive in many developing countries. More recently, the development of electrical wind turbines has become especially attractive for a greater variety of multipurpose applications. These turbines can directly produce alternating current (AC) or direct current (DC) power output. A wind turbine can be designed for one of four output configurations: grid connection, battery charging, direct resistance heating, and direct powering of an electric motor.

Another relatively new technology harnesses solar energy. This technology, referred to as *photovoltaics* (PV), converts the sun's energy into electricity through electromagnetic means when the PV module is exposed to sunlight. The solar radiation energy is converted into DC power and requires an inverter to convert it into AC power. This technology has uses similar to electrical wind turbines, and has become the power supply for such applications as operating lighting and refrigerating vaccines in health clinics. PV has also been used to power rural communications. This technology is ideal for water pumping applications because energy storage is not required for night pumping as the energy is stored in the form of water.

Hybrid systems (wind, PV, and diesel) are also popular in providing a reliable, uninterrupted power supply. Wind and PV hybrid systems are ideal combinations because oversized systems are not necessary. This is because the wind system can operate at night when solar radiation energy is absent. Diesel generators are used as a backup, in case of power shortages from the wind and PV systems.

1.2 Purpose of This Book

The world energy demand is increasing, and the search for alternative energy sources is a crucial issue to ensure future energy supplies. Developing countries currently account for 30% of global energy use, and approximately two billion people still live without electricity. As the world's population increases and the desire for basic services (such as electricity, water supplies, health services, and education) grows, supplying energy from the traditional grid system will be difficult because of infrastructure problems and the lack of economic resources in these developing countries. People not served by the power grid often rely heavily on fossil fuels. However, these fuels are often imported and price fluctuations in these fuels can disrupt the supply. Renewable energy technologies have great potential to fulfill the needs of people in these developing countries.

Water is one of the most basic necessities for rural development. This book provides valuable information on how these renewable energy technologies can be used for irrigation, livestock watering, and domestic water supplies. Chapter 2 emphasizes wind and solar energy resources, and chapter 3 provides detailed information on wind, PV, and hybrid water pumping systems.

Chapters 4, 5, and 6 present the design, installation, safety, and operation and maintenance aspects of these technologies. The design consideration includes the practical aspects of site and power source selection criteria, field data collection, monitoring procedures, and system sizing. The installation, safety, and operation and maintenance chapters include installation guidelines and advice on safe operation and maintenance of these systems.

Chapters 7 and 8 present the economical and external impacts evaluation techniques of these technologies through various methods and approaches. Case studies using evaluations of various water pumping systems are presented in the appendices. The appendices also include wind and solar radiation energy maps of the world, the tilted factor coefficients used for sizing PV pumps, and formats used for data collection and monitoring.

2. Wind and Solar Energy Resources

2.1 Wind Energy Resources

Wind is an intermittent resource; it can be calm one day and howl the next. Wind is extremely variable and unpredictable over even a day's time. The average wind speed can vary widely from month to month, season to season, and year to year. As examples, Figures 2.1 and 2.2 show the monthly and daily average wind speed at Bushland, Texas, as recorded by the U.S. Department of Agriculture (USDA), Agricultural Research Service, at 10 m height. Figure 2.1 shows that the monthly average wind speed over 14 years (from 1983–1996) varies from 4.5–7 m/s. Similarly, Figure 2.2 shows that the daily average wind speed varies from 3–10 m/s over the year 1992.

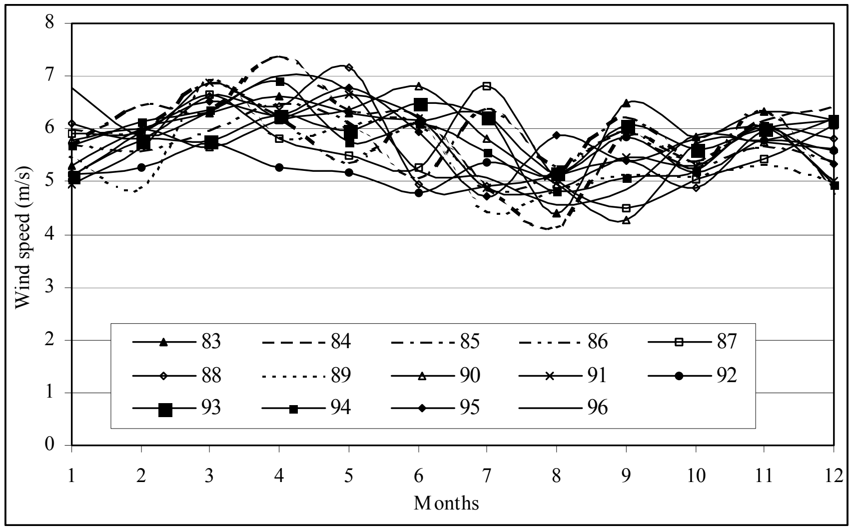


Figure 2.1. Monthly average wind speed at Bushland, Texas, U.S. Department of Agriculture, Agricultural Research Service, measured at 10 m height from 1983 to 1996.

Generally, wind is calm in the morning and gusty in the afternoon. Early spring is usually windy and summer is typically calm. The complex subject of the cause and behavior of wind is discussed in Gipe (1993).

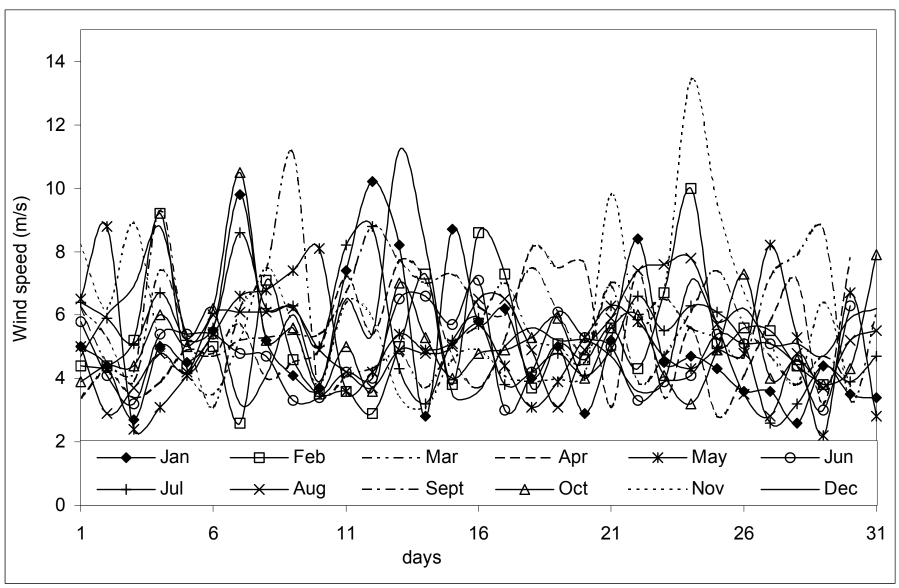


Figure 2.2. Daily average wind speed at Bushland, Texas, U.S. Department of Agriculture, Agricultural Research Service, measured in 1992 at 10 m height.

Winds gather strength near shores of big lakes and along coasts, basically because of unobstructed paths and sea-to-land breezes, caused by heat variations. Mountain-to-valley breezes are another example of local winds caused by heat variations. Wind speed increases as winds pass over mountain ridges, especially when they pass around the end of the mountain ridges. Ridge tops also have more frequent winds.

Wind speed varies with height above the ground. Wind moving across the earth's surface encounters friction caused by turbulence over and around buildings, mountains, trees, and other obstructions. These effects decrease with increasing height above the surface until unhindered airflow is maintained. Consequently, wind speed increases as turbulence decreases.

Any obstruction to the wind has a wake, which depletes the wind's energy and creates turbulence. In the vicinity of obstructions, wind speed decreases and turbulence increases. Turbulence can wreak havoc on a wind machine and shorten its life. Therefore, wind machines typically have to be mounted on a high tower so the rotor's bottom edge is at least 10 m (30 ft) above and 100 m (300 ft) away from any obstruction. Wind machines have to be located away from a zone of disturbed flow, shown in Figure 2.3.

Table 2.1. Surface Roughness (α) for Different Terrains.

Type of terrain	α
Smooth sea or sand	0.10
Low grass steppe	0.13
Smooth level, grass-covered terrain	0.14
High grass and small bushes	0.19
Woodlands and urban areas	0.32

Source: Fraenkel (1986), and Battelle Pacific Northwest Laboratory (PNL) (1987).

As mentioned, wind speed increases with height. The rate of increase depends partly on height and partly on the nature of the ground surface. Rough ground with uneven trees, buildings, and other obstructions causes turbulence. On the other hand, flat and unobstructed surfaces, such as the sea or a flat, grassy plain, allow the wind to flow smoothly and results in higher wind speeds near the surface. Table 2.1 shows the surface roughness (α) for different terrain. The relationship between wind speed and height, according to Fraenkel (1986), can be estimated as:

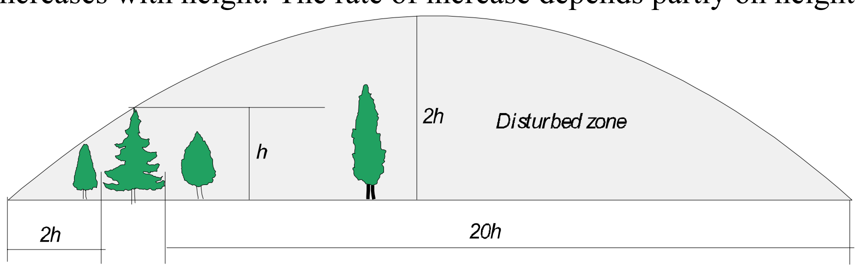


Figure 2.3. Zone of disturbed flow.

$$\frac{S}{S_r} = \left(\frac{h}{h_r}\right)^{\alpha}, \qquad (2.1)$$

where S is the wind speed at height h, and S_r is a reference wind speed measured at height h_r. The value α is a function of the surface roughness.

2.1.1 Wind Speed Measurements

The simplest method of measuring mean wind speeds is by using a cup-counter anemometer. In this method, the wind speed and time of each of two readings are noted and the difference between two readings is divided by the time interval. Another simple instrument used to measure wind speed is the anemometer with a meter, which displays the wind speed instantaneously, or on a recorder. The sensor (the anemometer head) generates an electrical signal that is proportional to wind speed. Cup anemometers with spinning cups driving either DC or AC alternators with digital displays are far more common. Anemometers with AC alternators, which measure frequency, are usually more accurate than those using DC generators. The strip-chart recorders once used are now obsolete. Instruments that measure wind speed instantaneously are useless for finding the average wind speed unless someone checks them 24 hours a day. Today, most instruments measure and store wind data, as well as giving wind speed instantaneously. They can collect, process, and store average wind speed, elapsed time, peak gust, and power density (in W/m^2).

According to World Meteorological Organization (WMO) recommendations, wind measurements must be made at a height of 10 m with no obstruction. Unfortunately, in most small, rural meteorological stations, anemometers are set up on 2-m-tall masts and are surrounded by trees or buildings. Any readings from such sites are practically useless for wind energy prediction purposes. Such readings are useful for agricultural purposes; however, by estimating water use by crops. In general, three years of recordings are required to obtain reasonably representative averages, as the monthly average wind speeds can vary by 10–20% or so from year to year. A wind energy map of the world is included in Appendix A.

2.1.2 Estimating Wind Energy Resources

The power in the wind is a function of its speed and air density, and is estimated by the relation,

$$P = \frac{1}{2}\rho_a A S^3, \tag{2.2}$$

where P is the power, ρ_a is the density of air (approximately 1.2 kg/m^3 or 0.075 lb/ft^3 at sea level), A is the swept area of the rotor, and S is the wind speed.

Table 2.2. Variation of Air Density with Altitude Above Sea Level (a.s.l.).

Altitude, ft	0	500	1000	2000	3000	5000	6000	7000	8000	9000	10,000
Altitude, m	0	152	305	610	915	1524	1829	2134	2439	2744	3049
Correction factor	1.00	0.99	0.97	0.94	0.91	0.85	0.82	0.79	0.76	0.73	0.70

Sources: Gipe(1993) and Fraenkel et al. (1986).

Density of air decreases with increasing temperature and increasing altitude. For example, at 3,000 m (10,000 ft), the density of air decreases by 30%. Density of air varies from season to season, from 10–15%. Table 2.2 shows the variation of air density with altitude.

Unlike the changes in air density, changes in the swept area of a wind turbine rotor significantly change the power. Doubling the area of the rotor doubles the power of the wind. The area of the rotor is estimated from

$$A = \pi r^2, \tag{2.3}$$

where A is the area, and r is the radius of the rotor. The most important factor for the amount of available wind energy; however, is the wind speed. This is because the power in the wind is a cubic function of the wind speed. In other words, double wind speed will increase the power eight times. *Power density* is a term frequently used for convenience, because it explains the intensity of the wind energy per unit rotor area for a given period of time.

2.2 Solar Energy Resources

The energy available at the surface of the sun is 60,000 kW/m^2, while the sun's radiation at the top of the earth's atmosphere is only about 1.4 kW/m^2. After it passes through the atmosphere, about 80 trillion kW of solar radiation energy is available globally. This is about 13,000 times the present world energy use. The energy we get from solar radiation is in the form of electromagnetic radiation, which includes radio waves, X rays, and ultraviolet, infrared, and visible light.

The solar spectrum on the earth's surface, beneath its protective atmosphere, is quite different from the incident spectrum at the top of the atmosphere. This is because of the absorption properties of atmospheric gases. The intensity of solar radiation at ground level, considering all wavelengths that reach the earth, is on average 47% of all incident solar energy reaching the top of the atmosphere. The atmosphere absorbs 19% of the solar radiation, and 34% is reflected away from the earth. Of the 47% of all the solar energy incident on the upper atmosphere, about 51% is direct and unscattered, and about 49% is scattered and diffused. On a relatively clear day, perhaps 75% would be direct and unscattered.

Although radiation from the sun's surface is reasonably constant, by the time it reaches the earth's surface it is highly variable because of absorption and scattering in the earth's atmosphere. When skies are clear, maximum radiation strikes the earth's surface when the sun is directly overhead, and sunlight has the shortest path through the atmosphere. The path can be approximated by $1/\cos\phi$ when the sun is at an angle ϕ to overhead. This path is referred to as the *air mass* (AM) through which solar radiation must pass to reach the earth's surface. Therefore:

$$AM = 1/\cos\phi \tag{2.4}$$

Hence, when $\phi = 0$, the air mass equals 1, or AM1 radiation is being received; when $\phi = 60^o$, AM2 conditions prevail. Air mass zero (AM0) is constant and referred to as the *solar constant*, with a generally accepted value of 1.367 kW/m^2. AM1 radiation (radiation when the sun is directly overhead) has a diffuse component of about 10% when skies are clear**.** The percentage goes up with increasing air mass or when skies are not clear. AM1.5 (when ϕ = 48.2^o from overhead) has become the standard for photovoltaics. The air mass, according to Wenham et. al, (1994), can be estimated at any location using the following relation:

$$AM = \sqrt{1 + \left(s/h \right)}\,, \tag{2.5}$$

where s is the length of the shadow cast by a vertical post of height h.

The effect of cloud cover in blocking sunlight is most marked when cumulus clouds (heavy clouds at low altitude) cover the sky. However, about half the direct-beam radiation blocked by cumulus clouds is recovered in the form of diffuse radiation. Two-thirds of direct-beam radiation can be converted to diffuse radiation from cirrus (wispy and high-altitude) clouds. On a totally cloudy day with no sunshine, most radiation reaching the earth's surface will be diffuse.

The intensity of the solar radiation energy reaching a PV array depends on the effect of the sun's angle on the array, the location of the array, the effects of the earth's orbit around the sun, and the effects of the earth's daily rotation around its axis. The principal geometric attribute of the PV array is the direction in which it faces. This direction can be characterized by a line perpendicular (normal) to the array surface. The orientation of the array can be specified by the tilt angle β and the azimuth angle γ. The tilt angle is measured from the horizontal and is usually equal to the latitude of the PV array's location. The azimuth angle, like a compass heading, is a bearing clockwise from the north to the horizontal projection of the array normal.

As the PV array is inclined away from facing directly toward the sun, the intensity of the radiation on the array decreases. The amount of solar radiation intercepted by the surface varies as the cosine of the incident angle θ between the sun's rays and the normal to the surface. The incident angle to a horizontal surface is called the *zenith angle* θ_z.

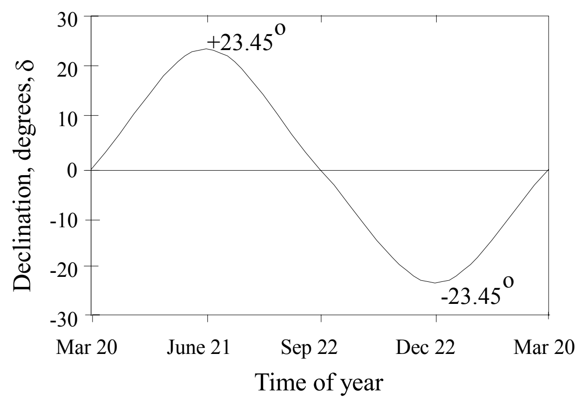


Figure 2.4. Yearly variation of the solar declination angle in the northern hemisphere.

The sun shines at different angles in different places on the earth. As the latitude increases, the curvature of the earth has the effect of lowering the observed sun angle in the sky. Therefore, the array needs to be tilted toward the equator to compensate for this effect. A PV array tilted south at an angle β at latitude ϕ has the same sun incidence angle θ as a horizontal PV array at latitude of $\theta-\beta$.

The earth revolves around the sun once a year in an elliptical orbit; it is closest to the sun in winter and farthest in summer. This variation in distance produces a nearly sinusoidal variation in the intensity of solar radiation G that reaches the earth. This is approximated by the equation:

$$\frac{G}{G_{sc}} = 1 + 0.033\cos\frac{360(D-2)}{365}, \qquad (2.6)$$

where G_{sc} is the solar constant (1.367 kW/m^2), and D is the day of the year. The day of the year can be found from the tables in many solar energy books.

Every day, the earth spins around an imaginary axis that is oriented at a fixed angle relative to the normal plane of the earth's yearly orbit around the sun. This angle is the inclination of the earth (23^{o}27'). The direction of the earth's daily rotational axis is essentially fixed in space. This causes a different tilt angle or declination δ of the equator plane relative to the sun–earth line for the different seasons of the year. The times of minimum and maximum declinations are known as the winter and summer solstices, respectively. Between winter and summer, the declination swings through zero, and these times are known as the vernal and autumnal equinoxes. Since the earth's orbit is nearly circular, this curve can be approximated by the sine function:

$$\delta = 23.45\ \sin\frac{360(D-81)}{365}, \qquad (2.7)$$

where δ is the solar declination, and D is the day of the year. Figure 2.4 shows the variation of the declination angle in the Northern Hemisphere at different times of the year.

The hour angle ω is 0^o at solar noon and increases with decreasing time to 360^o. Because the earth rotates 15^o per hour,

$$\omega = 15(H_s + 12) \text{ in the morning,} \qquad (2.8a)$$

or,

$$\omega = 15(H_s - 12) \text{ in the afternoon,} \qquad (2.8b)$$

where H_s is the standard time. The sunrise hour angle (ω_s), when the zenith angle of the sun θ_z is 90^o, is calculated from:

$$\omega_s = \cos^{-1}(\tan\phi\ \tan\delta) \qquad (2.9)$$

The sunset hour angle is equal to the sunrise hour angle except for the sign difference, when facing directly to south or north. The day length N_d is $2\omega_s$, and expressed in hours:

$$N_d = (2/15)\cos^{-1}(\tan\phi\ \tan\delta) \qquad (2.10)$$

The sunrise hour angle at a tilted surface ω_s' facing the equator, in degrees will be:

$$\omega_s' = \cos^{-1}\{\tan(\phi - \beta)\tan\delta\} \qquad (2.11)$$

For example, on June 21 at Addis Ababa City, Ethiopia, the sunrise hour angle is 86^o (at 6:16 a.m.) and the sunset hour angle is -86^o (at 5:44 p.m.). Day length is 11 hours, 28 min. The sunrise hour angle on a PV array tilted at 15^o, at the same location, is $92^o36'$ (at 5:50 a.m.) and sunset is at $-92^o36'$ (at 6:10 p.m.). The day length is 12 hours, 20 min. From this example we can see that it is possible to use PV arrays for longer hours and produce more energy just by changing the tilt angle of the PV array. But this is not always true; there are seasons when the horizontal position is more effective than tilting the PV array, because of the change in sun's position. This situation is explained by a term called *tilted factor*. Tilted factor is a non-dimensional coefficient used to calculate the solar radiation on a tilted surface by multiplying the tilted factor by the solar radiation energy on the horizontal surface.

The tilted factor F_T is the ratio of the cosine of the incidence angle θ to the cosine of the zenith angle θ_z, or the ratio of solar radiation on a tilted surface to that on a horizontal surface, for any season of the year at different latitudes and tilt angles. These factors are presented in appendix B. A solar radiation energy map of the world is included in appendix A.

The tilted factor varies from season to season. Like the intensity of solar radiation energy, the tilted factor values vary depending on the location, season of the year, and the tilt angle. For example, in Addis Ababa, the tilted factor varies from 0.9 to 1.13 on a 15^o tilt angle of a PV array facing directly south. Figure 2.5 shows the yearly variation of the tilted factor at the Addis Ababa meteorological station for a tilt angle $\beta = 15^o$ and azimuth angle $\gamma = 0^o$. It is obvious that solar radiation energy on a tilted surface will be lower than on the horizontal surface when the tilted factor is less than 1. Therefore, it is important to vary the tilt angle, depending on the season. For example, July is the rainy season in Addis Ababa, and the tilt factor is also smallest. In such cases, it is advantageous to use the PV array on the horizontal surface to get more solar radiation energy.

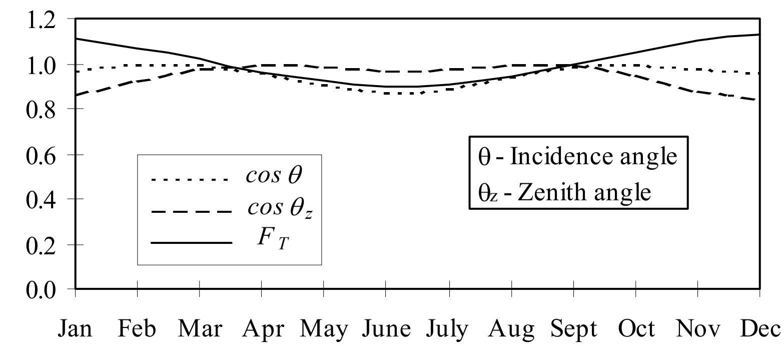


Figure 2.5. Yearly variation of the tilted factor at Addis Ababa meteorological station for tilt angle of $\beta = 15^o$ and azimuth angle $\gamma = 0^o$ (Argaw, 1996).

PV systems based on concentrated sunlight can usually accept only rays spanning a limited range of angles. A tracking system can be used to allow PV arrays to follow the movement of the sun to use the direct component of sunlight, with the diffused component wasted. This tends to offset the advantage gained by such tracking systems of intercepting maximum power density by always being normal to the sun's rays.

2.2.2 Measuring Solar Energy Resources

The effective design of PV systems depends greatly on the availability and accuracy of solar radiation data. Unfortunately, accurate data are rarely available from remote locations where many PV systems are to be installed. There are; however, numerous approaches that have been developed for estimating solar radiation energy, based on commonly available sunshine hour data, cloud cover data from satellite observation, or direct measurements.

Sensing equipment

Various instruments exist for measuring insolation levels. Direct beam solar radiation is usually measured by a pyrheliometer, and global solar radiation is usually measured by a pyranometer. Diffuse radiation can be measured if the pyranometer is shaded. Silicon-based sensors are used to measure incidence radiation. These types of instruments, categorized as photoelectric devices, measure the intensity of solar radiation directly through changes in electrical characteristics.

Other types of instruments include bolometric devices. These instruments operate on the principle of Ångström or electrical compensation. The simplest is the heliograph, which measures the bright sunshine hours by using focused light to burn a hole in a rotating chart. Campbell-Stokes recorders were the commonly used instruments for many years and are still in use today in many developing countries. It should be noted that estimating solar radiation based on sunshine hours data from Campbell-Stokes recorders is considered obsolete and can result errors of more than $\pm$10%.

Silicon-based sensors are the most advantageous for measuring the intensity of solar radiation for PV cells because they accept the same wavelength ranges as the normal pyranometers.

Weather data

Solar radiation is the only source of energy for PV systems, and the use of this technology for some applications, such as pumping water, requires systematically processed weather data. The most commonly used weather data in designing PV systems are solar radiation, ambient air temperature, and wind speed data. PV systems are sensitive to weather changes and their performance changes accordingly. Unfortunately, it is impossible to forecast long-term weather conditions. Therefore, it is necessary to depend on systematically processed historical weather information, which should cover as many years as possible. The simplest method for designing PV systems may be the use of long-term average weather data. Average data do not reflect the extreme solar radiation days; however, and the system must consistently meet its intended daily requirements. For this reason, typical meteorological year (TMY) is now used in designing PV systems. The term *typical* refers to the long-term database covering a one-year period. The TMY is a fictitious yearly database, since no actual year has the same diurnal solar radiation pattern represented by the TMY.

3. Wind, Photovoltaic, and Hybrid-Powered Water Pumping Technologies

3.1 Wind Pumps

Wind power has been used to pump water since the early thirteenth century, when the technology was employed for dewatering polders in the Netherlands (Fraenkel 1986). Small wooden wind pumps were also used in France, Portugal, and Spain to pump seawater to produce salt. Later the American wind pump, made of steel, with a multibladed fan-like rotor, became the most popular water pumping technology. It was introduced initially to pump water for domestic purposes and for use by railroads between 1860 and 1900. In the early 1900s the wind pumps were used to water livestock on the North American Great Plains.

During the last 100 years, more than eight million windmills have been manufactured in the United States alone, and the design has proven so successful that the technology has been copied around the world. Today over one million windmills are estimated to be in use, mostly in United States, Argentina, and Australia. This type of pump drives a piston (reciprocating) pump linked to reduction gear directly below in the borehole. More recently, the Intermediate Technology (IT) windmill has been produced. The IT windmill was designed by IT Wind Pumps in the 1980s and manufactured in Kenya as “Kijito” and in Pakistan as the “Tawana.” Although not as reliable as the all-steel American or Australian windmills, IT windmills are about half as expensive as the traditional windmills (Fraenkel 1986). In general, the traditional windmills are much less efficient than electrical wind turbines because the blades are not true airfoils.

Traditional windmills have a peak rotor efficiency of 25% to 30%, as compared to 35% to 45% for electrical wind turbines with true airfoils. The main difference is that windmills with numerous blades, typically 12–18, produce a high starting torque, which is required to operate the piston pump. The overall wind-to-water efficiency for water pumping windmills is 4–8%. In all cases, wind water pumping units have been designed beginning with the pump and then the rotor and gearing. The Dutch windmill uses a screw pump that has a medium starting torque and low speed requirement; thus uses a thick heavy rotor with four sails. The American and Australian windmills use a piston pump that has a high starting torque and a slow operating speed; thus uses a multibladed rotor that furls to slow down when wind speeds exceed 10 m/s. Electric wind pumpers use centrifugal pumps with low starting torques, requiring high operating speeds. For these pumps, a two- or three-bladed rotor with airfoils is designed to give high rotational speeds.

Development of electrical wind turbines to generate either DC or AC current began in the late 1920s. These types of turbines are designed to produce electricity ranging from a few watts (for charging batteries) to a few megawatts. The maximum-size turbine currently made is 1.5 MW in Europe and 5 MW in United States. The minimum common-size wind turbine is 50 W; however, there are also extremely small turbines that produce only few watts and can be erected and taken down by a single person. These turbines can be used for charging batteries on sailboats and recreational vehicles.

Typical wind machines can be designed to rotate either horizontally or vertically (see Figure 3.1). The horizontal-axis types are currently the most practical. One of the main advantages with the vertical axis is they accept the wind from any direction. The most common vertical-axis types of windmills are the Panemone differential drag devices, the Savonius rotor (or S-rotor), and the Darrieus wind turbine. Panemone differential drag devices were used in ancient Persia for grinding grains. The Finnish inventor, Sigurd Savonius, developed the Savonius rotor, with an S-shaped vertical axis, in 1924. The S-rotors, like the farm windmill, extract less than 15% of the wind's power, and because of this limitation, Savonius rotors have never been commercially successful. Darrieus turbines have different configurations, including H, delta, diamond, Y, and phi ϕ shapes.

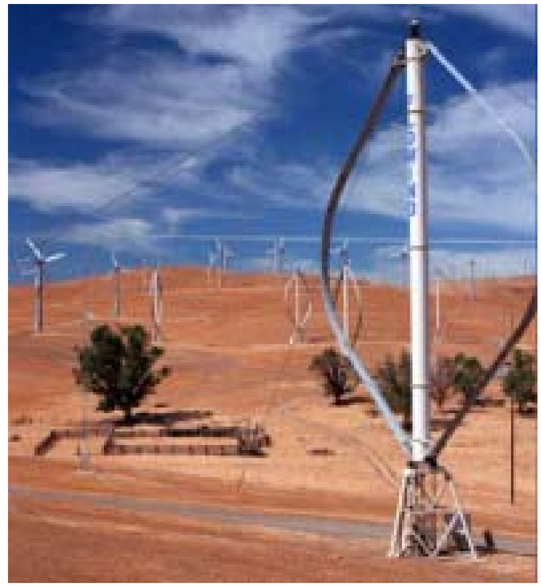


Figure 3.1. Horizontal- and vertical-axis wind machines at Tehachapi, California. These horizontal axis turbines are the typical medium-size, three-bladed turbines. The vertical turbines are the typical Troposkien-shaped, Darrieus vertical axis turbines commercialized by FlowWind, which were never successful in the market. However, there are still considerable numbers of Darrieus design turbines operating in California.

Regardless of whether a wind machine rotates in a vertical or horizontal axis, it depends on either of two aerodynamic principles (drag or lift) to derive power from the wind. Drag force works by simply obstructing the wind and creating turbulence. The drag force acts in the same direction as the wind. Drag devices are simple wind machines that use flat, curved, or cup-shaped blades to turn the rotor. Cup anemometers, Panemones, and Savonius rotors are typical drag devices. Drag devices can produce high starting torque because much of the rotor’s area is covered with blades. They are ideal machines for pumping water in low volumes. Drag devices also require more materials than the wind machines operating with lift.

Lift devices use airfoils to propel the rotor. The lifting force mechanism is operated by blades mounted at a small angle to deflect the wind and produce a greater force perpendicular to the direction of the wind, with much smaller drag force. The maximum possible power captured by wind-using lift devices is 59% (Bert limit). This makes lift devices more attractive for generating electricity than drag devices. Wind turbines operating with airfoils can be designed with single, double, or triple blades. Wind turbines with one slender blade, such as the German Messerschmitt-Bolkow-Blohm (MBB) turbines, can capture wind power efficiently, but two blades are often used for static balance. Two-bladed turbines; however, experience dynamic imbalance when the wind machine changes direction. Three-bladed wind turbines have better dynamic stability.

3.1.1 Mechanical Wind Pumps

The old American windmills (Figure 3.2) have evolved in terms of weight, cost, and efficiency. Two major improvements include the development of a counterbalance on the weight of the sucker rod and the variable-stroke design. These improvements could double the water output of the traditional farm windmill.

One of the problems with traditional windmills was their tendency to speed up when the sucker begins to go down, and then slow down on the upstroke, a result of lifting the weight of both the rod and the water. This speed variation changes the tip-speed ratio of the rotor and its efficiency. Adding a counterbalance weight on the suck rod or springs could solve this problem. In this way, steady rotor speed is maintained with a more optimum relationship between the wind speed and the rotor. This concept was tried experimentally, but windmills incorporating the improvement have not yet been manufactured.

Figure 3.2. Traditional farm windmill installed in Valantine, South Dakota.

A second fundamental problem with traditional wind pumps was the relationship between wind speed and stroke. The power in the wind increases cubically with wind speed, while the water discharge rate (pumping rate) of the piston pump increases linearly. This relationship affects the performance of the wind pump because the stroke of the old wind pumps had a fixed position. If the stroke is adjusted for optimum production at high speed for a given well depth and pump size, then the pump performs poorly at low winds, and vice versa. The stroke should be able to vary along with the wind speed for better matching of the pumping rate with the available power of the wind. For this reason, modern wind pumps are designed with variable stroke ability.

The principle of operation in the piston pump is that when water is sucked into the cylinder through a check valve on the upstroke, the piston valve is held closed by the weight of water above it, and simultaneously, the water above the piston is pumped out of the cylinder. On the down stroke, the lower check valve is held closed by both its weight and water pressure, while the piston valve is forced to open to displace the trapped water through the piston. Then, the upstroke follows to repeat the next cycle.

Modern wind pumps are designed to use only 6 to 8 blades of true airfoils, in contrast to the traditional windmills, which have typically 12 to 18 curved steel plates. (Traditional wind pumps rotor diameters are from 2 to 5 m (6 to 16 ft) and Australia's Southern Cross wind pumps are available up to 8 m (25 ft). As a result of these design changes, modern wind pumps are twice as efficient as traditional wind pumps. Similarly, the cost of wind pumps also decreases by using fewer blades. However, modern wind pumps are still bulky and are best suited for light wind regions.

"Third generation" windmills use a direct drive mechanism, rather than a geared transmission. They are designed to produce high torque at low wind speeds and provide rotor speed control at high wind speeds. The main objective of this type of design is to reduce starting torque. This is possible because of the counterbalance attached to the actuating pump beam, which is designed to reduce the starting rotor torque to start pumping. According to a report made by Kentfield and Cruson (1989), a direct-drive-type wind pump developed at the University of Calgary, Canada, can start pumping at 50% lower rotor torque (or 30% less wind speed) relative to a system with no counterbalance. The windmill basically uses a pump similar to an oil field jack style pump, called a *reciprocating* or *crank piston pump*, or a positive displacement pump. These types of wind pumps are promising because they are do not use gearboxes for power transmission from the rotor to the shaft.

3.1.2 Electrical Wind Pumps

A more promising technology than mechanical wind pumps is the development of electric wind turbine pumps. Modern wind generators can produce AC- or DC-electric output and can be used to pump water directly connected to AC or DC motors. Centrifugal pumps are used for this technology, since electric wind turbines are designed for low-solidity rotors. Bergey Windpower developed this innovative idea in association with the U.S. Department of Agriculture (USDA). This technology eliminates the use of batteries and inverters by directly coupling the wind turbine with an AC motor, which then drives the centrifugal pump at varying speed. This technology simplifies the problem of matching wind turbines with appropriate water pumps, by varying the load electrically instead of mechanically in much the same way as varying the stroke in windmills. This technology also allows wind turbines to be located where the winds are strongest, typically at the crest of hill. Traditional windmills must be located directly over the water source, usually at the foot of a hill. A 50 kW electrical wind turbine is shown in Figure 3.3.

Figure 3.3. A 50 kW electrical wind turbine located at the USDA-Agricultural Research Service, Bushland, Texas.

Unlike traditional windmills, electric wind turbines require a higher starting wind speed and perform better in high winds than low ones. Electric wind pumps are twice as efficient as traditional windmills and are cost-competitive compared to diesels, PV systems, or traditional windmills. Modern electric wind turbines have fewer moving parts than traditional windmills, which keep maintenance costs low. Electric wind turbines are also quite versatile.

As mentioned, the theoretical maximum conversion efficiency of kinetic energy used by the perfect wind turbine is 59.3% (the Betz limit). In practice; however, wind turbine rotors convert much less energy than the Betz limit. Optimally designed rotors reach slightly above 40% efficiency.

3.2 Photovoltaic Pumps

PV-powered water pumps are basically similar to any other pumping system. Just as wind turbine pumps, PV pumps use intermittent power. When there is enough sunlight, the system functions well. When there is no sunlight, the system stops, unless battery storage is available. The two basic design approaches for PV water pumping systems are to use battery backup or to use PV power directly.

The simplest PV water pumping system consists of a PV array directly connected to a DC motor and a pump. This type of configuration is used for smaller applications and is economically competitive up to a hydraulic equivalent load (the product of the daily water production and the total pumping head) of 600 m^4/d. (See appendix E for details of a case study of economic evaluations of water pumping systems.) PV pumps using DC motors are useful for individual homes and small communities.

The next simplest system is a PV array that incorporates a storage battery. Unlike other PV systems, energy from water pumping systems can be stored in the form of water in water tanks. In this case, battery storage is not necessary for night pumping. The use of battery storage is not the most efficient option, because there are unnecessary power losses in the process. A PV array used directly to pump water can also be used to store water in tanks for use at night and on days when there is poor solar radiation.

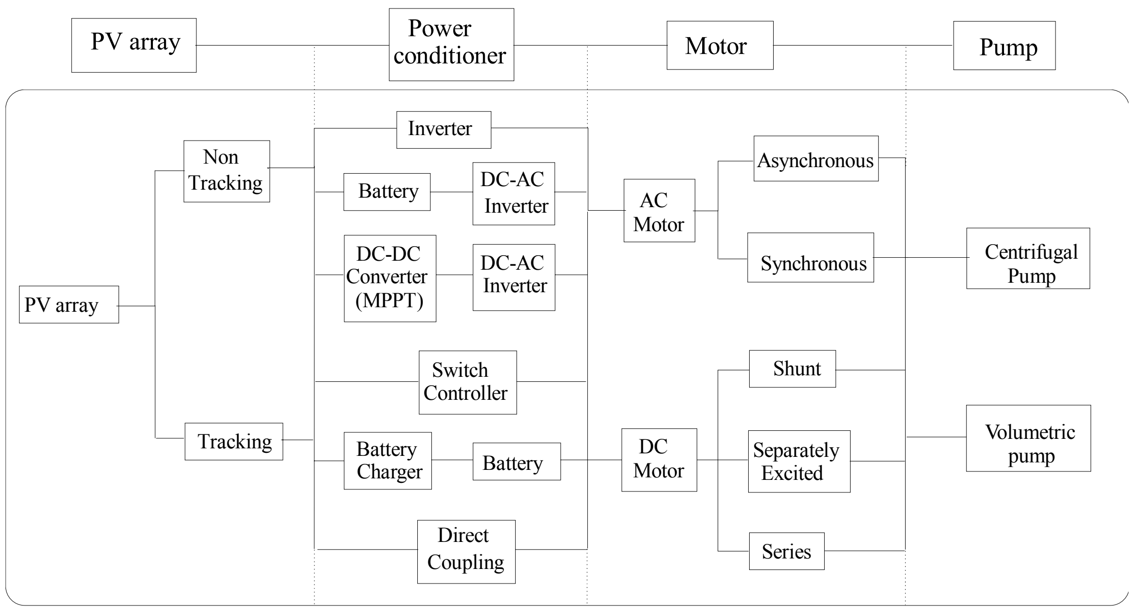


Figure 3.4. The most common components of PV water pumping systems.

PV systems coupled with AC motors require DC/AC inverters. These types of PV systems can be used for higher capacities. In complex PV systems, a backup system (diesel or wind generator, or grid connection) is required as a supplementary source of energy for poor solar radiation days (refer to Section 3.3). Generally, motors powered by PV are connected to any variable-speed (centrifugal) pump. Maximum power point tracking (MPPT) systems can be used to track the maximum power available from the PV array. Currently; however, inverters are designed to be incorporated with an MPPT device so that additional MPPT devices are not needed. Figure 3.4 shows some of the most common components of PV water pumping systems and possible combinations of these components. These combinations are determined based on the location, climate, population size, site characteristics, and the equipment used.

PV pumps for rural applications should usually be as simple as possible, so they can be easily operated and locally maintained. Simpler systems are usually cheaper and, therefore, more attractive to rural communities.

The use of PV water pumping systems varies widely, depending on the requirements and conditions under which pumping takes place. The volume of water required varies by season, time of day, and type of application. For example, water for irrigation is seasonal, while water for drinking requires a continuous supply. The availability of water from a PV pump over the course of a year also depends on several factors, such as borehole yield (the capacity of the water resource), borehole recovery rate, pumping head, seasonal variability of static head, and more importantly, the availability of solar radiation energy. The availability of solar radiation energy varies seasonally and by time of day. Therefore, a PV pumping system must be properly configured and designed, based on the need and type of application. Selection of the most suitable components, configuration, and location of the system are critical to the system's economic viability and long-term performance.

Properly matching the water pumping subsystem with a PV array is essential for maximum use of the system, yet is the main problem with many of existing PV systems. This problem is related to the non-linear solar irradiance and cell temperature-dependent voltage and current characteristics of the PV array generator. It is essential to use a unified approach to analyze the mathematical relations and models of the subsystem and the PV array.

The load-matching factor, as defined as the ratio of the energy acquired by the motor pump subsystem to the maximum PV-array power produced in a one-day period, is used as a measure of the quality of load matching. This method is based on maximizing the total gross electromechanical energy delivered to a mechanical load for given solar radiation energy and temperature profiles. Therefore, every component of the PV system should be optimized for the best possible matching of the whole system. For this reason, each component should be separately optimized beforehand, and the complete system must be configured to maximize the overall efficiency.

3.2.1 Photovoltaic Arrays

PV cells are made of semiconductor materials that generate electricity by electromagnetic means when exposed to sunlight. If a minority electron-hole pair generated by absorption of photons in the semiconductor material (the holes in n-regions, and the electrons in p-region) diffuses into a boundary region in which there is an electric field, then the electron will be accelerated into the n-region, and the hole into the p-region. This causes the n-region to accumulate a negative charge, and the p-region a positive charge, which results in a photovoltage. If there is a closed external circuit, a photocurrent and photovoltage can be measured by the external resistance. This process is explained using a simple diagram shown in Figure 3.5.

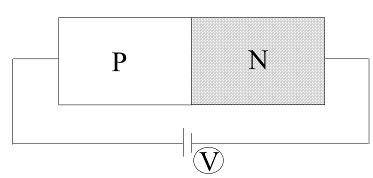


Figure 3.5. Diagram of a simple p-n junction PV cell.

It is possible to shift the balance of electrons and holes in a silicon crystal lattice by doping it with other atoms. Atoms with one more valance electron than silicon are used to produce n-type semiconductor material. Atoms with one less valence electron result in p-type material. Once the n- and p-type semiconductor materials are created, the process mentioned above will produce photovoltage. The most common materials used in forming n- and p-type semiconductor materials are phosphorus (Group V) and boron (Group III). A p–n junction can be formed either through a high-temperature diffusion process or an ion implantation process. Diffusion can be made either from a vapor phase, or out of a solid phase.

Types of semiconductor materials used to produce PV cells

The most common semiconductor materials used are mono- (single) and polycrystalline silicon (c-Si), amorphous silicon (a-Si), gallium arsenide (GaAs), copper-indium-diselenide ($CuInSe_2$), and cadmium telluride (CdTe). Crystalline silicon and amorphous silicon are the most dominant semiconductor materials for commercial PV cells. The other semiconductor materials, GaAs, $CuInSe_2$, and CdTe, do not play a big role in the short term for terrestrial purposes.

Crystalline silicon has an ordered crystal structure, ideally with each atom lying in a preordained position. Monocrystalline silicon is the most expensive type of silicon because of the careful and slow manufacturing processes required. The techniques for production of multi- or polycrystalline silicon are less critical, hence cheaper than those for a single-crystal material. The grain boundaries reduce the cell performance by blocking carrier flows and allowing extra energy levels in the forbidden gap, thereby providing effective recombination sites and shunting paths for current flow across the p–n junction.

Amorphous silicon can be produced even more cheaply than polycrystalline. There is no long-range order in the structural arrangement of the atoms, which results in areas within the material that contain unsatisfied or dangling bonds. These in turn result in extra energy levels within the forbidden gap, making it impossible to dope the semiconductor when pure, or to obtain reasonable current flow in a solar cell configuration. The incorporation of atomic hydrogen to the level of 5–10% in amorphous silicon saturates the dangling bonds and improves the quality of the material. It also increases the band gap E_G from 1.1 eV in crystalline silicon to 1.7 eV, and is much more strongly absorbing for photons of energy above the latter threshold. The thickness of material required to form a functioning solar cell is therefore much smaller.

Amorphous silicon and other thin-film technologies, in which films of very thin semiconductors are deposited onto glass or other substrates, are used for solar cells in many small consumer products, such as calculators, watches, and non-critical outdoor applications. In principle, thin film provides a low-cost means of production. However, performance and lifetimes are not yet good enough to warrant large-scale applications.

Under laboratory conditions, single-crystal PV cells with higher than 23% efficiency can be produced. The efficiency of commercial modules using silicon cells is presently around 15%. That efficiency will continue to increase gradually and is expected to be over 20% in coming years. General consensus is that 20% efficiency is feasible for commercial modules based on silicon technology. Crystalline silicon ingot technologies are most compatible, reaching 20% module efficiency. Multicrystalline ingot technologies are capable of further improvement, but are unlikely to exhibit the highest performance.

Building Photovoltaic arrays

Many individual PV cells are combined into modules sealed between layers of glass or transparent polymers to protect the electrical circuit from the environment. One or more modules are then attached to the supporting structure to form a panel, and a number of panels make up an array. The array, together with the balance of system (BOS) components, makes a complete system. The array field may be subdivided electrically into a number of sub-arrays that perform in parallel.

As the maximum voltage from a single silicon cell is only about 600 mV, cells are connected in series to obtain the desired voltage. Usually about 36 cells are used for a nominal 12-volt charging system. Standard PV modules currently available in the market range in output from less than 2 watts to about 110 watts. The PV module constitutes the basic building block from which any PV array size can be configured to suite the application.

The PV array can be a fixed, flat-plate module, or it can consist of various types of collectors, either tracked or untracked. Flat-plate arrays are normally fixed with the module supported by a structure so they are oriented due south (in the Northern Hemisphere), or north (in the Southern Hemisphere), and inclined at about the angle of latitude to maximize the amount of solar radiation received on an annual basis.

Flat-plate and concentrated modules

One possible approach to reducing the cost of a PV array, even with the present cell technology, is to reduce the area of cell required for a given power output by concentrating the light. In general, the higher the concentration ratio, the smaller the range of angles of light rays that the PV array will accept. Once the concentration ratio becomes greater than about 10, the system can only use direct sunlight and must track the sun in its path across the sky. The higher the concentration ratio, the more accurately the sun must be tracked. Concentrating the sunlight on a cell will also tend to increase its operating temperature and will decrease its efficiency, so cooling might be necessary. According to Green (1986), passive cooling is adequate for concentration ratios up to about 50. Active cooling is required for higher concentration ratios.

The PV array output can be increased by 20% compared to a fixed array by using single-axis tracking systems. A single tracker can be tilted automatically every hour along a single axis, following the sun from east to west. This system does not require a control system or power for non-concentrating PV arrays. It can be driven by a closed Freon system mounted on a pole. By using a two-axis tracker, the power output can be increased by 40% compared to the fixed array by tracking the sun along both the north–south and east–west axes. However, both the capital and maintenance costs of tracking systems are high at present. Therefore, in view of the additional complications, costs, and the need for skilled operation and maintenance, tracking and concentrating systems are not appropriate for remote sites; fixed flat-plate PV arrays are preferable.

Most arrays are designed to carry the modules at a fixed tilt angle, which maximize the amount of sunlight received over the year. The rotation of the earth accounts for the higher and lower positions of the sun, depending on the time of the year. In spring and autumn, the sun has a horizontal angle that makes the optimum tilt angle almost equal to the latitude for that location. In practice, the actual angle for an array sometimes varies, so the optimization is adjusted to suit a season with more cloud cover. For example, in areas with a marked rainy season, it may be advantageous to incline the array to be more normal to the sun in that season, thereby sacrificing a little solar energy in the dry season, when more energy than necessary may be intercepted. On the other hand, mounting the array at zero degrees from the horizontal (flat) position can be optimal at the equator. Normally it is recommended that an array be mounted at 10° at the minimum so there will be good rainwater runoff, which helps keep the array clean. The array can also be adjusted manually, on a monthly or seasonal basis, to allow for changing the solar elevation at noon. This is a relatively simple way of increasing the power output and does not add significantly to the cost. Flexibility in tilt angles for seasonal changes is marginally more economical for small systems than using a tracking system.

3.2.2 Power Conditioning Devices

Electrical power can significantly deviate from the ideal as a result of overvoltage, undervoltage, voltage spikes, chopped voltage waveform, harmonics, electromagnetic interference, etc. Power conditioners are used to suppress some or all of the electrical disturbances. Power losses may occur from using these power conditioners; however, and there may be additional costs to the system and possible system failure. So these factors have to be compensated for by improving the reliability and safety of equipment, and by adding extra water output. Some of the power-conditioning devices for PV system applications, as shown in Figure 3.4, include batteries, battery charge controllers, MPPT, DC-DC converters, DC-AC inverters, and switch controllers.

PV modules connected directly across the battery are not generally recommended. However, this connection could be suitable for certain types of batteries and systems, particularly if the solar radiation level and the load are consistent, and the system is designed conservatively. With such a connection, one must consider unexpected high temperatures or load disconnection. Blocking diodes are available to protect batteries from short circuits in the PV array, as well as to prevent discharge through the PV cells when they are not illuminated. Diode voltage droppers can also be used to ensure that the batteries do not supply excess voltages to the load. Battery voltage controllers are needed in PV-based power systems to limit discharge levels and overcharging. One of the main drawbacks with using batteries for water pumping is that battery efficiency can be as low as 60% through self-discharge; this offsets the benefit gained by operating the PV pump on poor solar radiation days or at night.

Controllers can be incremental or linear. With some systems, no separate controller is used because of the self-regulation property of the PV arrays. PV arrays rely on shunt or series regulators (such as blockingdiodes), natural self-regulating characteristics of the PV modules, and incremental or switching regulators that operate by disconnecting one array section at a time as charging current increases towards midday.

Modern electronics systems demand high-quality, small, lightweight, reliable, and efficient power processors. Linear power regulators can handle only low power levels (typically below 20 W), have a low efficiency, and a low power density because they require low-frequency (50 or 60 Hz) line transformers and filters. The higher the operating frequency, the smaller and lighter the transformers, filter inductors, and capacitors. In addition, dynamic characteristics of converters improve with increasing operating frequencies. High-power processors can be classified into three categories: DC-AC inverters, AC-DC rectifiers, and DC-DC converters.

Inverter

The main functions of an inverter include inverting the DC voltage of a PV array output into AC output, wave shaping the AC voltage output, regulating the effective value of the voltage output, and operating at or near array peak power point. The input power source can be either a DC voltage source or a DC current source. Inverters deliver AC power to load impedance. In many applications, a sinusoidal output voltage or current is required. To generate sinusoidal voltage and/or current waveforms, DC-AC inverters contain a resonant circuit, therefore they are called *resonant DC-AC inverters*. Power MOSFETs are usually used as switching devices in resonant inverters at high frequencies, and insulated gate bipolar transistors (IGBTs) and MOS-controlled thyristors (MCTs) are used at low frequencies. Transistors, power MOSFETs, and bipolar transistors predominate as power switches in low- to medium inverters. High-power inverters typically use thyristors. Transistors and MOSFETs, rather than thyristors, are normally used with pulse-width modulation (PWM) switching regulators because of their fast switching time.

Inverters can be classified into two groups: voltage source inverters (VSIs) and current source inverters (CSIs). VSIs are fed by a DC voltage source. If the load quality is sufficiently high, the current through the resonant circuit is sinusoidal and the currents through the switches are half-wave sinusoids. The voltages across the switches are square waves. This type of inverter operates independently, being activated solely by the input power source, such as PV and wind power sources. In contrast, the CSIs are fed by a DC current source. The voltage across the resonant circuit is sinusoidal for high values of the loaded quality factor. The voltages across the switches are half-wave sinusoids, and the currents through the switches are square waves. CSIs can function only when the output AC line voltage is present. The source of this voltage can be the utility grid or any other power source tied to the inverter output.

One of the main advantages of VSIs is the low voltage across the transistors, which is equal to the supply voltage. This makes VSIs suitable for high-voltage applications, where, for example, a 220- or 277-volt rectified line voltage is used to supply the inverters. In addition, low-voltage MOSFETs can be used. Such MOSFETs have low on-resistance, reducing conduction losses and operating junction temperatures, which yields high efficiency.

The CSIs are used only for high-horsepower applications. They typically operate at a poor lagging power factor and have high harmonic distortion at their AC output. They are also susceptible to commutation faults during AC line failures, but are cheaper than high-frequency types. On the other hand, the VSI has an inherent stand-alone operating capability and with proper design and control, operates at a high power factor. Most VSIs exhibit low harmonic distortion.

VSIs can be further divided into three general categories: pulse-width-modulated (PWM) inverters; square-wave inverters; and single-phase inverters with voltage cancellation. The input DC voltage in PWM inverters is essentially constant in magnitude when a diode rectifier is used to rectify the line voltage. The inverter must control the magnitude and frequency of the AC output voltages. This is achieved by pulse-width modulation of the inverter switches, hence such inverters are called *PWM inverters*. There are various schemes for pulse-width modulating the inverter switches to shape the output AC voltages as close to a sine wave as possible. PWM inverters complex—both the magnitude and the frequency of the AC voltage outputs need to be sinusoidal and controllable.

The input DC voltage in square-wave inverters is controlled to manage the magnitude of the output AC voltage. Then the inverter has to control only the frequency of the output voltage. The output AC voltage has a waveform similar to a square wave, hence these inverters are called *square-wave inverters*. In the case of single-phase inverters, it is possible to control the magnitude and frequency of the inverter output voltage, even though the input to the inverter is a constant DC voltage and the inverter switches are not pulse-width modulated (so the output voltage wave-shape resembles a square wave). These inverters combine the characteristics of the two previously described inverters. The voltage cancellation technique works only with single-phase inverters, not with three-phase inverters.

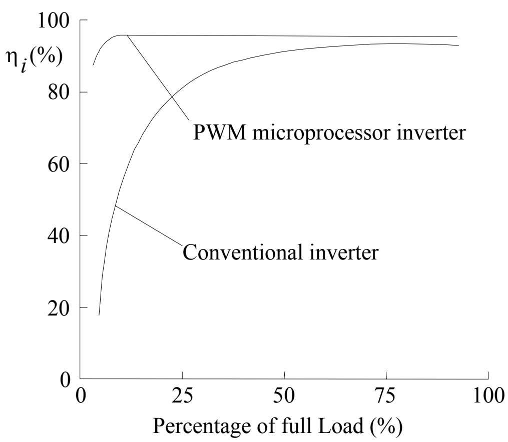


Figure 3.6. A typical inverter efficiency curve.

The efficiency of a typical inverter varies with its output power. The efficiency of a conventional inverter on a given day can be very low, as shown in Figure 3.6, if it is operating at a fraction of its rated load during that day. On the other hand, the new speed control approach, for AC-motor drives using a programmed PWM switching technique can give an inverter output voltage close to unity (0.98). Enjeti et al. (1990) and others noted that the PWM switching technique can optimize various objectives, such as minimizing voltage harmonics, obtaining minimum losses in the motor, reducing torque pulsation, and minimizing the generated acoustic noise. A three-phase PWM inverter controlled by a microprocessor integrated with an MPPT circuit developed by Grundfos International is shown in Figure 3.6. This type of inverter has almost constant efficiency of 96%, even at 10% load.

Rectifier

Rectifiers convert an AC voltage or current into a DC voltage. At low frequencies of 50, 60, and 400 Hz, peak rectifiers are widely used. The ratio of the diode peak current to the diode average current; however, is very high in these rectifiers, and the diode current waveforms contain a large amount of harmonics. Therefore, peak rectifiers are not used at high frequencies. Currently there are high performance rectifiers , which reportedly have over 0.98 rated power factor, low harmonic distortion in the input current (less than 5%), and high conversion efficiency (greater than 96%).

Converter

DC-DC converters are widely used in regulated switch-mode DC power supplies and in DC-motor drive applications. Normally, a DC-DC converter is a combination of inverter and rectifier. High-frequency power processors are used in DC-DC power conversion. The power processors usually consist of more than one power conversion stage where the operation of these stages is decoupled on an instantaneous basis by means of energy elements, such as capacitors and inductors. Thus, the instantaneous power input does not have to have equal instantaneous power output. The functions of DC-DC converters are to (1) convert a DC input voltage into a DC output voltage, (2) regulate the DC output voltage against load and line variations, (3) reduce the AC voltage ripple on the DC output voltage below the required level, (4) protect the supplied system from electromagnetic interference, and (5) provide isolation between the input source and the load, where it is required. DC-DC converters can have two distinct modes of operations, which are based on continuous and discontinuous current conduction. In practice, a converter may operate in both modes, which have significantly different characteristics. Therefore, a converter and its control should be designed based on both modes of operation.

Maximum Power Point Tracker (MPPT)

MPPTs are intelligent devices that can provide adequate modulation to the switch to maintain the PV array's maximum power point by sampling the array's power output at frequent intervals (every few milliseconds) and comparing those values with previous ones. If the power output has increased, then the PV array voltage is stepped in the same direction as the last step. If the power has decreased, then the voltage is stepped the opposite way. In this way, the MPPT always allows the PV array to operate at its peak power point. Generally, maximum power point controllers' power consumption is between 4 and 7% of the PV array output.

There are two types of MPPT circuits. The first applies alternative modulation to the PV voltage. Synchronous demodulation of the PV array power signal allows one to display on which side of the maximum-power voltage the PV is operating at present, then it provides suitable information to the PWM to cause the switch in and hence corrects the voltage. The second MPPT circuit type applies the steady state condition at the maximum power point as differential of power equal to zero ($\partial P = 0$). The MPPT circuit can be integrated with a DC-DC converter or a DC-AC inverter, so it does not need to have a separately built MPPT.

3.2.3 Motor-Pump Subsystems

Optimum matching of the motor and the mechanical load (pump), prior to optimum matching of the PV array with the motor, depends on the drive components, the load parameters (such as load inertia, maximum speed, speed range, and direction of motion), and the coupling of the load to the motor. The type of rotating mechanism of the load is the main factor for properly matching motors and pumps. Typically, there are two rotating mechanisms: coupling and gearing. Coupling mechanisms, such as rack-and-pinion, belt-and-pulley, or feed-screw, are used to couple a load with a linear motion to a rotating motor. Direct coupling of the pump with the motor will avoid the problems and losses associated with a gearing mechanism. The efficiency of the driving mechanism depends on the coupling ratio, which is the ratio of the torque of the motor to the torque of the load.

The power electronic converter topology and its control depend on the type of motor drive selected. In general, the power electronic converter provides a controlled voltage to the motor to control the motor current and, therefore, the electromagnetic torque produced by the motor.

Some of the basic factors in matching motors and power electronic converters are current and voltage ratings, switching frequency, and motor inductance.

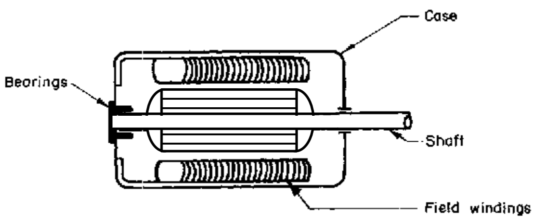
Motors

Motors are usually divided into two types: DC and AC. DC motors are categorized further into two types: permanent magnet (brushed or brushless type) and wound-rotor-field. Similarly, AC motors are divided into induction (asynchronous) and synchronous types. Induction motors are further divided into squirrel-cage and wound-rotor types. Wound-rotor motors are generally used for industrial applications, thus only the permanent-magnet DC motors and the squirrel-cage induction motors will be discussed in this handbook. Schematic diagrams of the four main types of electrical motors are presented in Figure 3.7.

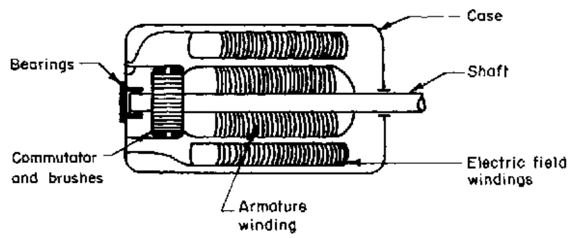
All PV-powered pumping systems have, as a minimum, a PV array, a motor, and a pump. The array can be coupled directly to a DC motor or, through an inverter, to an AC motor. The motor is connected to any one of a variety of variable-speed pumps. Normally, the choice of a motor for a PV-powered system depends on the size required, the water source type (borehole or surface water), and the availability of electronics that go with it. DC motors are attractive and efficient for low water demand and for a short cable distance between the PV array and the motor. DC motors are not attractive for long-distance cabling, because the power loss in the cable increases as the location of the water well becomes farther from the PV array. In terms of simplicity, DC motors are appealing for PV pumping, because PV modules produce direct current and can be directly coupled to the DC motor with or without power conditioning.

Permanent-magnet (brushed) types of DC motors are typically used for PV applications because the rotation of the motor is caused by the brushed commutator without inducing the surrounding magnetic field electrically. No power is consumed in the field windings, which leads to a higher efficiency and smaller PV array sizes. One disadvantage to using brushed motors is the need for new brushes about every 2,000–4,000 hours (about every two years for PV pumps). This is considered to be costly maintenance.

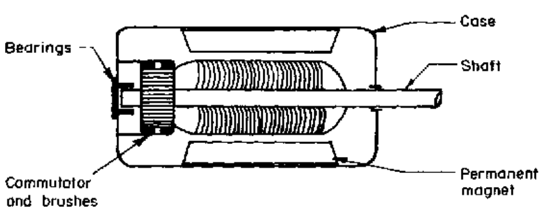
On the other hand, brushless motors have a permanent magnet rotor and electronically switched field windings that operate by means of a rotor position sensor. Although these types of motors have no special maintenance requirements, they are relatively new for PV pumping applications and are not yet reliable. The extra electronic circuit for the rotor position sensor also adds to the cost. During the last few years; however, designs have improved greatly and they are likely to be attractive for small pumping applications in the future.



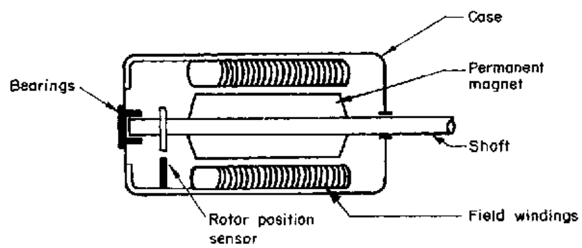
a) Squirrel cage AC motor



b) Wound field (AC or DC) motor



c) Permanent magnet (brushed) DC motor



d) Permanent magnet (brushless) DC motor

Figure 3.7. Schematic diagrams of the four main types of electric motors.

AC motors are typically used for medium- to high-power demand applications. Induction motors with squirrel-cage rotors are most commonly used, because of their low cost and rugged construction. An induction motor operates at nearly constant speed, although it is possible to vary the speed using electronic converters (inverters). The use of inverters for controlling induction motor speeds is highly efficient over wide speed and load ranges.

Field experience shows that, when the motor and pump are operating at nearly constant speed, partially closing the throttling valve can reduce the flow rate in an induction motor driving a centrifugal pump. This causes an energy loss across the throttling valve, a condition that can be avoided by eliminating the throttling valve and driving the pump at a speed that produces the desired flow rate. So instead of using a throttling valve to control flow rates, an adjustable-speed-driven pump can substantially save energy. This is normally not a problem in PV-powered pumping systems; however, because the pumps are designed to be compatible with the system. This is accomplished by matching the current-voltage (IV) characteristics of the motor—pump subsystem with that of the PV array.

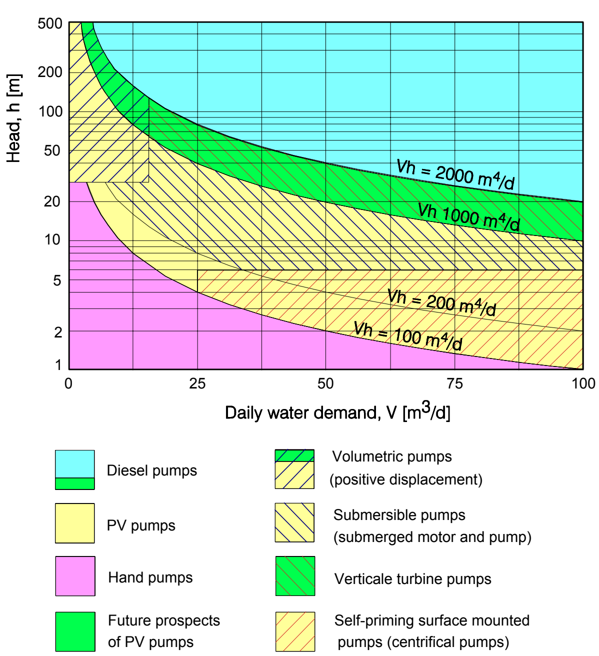


Figure 3.8. Types of pump sets for different ranges of head and flow rates suitable for pumping applications.

Pumps

Many different types of pumps are available for PV-powered pumping systems. These pumps are categorized into two types: volumetric (positive displacement) and centrifugal (rotodynamic). The water output of volumetric pumps is almost independent of head, but directly proportional to volume. Centrifugal pumps are ideally suited to the medium to high water demands of pumping water from boreholes or from surface water reservoirs. These pumps are designed for a fixed head and their water output increases with rotational speed. Their efficiency decreases when the pumping head and flow rate deviate from the design point.

Commercially available centrifugal pumps are categorized into two types: submersible (stacked impeller) and nonsubmersible (vertical turbine, floating, and surface centrifugal). Similarly, commercially available volumetric pumps are also categorized into two types: submersible (diaphragm) and nonsubmersible (jack, piston, and rotary vane). The most common is the jack pump. Figure 3.8 shows the most suitable types of pumps for different ranges of head and flow rates for pumping applications.

The operational characteristics of centrifugal pumps are reasonably well matched with PV arrays. They can be directly coupled by carefully choosing the motor speed, voltage, coupling ratio, and pump characteristics. Electronic controls can enhance performance of a well-matched PV pumping system by 10–15%, although they consume 4–7% of the PV array's power output.

The operational characteristics of volumetric pumps, on the other hand, are not a good match to the output of PV arrays. The motor driving a volumetric pump requires a constant current for a given head, apart from the starting current, which tends to be higher. This condition does not match the PV array characteristics where the current varies almost linearly with solar radiation. Therefore, MPPT controllers are usually used with volumetric pumps.

Helical rotor pumps can operate efficiently over a wide speed range, whereas the efficiency of centrifugal pumps deteriorates from the rated speed. Another advantage of helical rotor pumps is their ability to pump water at low solar radiation levels, corresponding to low pump speeds, which leads to higher volumes of pumped water per day.

The best type of equipment for a particular pumping application depends on the daily water requirement, pumping head, suction head (for surface-mounted pump-sets), and the water source. Generally, positive displacement pumps are best for low flows (under 15 m^3/d) and high pumping heads (30–150 m). Submersible centrifugal pumps are best for high flow rates (25–100 m^3/d) and medium heads (10–30 m). Field experiences have prompted a move away from surface-motor shaft-driven submersible pumps for deep wells because of bearing problems and installation difficulties. Submersible centrifugal pump-sets are now almost exclusively used in such cases. The most suitable pump-set types for various ranges of head and flow for PV-powered pumping systems can be found in manufacturer's catalogues and motor-pump manuals and books.

3.3 Hybrid Water Pumping Systems

Hybrid water pumping systems can consist of several combinations, including wind with PV; wind, PV, and another renewable energy source; wind with diesel; or PV with diesel. Each combination can have battery storage and/or inverters with or without a backup generator or utility power line. A schematic diagram of a hybrid stand-alone power system with a backup generator is shown in Figure 3.9.

Hybrids offer greater reliability than either wind or PV technology alone, because each power source (wind or solar) is independent of the other. For example, in winter, when solar energy is low, sufficient wind energy is usually available to compensate for the loss from a PV power source. Another advantage of a hybrid system over an individual wind or PV system is the use of the technology's reliability for integrated applications. With a hybrid system, the entire community can get reliable power for individual home lighting, street lighting, TV and radio, and such community services as water pumping, health clinics, school lighting, telecommunications, and many other infrastructure functions.

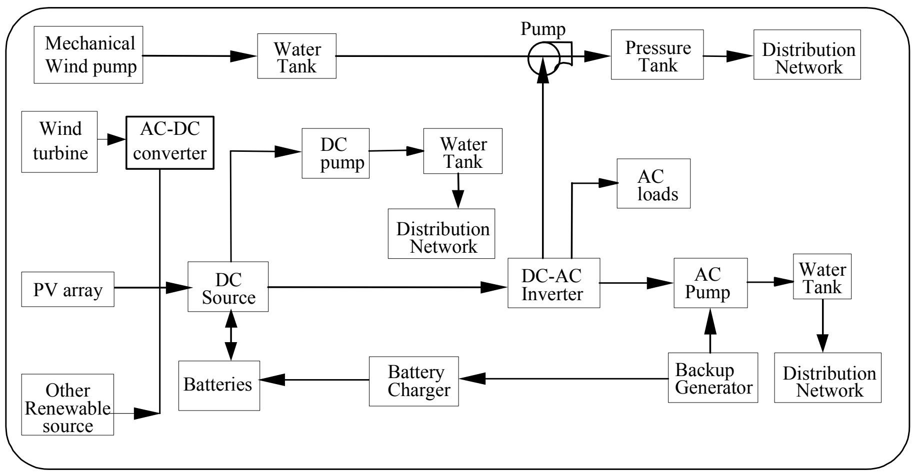


Figure 3.9. Schematic diagram of stand-alone hybrid system with a backup generator for water pumping applications.

As wind and PV technologies advance, the use of hybrid systems as stand-alone systems is becoming preferable and less expensive than individual wind or PV systems. Hybrid systems do not need to be designed for worst-case scenarios, because the power is not from a single source. Hybrid systems permit the use of smaller component sizes, and this lowers the cost of the system. Although hybrid systems are improving in reliability and are reducing the overall size of the power system, their initial costs are still high. Maintenance of hybrid systems also requires a highly skilled person. Therefore, hybrid systems are especially suitable for economically strong communities with well-equipped, skilled manpower for maintaining the systems.

3.4 Water Storage and Distribution

3.4.1 Water Storage

Water storage tanks can be made of steel, polyvinyl chloride (PVC), concrete, or masonry. Open ponds can also be used to store water, depending on the volume required and type of application. Steel, fiberglass, and PVC water tanks are those mostly used for wind and PV water supply applications. Small- to medium-sized concrete and masonry water tanks can also be used for wind and PV water supply schemes, but they can be more expensive than readymade fiberglass, steel, and PVC water tanks. Larger concrete and masonry water tanks are usually more practical for large water supply schemes.

Water for livestock can be stored in an open tank made of steel or concrete. The number of cattle served determines the size of the tank. Three to five days' storage is typically recommended for livestock water storage.

Open ponds are mainly used for long-term water storage for irrigation purposes. Long-term storage for irrigation systems is not usually feasible for both practical and economic reasons. Short-term storage for a day or so is more economical and offers better water management control. The least favorable option is pumping water directly to an irrigated field. Although this is the least expensive option, it makes it difficult for farmers to practice effective water management. Usually, pumping water to an open-earth or earthen-walled canal, which may be lined to minimize seepage, is recommended for irrigation purposes.

Water tank size is often not given special attention in designing wind and PV water supply schemes; it is considered the least important factor in the design of such systems. Two mistakes are commonly made in selecting the proper size and type of water tank for wind and PV water pumping systems. First, the size of the water tank is often selected as if it were to be used for a conventional water supply scheme. Secondly, the material used to construct the tank does not take into consideration the local conditions. The size of a water tank is very important for wind and PV pumps because of the uncertainty of prevailing weather conditions. Solar radiation and wind energy, unlike conventional energy sources, are not available on demand, thus more water storage is necessary to be prepared for a worst condition. It is usually recommended that there be at least three days' of storage in an enclosed tank (see Section 4.6, Design consideration of water tanks).

Water tank types should also be selected based on topography and local conditions. Although it may be less expensive to use locally made steel tanks, they can easily and quickly rust. While antirust treatments can solve the problem, it is imperative to select the right type of painting chemical for drinking water storage. Another problem with steel tanks is the possibility of water in the tank getting hot during the day. In warm climates, the water inside steel tanks gets hotter more rapidly than in concrete or masonry tanks, which can increase the risk of bacterial growth and waterborne diseases.

3.4.2 Water Distribution

Large water distribution networks are usually not considered for rural water supply systems because of the additional cost of distribution pipes and plumbing work. There is also the problem of overcoming head loss, which also adds costs to the system. In rural villages, water is often distributed through small pipes to just a few water points. Each point might have four to eight water taps. The number of water points is estimated, based on the population size and density of houses. Figure 3.10 shows a schematic diagram of a village water supply powered by an electrical wind turbine with a typical water distribution network.

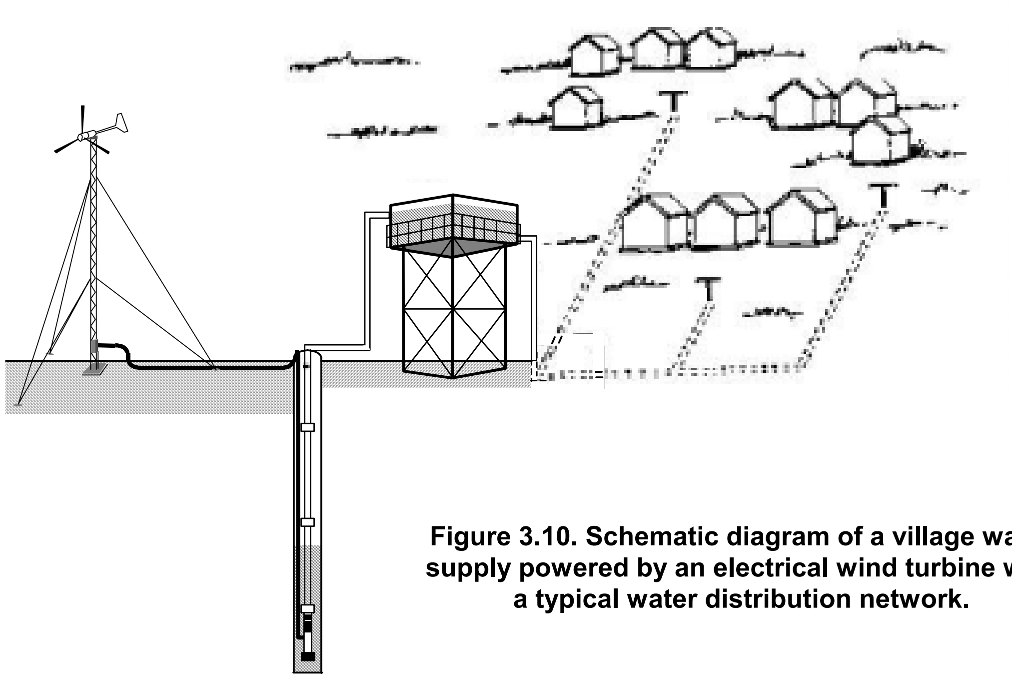


Figure 3.10. Schematic diagram of a village water supply powered by an electrical wind turbine with a typical water distribution network.

It is recommended to first pump water to the water tank, and then have a distribution network to supply the communities. By doing so, enough pressure can be built up to pump water to the water tank, then water can be distributed by gravity to the communities. This allows for continuous water flow in the tank, which helps reduce the growth of bacteria.

Water distribution in many wind and PV water pumping systems installed for irrigation applications simply feed into the existing network of earth channels. At least 50% of the pumped water using this type of distribution method is wasted through seepage and weeds, and more through evaporation. Where costs are directly proportional to water output, losses of such magnitude are unacceptable, so it makes sense to construct cemented canal or lined earthen walls to minimize seepage.

The most common methods of watering crops are channel, drip, flood, sprinkler, and hose and basin irrigation. Drip irrigation is the most effective method, with minimum water losses (efficiency around 85%). In areas where manpower is cheap, the hose and basin irrigation method is most appropriate. Flood and channel irrigation methods are not economical for wind and PV water pumping systems.

4. Design Considerations and Evaluation Techniques

4.1 Site Selection Criteria

Site selection is vital for a sustainable water supply scheme, yet many designers in sizing wind and PV water pumping systems frequently underestimate its importance. The main criteria for site selection include availability, quality and type of water resource, and the amount of water required for the intended use. Installing the best system without a reliable water source is a waste of financial resources. Similarly, designing a system without estimating the realistic water demand might result in insufficient water supplies or unnecessary financial expenditures for a system that is too large. The quality of the water resource is also crucial to the overall cost of the system. Surface water resources, such as river water, need treatment. Flooding and the activities of livestock and humans in the area can contaminate and increase the turbidity of the water. In such cases, a simple clarifier and filter might be necessary to cleanse and disinfect. On the other hand, spring and underground water supplies usually do not require treatment, unless the water contains certain chemicals, such as salt and fluoride.

4.1.1 Water Resources

The main criterion in water resource assessment is water quality and availability. Proper surveying is necessary to ensure the water resource is sufficient and has a reliable source, even in droughts, as well as for future water demands or possible expansions. The other important factor in water resource assessment is the type of source, usually rainwater, surface water, or groundwater. Surface water can be derived from river water, lakes, seas, or ponds. Drilling, digging wells, or tapping into springs can obtain ground water. Drilled wells usually use steel or PVC casings, which extend into the ground until a water-bearing aquifer is reached. Normally, a screen surrounded by packed gravel is added to filter and clean the underground water. Casings typically are from (4–12 in.) in diameter, depending on the borehole recharge rate and water demand. The well depth varies, depending on water demand, hydrogeological formation of the ground, and type of aquifer. Depths can range from 50 m to several hundred meters. Depths more than 250–300 m are not usually economical; however, if there is no other water resource option, a well can be drilled even to greater depths. Water from drilled wells is generally safe to drink, providing its chemical content is under the acceptable limits of the World Health Organization (WHO) standard, i.e., free from bacteria and waterborne diseases.

Dug wells are usually shallow wells and, depending on the location and external activities, can be polluted more easily than deep wells. Shallow wells can be dug by hand or by machine. Dug wells are basically for open well (bucket use) or have a hand pump or small diesel/gasoline pump installed. Similar to deep wells, the water from shallow wells can be easily contaminated from human and animal activities. It is less likely that dug wells contain chemicals like salt; water from shallow wells is mainly fresh water replenished by rainwater.

Spring water is another type of groundwater. Spring water comes to the surface via water pressure when the water is pressed through permeable strata. Springs are usually found at the foot of mountains and are often clean and safe for drinking without disinfection. Springs can be any size, with discharge as little as 1 l/s or as much as 100 m^3/s or more. A small spring normally requires a reservoir to be added before it can ensure reliable water supply. Large springs with adequate discharge can be directly distributed without having a reservoir, as long as the water source is greater than the water demand. Nonetheless, some storage is necessary at the catchment to settle some sediments.

The main factors that should be examined in assessing water resources are water flow (discharge) and water quality. Water discharge can be measured by a standard weir notch for surface water and springs, and by using a flow meter for deep wells. A drilling test is also necessary to check deep wells for their drawdown and dynamic water level, and for ensuring the total pumping head is designed for the most suitable size and type of pump. Drawdown is the distance from the static water level (the water level before pumping is started) minus the dynamic water level. The dynamic water level is the minimum level that the water can drop in the well, or the point where the water level cannot produce any more drops after long hours pumping. (See Figures 4.6 and 4.7 for further clarification). Drillers normally test pumps or bail the well before pump operation. Then the water flow should be checked every 3–5 years to see if the well needs rehabilitation (cleaning). In test pumping, the pump in the well should generally operate for about 48 hours at peak water demand while measuring the drawdown.

The water level in the well is measured with a special type of cable with an electrode at the end. When the cable is lowered slowly into the well, the electrode touches the water's surface, a light appears on the top of the cable, and the depth is recorded. Both the static and dynamic water levels can be measured in this manner and the drawdown can then be calculated. For routine use, a permanent water-level indicator can be installed with the pump.

4.1.2 Water Demand

Planning a water supply system depends mainly on water demand. The level of water demand is the sum of supplying water for villages, livestock, and irrigation.

Water demand for a village is estimated from population size and daily per capita water consumption. Once these factors are known, daily demand can be estimated. Daily water demand does not provide enough information though, because water consumption varies over 24 hours. Peak hour demand has to be estimated for a water supply system to be reliable any time of the day. The peak hour demand is the hour when water consumption is the highest, usually at noon. In contrast, consumption is usually lowest at night.

Estimating water demand for livestock is similar to figuring the water supply for a village. Water demand is estimated from the number of cattle and other animals using the system, multiplied by per capita water consumption. Typical daily water consumption for farm animals is presented in Table 4.1.

Table 4.1. Typical Daily Water Consumption for Farm Animals.

Type of animal	Daily water consumption (liter/animal)
Dairy cows	80
Beef brood cows	50
Horses and mules	50
Calves	30
Pigs	20
Sheep and goats	10
Chickens	0.1

Unlike water demands for human and animal supply, water demand for crop irrigation is seasonal. Some crops require their maximum water supply for a relatively short period during their growing season. Thus, all irrigation systems need to be designed at peak water demands. Irrigation water pumps are characterized by the need for large quantities of water. Wind- and PV-powered irrigation pumps are usually practical for surface water sources or high-yield shallow wells. For this reason, producing high-value cash crops is advantageous for the system to be economically viable.

Water demand for irrigation varies from crop to crop. It also changes with the type of soil, soil preparation and irrigation methods, rainfall regimes, and other meteorological factors (such as temperature, humidity, wind speed, and cloud cover). Estimating water demand for an irrigation application is beyond the scope of this book. However, local practice and experience are probably the best guides to estimating water requirements for a specific application. Estimated water demand for various types of crop irrigation is presented in Table 4.2.

Table 4.2. Estimated Maximum Daily Water Demand for Various Types of Crop Irrigation.

Type of crops	Daily water requirement (m^3/ha)
Lawn/Garden	240
Rice	100
Rural village farms	60
Cereals	45
Sugar cane	65
Cotton	55

As a guideline, the following steps can be used to estimate the water demand for crop irrigation.

1. Determine the size and shape of the irrigation plot.
2. Estimate the water resources and the wind and solar energy resources of the area.
3. Determine the type of crop that will be harvested on the plot.
4. Estimate the water demand from Table 4.2.

4.1.3 Water Treatment

Water used for drinking and dishwashing purposes has to be safe and clean. Water for irrigation purposes does not need water treatment; however, if the water is salty, it can damage the soil and it can be costly to clean up. Surface water sources can be easily polluted from human and animal activities in the surrounding areas. The water can also be turbid from heavy rain and flooding. For these reasons, surface water must be treated if it is to be used for a water supply. Because of the necessary chemicals and extra energy required, treating water for a village water supply is expensive.

There are several types of water treatment systems available, from simple sand filtration by gravity, to highly computerized clarifiers and filters. Even with the simple sand filtration system, proper types and grades of sands have to be arranged in the filtration basin. Once the sand is in place, water is fed to the sand filtration basin and passes through the aggregated sands. Finally, the filtered water will be collected below in a smaller ground reservoir (booster station) and disinfected before being pumped to the pressure tank. Water needs to be pumped to higher elevations (i.e., a pressure tank) to get enough pressure to flow by gravity through the distribution network.

As mentioned earlier, underground water (springs and wells) may not require treatment, unless the water contains certain chemicals, like salt and fluoride. However, disinfection may be necessary to kill bacteria and other waterborne disease-spreading organisms if the groundwater is exposed to pollution from activities of nearby livestock and humans. Groundwater sources are usually the least expensive option for village water supplies.

Once the water resource is developed, the water usually has to be checked for chemical and bacteriological quality. After the water resource passes these requirements, periodic testing is still necessary to ensure the source has not been polluted. Water sources exposed to surface activity, such as springs, cisterns, lakes, and rivers, must be tested regularly. Samples must be taken when open water storage reaches temperatures higher than 15°C (59°F) for more than three days before tapping. "Do-it-yourself" test kits are available to test for pH and the most frequent types of pollution, such as coliform bacteria from human and animal activities, and nitrates from natural and artificial fertilizers.

A detailed laboratory investigation is usually still required on water stored in closed water tanks. Waterborne diseases can develop, even in closed tanks, if the water is stored too long. Water stored for several days must be tested against water that has been recently pumped, and the biological processes associated with the different samples must be reviewed. The growth of bacteria and other waterborne-disease-spreading organisms mainly depends on the ambient air temperature, the water temperature in the well, the type of water tank (steel, PVC, concrete, or masonry), and various other factors. These include the exposure of water tanks to humans and livestock, and other environmental conditions. Issues relating to storing water in water tanks for long periods of time and the possible health risks associated with that practice is beyond the scope of this book.

4.2 Power Sources Selection Criteria

Power source selection is typically based on the technical and economical aspects of the power source. Other influencing factors include the location of the installation, and issues relating to social and institutional factors. Although the reliability of the power source is frequently the main factor, affordability is another important criterion for selection and may be primary in rural areas of developing countries where income levels are very low. PV pumps may be more reliable than hand pumps, but if the rural community cannot afford to buy a PV pump, hand pumps can be an alternative.

The location of the power source is another important factor. In a remote rural village, reliability might be the prime consideration, perhaps because of the lack of maintenance personnel for diesels and the scarcity of fuels and spare parts. In an environmentally sensitive area, for example, near an artificial water reservoir used for water supply purposes, diesel systems might be undesirable because of the potential risk of an oil spill. Social factors could also be important for some communities. Wind turbines may be viewed by some communities as nearby monsters, and may not be accepted. Institutional aspects are other factors for power source selection. If rural water supplies are administered by a centralized government system, which is not uncommon in many developing countries, the rural water supply systems can be standardized. In this case, power source selection could be limited to just a few standardized water-pumping systems. This basically solves problems related to lack of spare parts, skilled manpower, and shortage of foreign currency. Trained maintenance personnel could be available for few types of power source systems.

Hand pumps could be ideal for single families or in rural areas with a few households and a hydraulic equivalent load of up to 250 m^4/d. (Hydraulic equivalent load is the product of the daily water demand *V* and the total pumping head *h*). Hand pumps operate well with shallow wells, with a capacity of up to 15 m. Their use becomes more difficult with increasing well depth. Depending on per capita water consumption, hand pumps can serve up to a thousand people.

Presently, AC PV pumps are ideal for medium-sized communities up to 2,000–2,500 people and up to a maximum hydraulic equivalent load of 1,500 m^4/d. The hydraulic equivalent load of PV pumps can be lower or higher than this figure, depending on the intensity of solar radiation energy of the area. PV pumps in an area of low per capita water consumption can serve as many as 4,000 people. DC PV pumps are advisable for smaller applications up to a hydraulic equivalent load of 600 m^4/d.

Diesel motors are best for higher water demands and larger communities. Diesels are more economical for a hydraulic equivalent load above 1,500 m^4/d. Mechanical diesel pumps (positive displacement) are not affected by well depths, and can even operate at high pumping heads with minor loss, as long as the pump operates at the designed point and the system is well matched.

Wind pumps are typically the first choice in windier locations, such as near large lakes, seashores, and open plain areas. PV systems are better for sunny locations, where solar energy abounds, such as tropical, arid, and semiarid areas. Winds are especially gusty over long ridges; wind speed accelerates as it passes over ridges and around ridge edges. Mountains and ridges often experience higher winds not only because of channeling, but also because of temperature inversion.

The competitiveness of wind pumps depends on the wind speed. Mechanical wind pumps are designed to start pumping at low wind speeds, from 2.5–3.5 m/s. The highest overall efficiency of most mechanical pumps is achieved at wind speeds of 6–9 m/s. These type of pumps normally operate best up to 10 m/s before they start furling. Mechanical wind pumps are basically grouped into three sizes: light, medium, and strong. Light wind pumps normally start pumping at wind speeds of 2–3 m/s and medium-sized pumps start pumping from 3-4 m/s. The larger pumps start pumping from 4–5 m/s.

Electrical wind turbines usually require a high wind speed to start pumping. Small turbines (about 1.5 kW rated output) require an average wind speed of 4–5 m/s to start pumping. For medium to large turbines, the wind speeds need to be much higher to start the rotor. For wind turbines with less than 1 kW rated output, the rotor can start at lower wind speeds (3–5 m/s). Tower height up to the hub is normally about 10 m for mechanical wind pumps; electrical wind turbines require higher tower height.

Wind pump prices depend on the diameter of the rotor and where the system is manufactured. Mechanical wind pumps manufactured in most developing countries are cheap. For example, according to the report made by Fraenkel (1986), the Tawana wind pump (described in chapter 3) cost about $130 (US) per rotor area in 1985. Electrical wind pumps can be three times more expensive per unit of rotor area than mechanical wind pumps for small wind machines, and twice as expensive for large machines. Mechanical wind pumps begin to be economically attractive at about 2.5–3 m/s mean wind speeds, while their counter electrical pumps need 5–6 m/s wind speeds to begin to be economically attractive.

Hybrid systems are always the best choice for reliable renewable energy water supplies. However, hybrid systems are more expensive than stand-alone PV or wind systems. A simple initial appraisal chart for stand-alone pumping systems is shown in Figure 4.1. This chart does not apply to hybrid systems.

The decision chart helps to make an initial appraisal in selecting the right type of water pumping technology. It shows how to start with the basic data and makes an initial selection of the most suitable type of pumping technology. First, the daily hydraulic and energy demands have to be determined, based on daily water demand and total pumping head. Then, using the basic criteria of selection (shaded boxes), the best possible pumping option can be selected. The shaded boxes show the basic criteria required for different types of pumping options. Average solar radiation energy of 3 $kWh/m^2/d$ is considered the minimum requirement to operate PV pumps; below this value PV pumps are not economical. Similarly, mean wind speed above 3 m/s is also a basic criterion for wind pump selection. This wind speed limit is basically for mechanical wind pumps. The mean wind speed limit should be higher than 5 m/s to use this chart for medium-sized electrical wind pumps.

It is important to screen out different pumping options by using a decision chart, such as the one shown in Figure 4.1. After the best possible technology options are selected, the system must be designed properly. Then an economical evaluation has to be made to select the best pumping option. The final selection of the best pumping system should be made after an external impact assessment of the selected technology is completed.

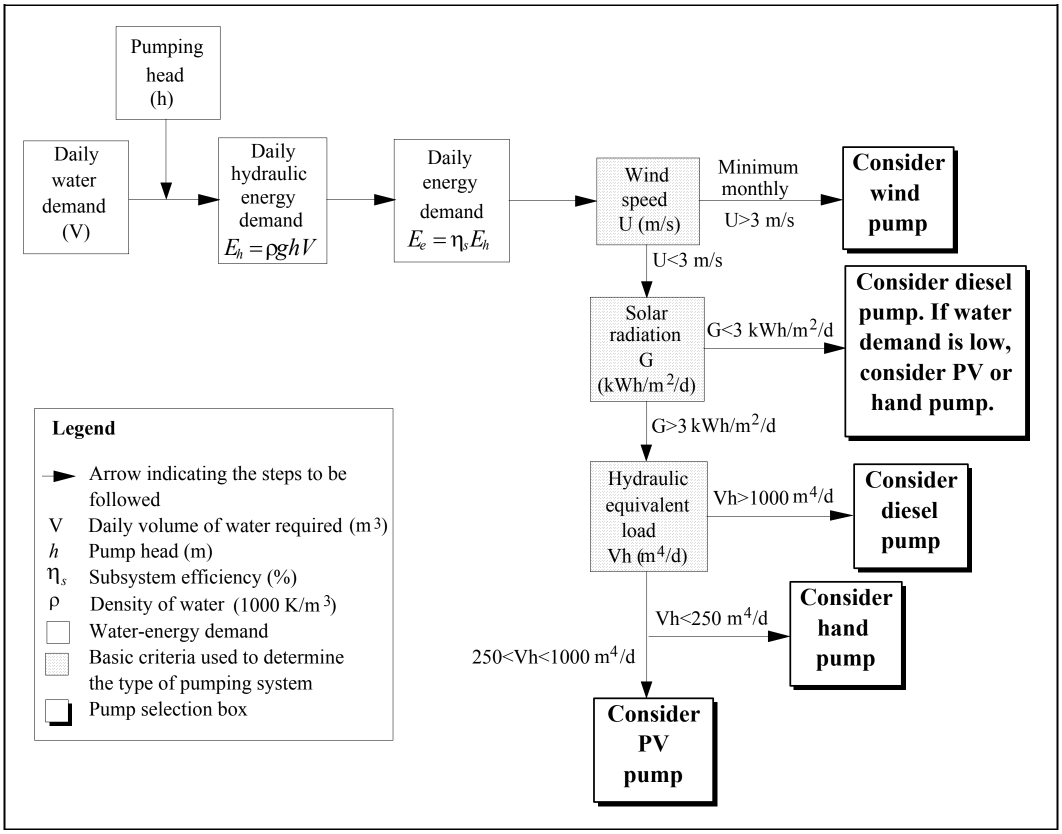
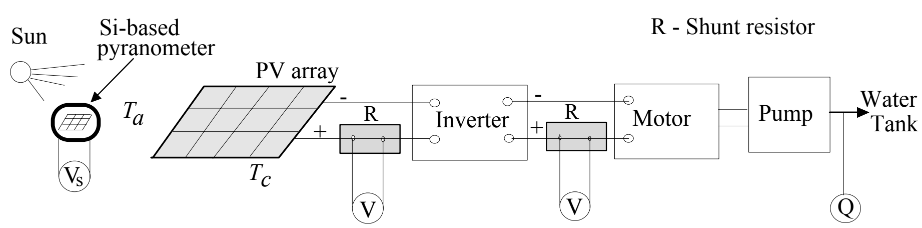


Figure 4.1. Decision chart for an initial appraisal of various water pumping options. (This chart does not include electrical wind turbine pumps.)

4.3 Field Data Collection and Monitoring Procedures

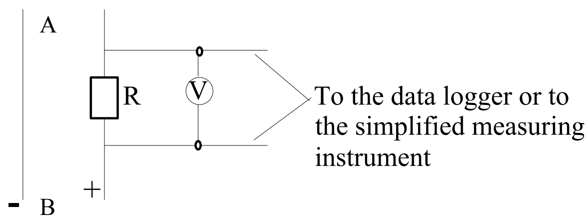
Field data recording and monitoring of any renewable energy water pumping system are crucial for further development of the technology, evaluating the system's performance, and performing an economic analysis. Field data recording provides a great opportunity for the developer and designer of the technology to evaluate the system in a real situation and look for future improvements. The end user also benefits because he or she can evaluate the performance of the system. The collected field data prove the design and product qualities of the system. Such information is invaluable to researchers, and scientists can expose irresponsible manufacturers and designers.



Note: R is shunt resistor (Ω), V is voltage across the shunt resistor (mV) and Q is the water flow meter (m³).

Figure 4.2. Schematic diagram of the discrete-time data measuring points for monitoring PV water pumping systems.

Field data monitoring is usually made in two ways: discrete and real-time monitoring. The discrete type of field data collection is made by taking measurements at certain intervals, for example every 5 minutes, half hour, hour, day, or even once a month. The time interval depends on the purpose of the data and who needs it. Data for scientific research would likely be taken in short intervals, although, if detailed information is needed for such purposes, real-time measurements may be necessary. The discrete data measurement procedure is accurate enough to evaluate the performance of the system and to estimate the matching of the system. This method is popular for evaluating systems in remote areas, as it does not require an additional power source or highly qualified personnel.



- V can be DC or AC depending on the place of shunt resistor, R.
- Position A could be output from PV array, inverter, or motor.
- Position B could be input to inverter, motor, or pump.

Figure 4.3. Schematic diagram of shunt resistor connection and the measuring points.

In discrete-time data monitoring, simplified measuring instruments can be used even for short periods, from a month to a year. Using a discrete data monitoring system, readings can be taken hourly or every half hour, and averaged into hourly data. Unusual weather conditions in between can also be closely monitored, and when necessary, several measurements can be taken every few minutes and computed into an hourly average. A daily PV pump-monitoring form is shown in appendix C. (A similar format can be used for wind pump monitoring).

Figure 4.2 shows the schematic diagram of the discrete-time measurement procedure for PV pumping systems. Shunt resistance is required to measure the actual current passing through each component (that is, through the PV array, inverter, and motor). Wind-powered water pumping requires an anemometer instead of the silicon-based sensor. Figure 4.3 shows the connection of the shunt resistance and the measurement points. A silicon-based (Si-based) solar radiation sensor should be used (instead of the standard pyranometers) to measure the solar radiation on the surface of the PV array. Standard pyranometers measure wider wavelengths than the Si-based sensors and give higher solar radiation values than the Si-based sensors. PV arrays, like the Si-based sensors, cannot accept wider wavelengths. PV arrays or Si-based sensors can measure a spectrum wavelength in the range of 400 to 1,100 nm, while the normal pyranometer can measure a spectrum in the range of 200 to 11,000 nm. Therefore, Si-based sensors are recommended for measuring the solar radiation energy for PV systems.

The solar radiation on the surface of the array G is calculated from the voltage drop across the sensor divided by the sensitivity of the sensor. Thus:

$$G = \frac{V_s}{S}, \tag{4.1}$$

where V_s is the measured voltage drop across the silicon-based sensor in mV, and S is the sensitivity of the sensor in $mV/(W/m^2)$.

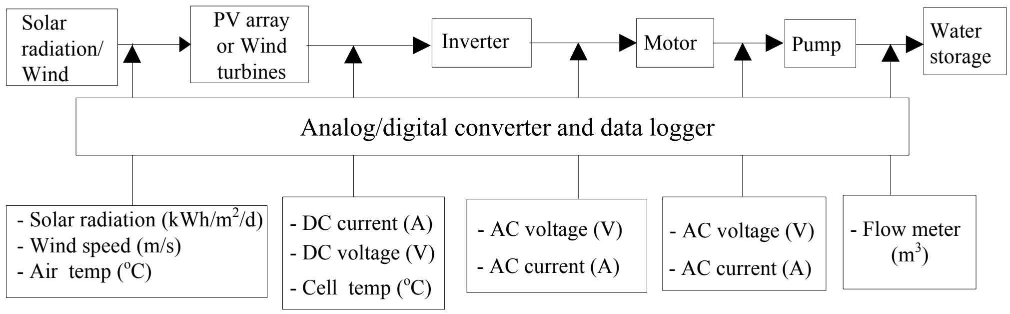


Figure 4.4. Schematic diagram of the real-time data measurement points for monitoring PV and wind pumping systems.

The AC and DC currents passing through the shunt resistors are measured using the relation:

$$I_{ac(dc)} = \frac{I_{sh}\mathrm{V}}{V_{sh}}, \qquad (4.2)$$

where I_{sh} is the maximum shunt resistor current limit (in A), V is the voltage measured through the shunt resistor (in mV), and V_{sh} is the maximum voltage drop through the shunt resistor (in mV).

The maximum shunt resistor current and the maximum voltage drop through the shunt resistor are determined from the shunt resistor label. For example, for a maximum shunt resistor current of I_{sh} = 10 A, and for a maximum voltage drop through the shunt resistor of V_{sh} = 60 mV, the AC or DC current of the shunt resistor, from Equation 4.2, will be:

$$I_{ac(dc)} = \frac{\mathrm{V}}{6} \qquad (4.3)$$

Real-time measurement is an accurate data collection system, which uses a data logger and a full data transmit–receive device (DTR). The schematic diagram of the real-time data measurement points for PV or wind pumping systems monitoring is shown in Figure 4.4. This monitoring equipment typically consists of a serial chain of sensors, signal-conditioning devices, a data acquisition system (DAS), and data transmission/receiving devices. This whole chain is defined as the data collection system (DCS). The heart of this chain, the DAS, is the most critical part. The DAS itself has several elements, each of which can cause a failure in the data collection process. The typical data acquisition system is shown in Figure 4.5.

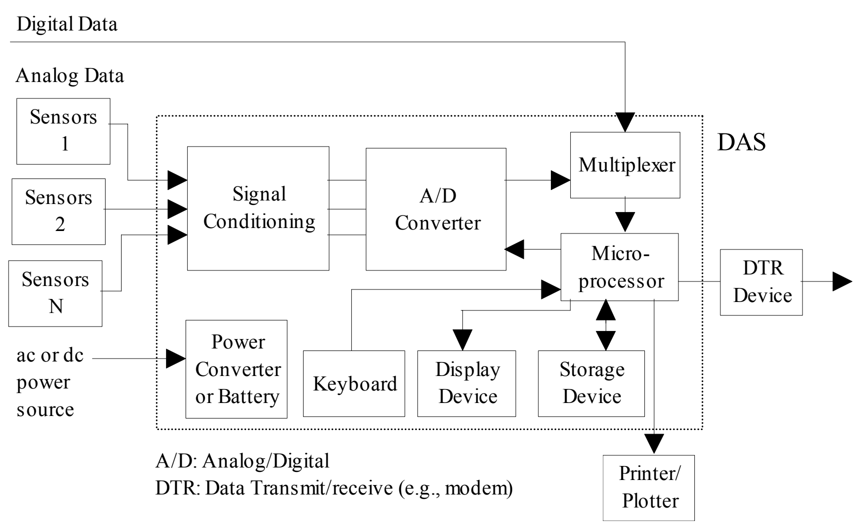


Figure 4.5. Typical data acquisition system (DAS) and its interface devices (Source: Imamura et al., 1992).

4.4 Sizing of Systems and Equipment Selection

4.4.1 Wind Pumps

The rotors of mechanical wind pumps are built-in with high solidity and typically use positive displacement (piston) pumps. Piston pumps need about three times (exactly π times) as much torque to start them as to keep them running. Many prime movers (such as engines and electric motors) cannot readily produce three times the torque needed for starting. Therefore, centrifugal pumps are commonly used with engines and electric motors, because the starting torque needed by the pump is less than the running torque. Low-solidity rotors (modern electric wind turbines) are suitable for electric generations and for centrifugal pumps.

Information such as the water demand, population size, water resources, and total pumping head are required for proper sizing of wind pumping systems. Water resource assessment is one of the main criterion for site selection, and the designer must ensure there is enough water resource to fulfill the water demand. Daily water demand and the peak hour water demand can be estimated from the population size and from per capita water consumption. Per capita water consumption varies from 10–1,000 LCD (liters per capita per day), depending on the affordability, the climate, and the populations' personal habits. In remote African villages, water consumption can be as low as 10 LCD; in California, the daily per capita water consumption can go up to 1,000 LCD. Once the water resource, water demand, and population size are known, the proper size of the wind pump can be estimated from the mean wind speed of the location and the total pumping head.

The total pumping head is the total head required to pump water from the borehole, that is, the sum of the pumping head, friction, and discharge head. The discharge head is the height from the surface of the ground to the pipe outlet. The pumping head is the static water level plus the drawdown. The friction head is the energy loss in pipes and fittings. For further clarification, these terms are presented in the schematic diagrams of both mechanical and electrical wind pumps in Figures 4.6 and 4.7.

Mechanical wind pumps

The energy needed to pump water depends heavily on the hydraulic equivalent load (m^4/d), which is the product of the pumping head h (meters) and daily water production V (m^3/d). For example, 1,000 m^4/d can supply as much as 50 m^3/d at a 20-m pumping head, or as little as 10 m^3/d at a 100-m total pumping head. Figure 4.6 shows a schematic diagram of a typical mechanical wind pump.

The mathematical relationship between the wind speed and the power at the rotor, from Equation 2.2, is

$$P_r = \frac{1}{2}\eta_r \rho_a A_r S^3, \tag{4.4}$$

where P_r is wind power in the rotor, A_r is area of the rotor, ρ_a is density of air (1.2 kg/m^3), η_r is efficiency of the rotor, and S is the daily (monthly) average wind speed (m/s). Typically, 30–50% of the wind that blows against the rotor is captured, 25–30% of the energy on the rotor is transferred to the shaft, and 92–97% of the energy on the shaft is transferred to the pump. Pump efficiency is about 60–75%. The actual wind energy calculated is generally much higher (180–250%) than the energy calculated from average wind speed. Therefore, the overall conversion efficiency of mechanical wind pumps using average wind speed is 7–27%.

The useful energy we get from the wind pump is the hydraulic energy and is estimated from:

$$P_h = \frac{1}{2}\eta_{ov}\rho_a A_r S^3, \qquad (4.5)$$

where P_h is hydraulic power output, and η_{ov} is the overall efficiency of the wind pump.

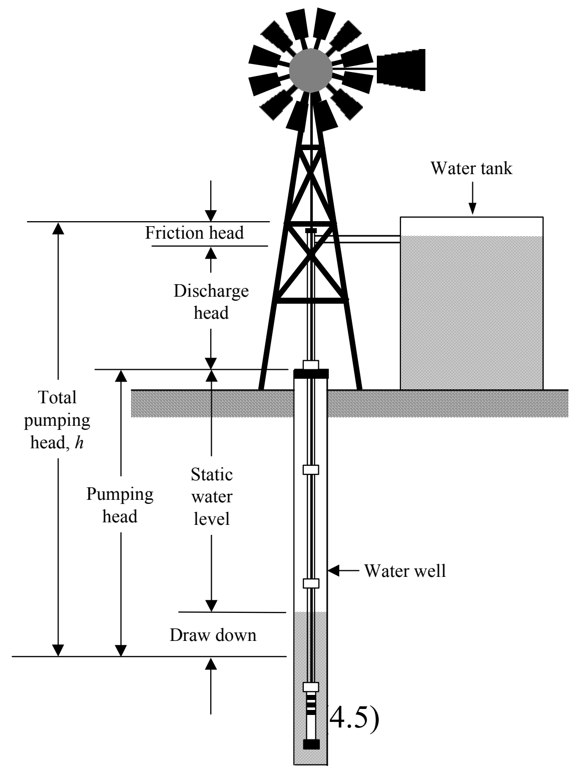


Figure 4.6. Schematic diagram of a typical mechanical wind pump.

The hydraulic energy output can be also estimated from the daily water output and total pumping head. That is,

$$P_h = \rho_w g h V \qquad (4.6)$$

where g is acceleration due to gravity (9.81 m/s^3), ρ_w is density of water, h is the total pumping head (meters), and V is the daily or monthly volume of water (m^3). Equating Equations 4.5 and 4.6, and substituting the rotor area A_r by 0.25πd^2, the average daily (monthly) volume of water produce will be

$$V = 0.048\frac{\eta_{ov}d^2S^3}{h} \qquad (4.7)$$

where d is rotor diameter. Note that Equation 4.6 refers to hydraulic energy, rather than hydraulic power. However, it can also refer to hydraulic power, if the daily volume of water produced is replaced by daily water discharge (production) in m^3/d.

Electrical wind pumps

Similar to mechanical wind pumps, the energy needed to pump water using electrical wind pumps, depends heavily on the hydraulic equivalent load (a product of the total pumping head and daily water production).

Sizing electric wind pumps is also similar to mechanical wind pumps and PV pumps. The mathematical relationship of the electric power from the wind turbine with the daily volume of water produced can be estimated using Equation 4.7:

$$V = 0.048\frac{\eta_o d^2 S^3}{h}, \tag{4.8}$$

where η_o is the overall efficiency of the electric wind turbine. Figure 4.7 shows a schematic diagram of a typical electrical wind pump.

The theoretical maximum conversion efficiency of kinetic energy utilized by the perfect wind turbine is 59.3% (the Betz limit). In practice, wind turbine rotors convert much less than the Betz limit. Optimally designed rotors reach slightly above 40%.

Electrical wind turbines typically capture 12–30% of the energy in the wind. Rotor efficiency is about 40%, transmission is about 90%, generator efficiency is about 90%, and power conditioning, yawing, and gusts efficiency is about 90%. Typically, small electric wind turbines convert 25–30% of the power in the wind at places with average wind speeds below 5.5 m/s (12 mph) and less than 20% at windier sites. In general, medium-sized wind turbines perform better at high-wind sites than small turbines.

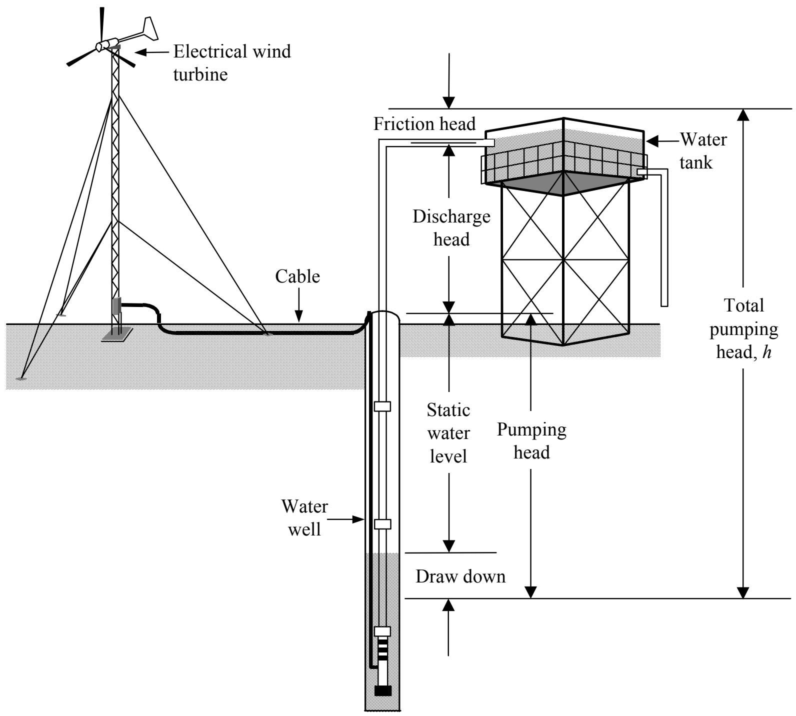


Figure 4.7. Schematic diagram of a typical electrical wind pump.

4.4.2 Photovoltaic Pumps

The two most important factors in the operation of a PV pump are the availability of sufficient solar radiation to enable the pump to start (until the solar radiation reaches the threshold level), and the non-linear relationship between the pumping rate and solar radiation. The threshold level of a PV pump depends on the system components. Figure 4.8 illustrates a schematic diagram of typical PV pump components. It consists of a PV array, an inverter, the motor–pump subsystem, and the water tank.

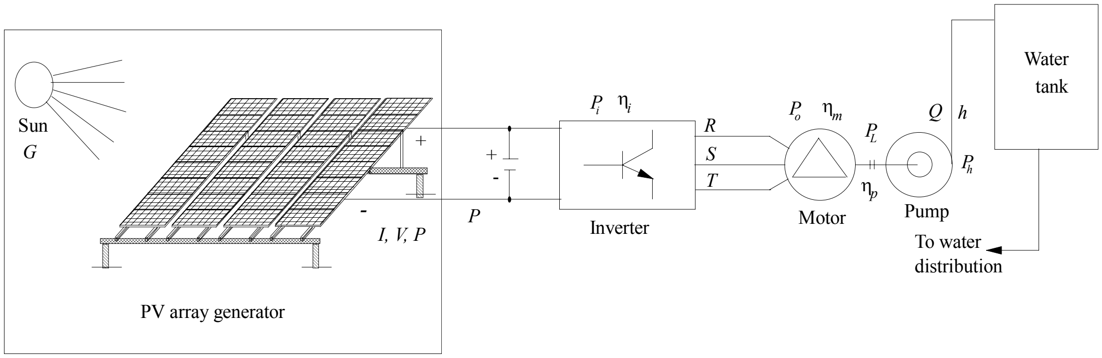


Figure 4.8. Schematic diagram of a PV water pumping system.

As described in chapter 3, PV pump components have to be selected carefully for a proper matching of the system. Unlike conventional pumping systems, PV pumps have to be designed and installed properly to be competitive with other pumping technologies. Each component of a PV pump has intrinsic characteristics affecting the overall operating conditions. Therefore, it is desirable that the intercept of all respective component characteristics follows the maximum power line of the PV array generator. Depending on this internal matching, the efficiency of the overall system and related performances will meet an acceptable range. System design, particularly the PV array capacity, should be reviewed to ensure that sufficient energy is produced to start the motor as early in the day as possible.

In principle, modeling components individually and combining them into a single system can optimize PV pumps. This approach could be the most accurate method to maximize the efficiency of each component and, ultimately, the overall system efficiency. This method requires an understanding of each component. Detailed information, such as the ideality factor, the operating principles of diodes, the shunt and series resistance, etc., is not easily ascertained from catalogues. To use this approach, one must know the basic functions of diodes, inverters, motors, and pumps.

Another simple, fairly accurate design method is to create a clear mathematical relationship between the solar radiation energy, the PV array power, and the required hydraulic energy to fulfill the water demand. This method can easily be used by field technicians or by end users.

The mathematical relationship between the PV array power and solar radiation energy is:

$$P = A_{pv} G_r \eta_r , \qquad (4.9a)$$

where P is the PV array power (in Watt-peak, Wp), η_r is the efficiency of the PV array at reference temperature (T_r = 25 ^{o}C), G_r is the solar radiation at reference temperature (G_r = 1000 W/m^2), and A_{pv} is the effective area of the PV array, in m^2 (A_{pv}=$n_p n_s A$, where A is the area of a single module, and n_s is the number of the group of PV cells connected in series each containing n_p strings in parallel). Equation 4.9a can be rewritten as:

$$P = 1000\ A_{pv} \eta_r \qquad (4.9b)$$

The effective PV array area is calculated from the relationships of the daily energy output E_e and the daily hydraulic energy E_h (both in kWh):

$$E_e = A_{pv} G_T \eta_{pv} , \quad (4.10)$$

and,

$$E_h = \eta_s E_e = \rho g h V, \quad (4.11)$$

where η_{pv} is the efficiency of the PV array under operating conditions, G_T is the daily solar radiation on the PV array surface (kWh/m^2), V is the daily amount of water required (m^3), h is the total pumping head (m), η_s is the subsystem efficiency, ρ is the density of water, and g is the acceleration due to gravity. The efficiency of the PV array is determined from:

$$\eta_{pv} = f_m \left[1 - \alpha\left(T_c - T_r\right)\right]\eta_r , \quad (4.12)$$

where f_m is the matching factor, that is, the ratio of the power output of the PV array under operating conditions to its power output at the maximum power point. The generally accepted value for designing a PV system is $f_m \approx 0.90$. The value α is the cell temperature coefficient and is from 0.2% to 0.6%/^{o}C (0.004 to 0.005/^{o}C for Si), and T_c is the daily average cell temperature (in ^{o}C).

Cell temperature is dependent on solar radiation, ambient temperature, and wind speed. Many researchers have tried to develop a relationship that includes solar radiation, ambient temperature, and wind speed through an experimental method. The experimental relation developed by Risser and Fuentes (1983), from Sandia National Laboratories, is a linear relationship of solar radiation, ambient temperature, and wind speed. The relation is in the form:

$$T_c = 3.12 + 0.025 G_T + 0.899 T_a - 1.3 W_s \quad (4.13)$$

where T_c and T_a are in ^{o}C, G_T is in W/m^2, and the wind speed W_s is in m/s.

The simplified cell temperature model that was commonly adopted by many researchers is the relation that includes solar radiation and ambient temperature. The relation is of the form:

$$T_c = T_a + \frac{G_T}{800}(NOCT - 20) , \quad (4.14)$$

where T_a is the hourly ambient temperature, $NOCT$ is the module junction temperature under normal operating temperature (G = 800 W/m^2, T_a = 20^{o}C and at 1 m/s wind speed). For a wind speed over 1 m/s, the cell (module) temperature will be lower, and the cell temperature decreases as the wind speed increases.

Field data were used to compare Equations 4.13 and 4.14; this is presented in Figure 4.9 to show the variation of these models from actual field data. From the graph, Equation 4.13 tends to be lower than the actual field data, while Equation 4.14 tends to estimate higher temperatures than the actual reading at peak hours. However, the deviation of both equations from the actual field data is minimal and both equations can be used to estimate cell temperature.

Once the efficiency of the PV array is determined from Equation 4.12, the PV array area can be calculated from Equations 4.10 and 4.11. Thus,

$$A_{pv} = \frac{\rho g h V}{G_T \eta_{pv} \eta_s}, \tag{4.15}$$

Substituting Equation 4.15 into Equation 4.9b, the PV array size in terms of hydraulic energy and solar radiation energy will be:

$$P = 1000 \frac{\rho g h V \eta_r}{G_T \eta_{pv} \eta_s} \tag{4.16}$$

From Equation 4.16, it is possible to determine the required size of the PV array for a given pumping head and daily water demand, or conversely, to estimate the daily amount of water produced for the given array size and solar radiation energy.

The overall efficiency of a PV pump can be determined from the hydraulic energy and from the solar radiation energy input P_{in}. That is,

$$\eta_o = \frac{P_h}{P_{in}} = \frac{\rho g h V}{A_{PV} G_T} \tag{4.17}$$

A simple nomogram can be developed using these relationships (Equations 4.9 to 4.16) at various ambient air temperatures. The nomogram shown in Figure 4.10 was developed for ambient air temperature T_a of 25ºC. This nomogram can be used either to determine the size of a PV array required for the desired pumping head and water demand, or conversely, to estimate the daily amount of water production for a given PV array size and pumping head. If the hydraulic energy varies from month to month as a result of variation in water levels or water demand, the nomogram should be used for each month of the year with the corresponding solar radiation and hydraulic energy. The month with the worst-case combination of solar radiation energy and water demand is usually the design month.

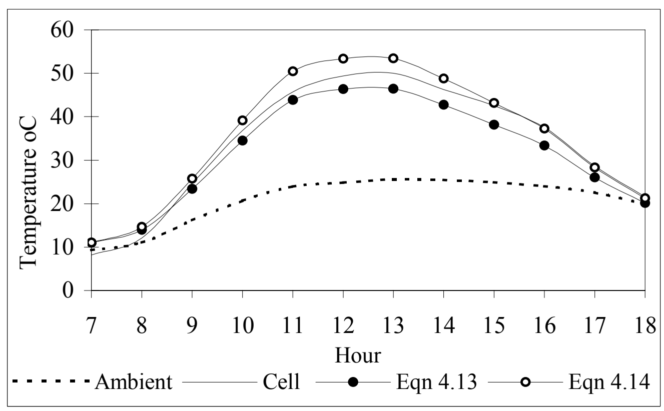


Figure 4.9. Deviation between the measured and calculated values of the monthly average hourly cell temperature in October at Addis Ababa Station.

To use this nomogram, first determine the water demand from the size of population to be served and the total pumping head. Then draw a line counterclockwise on the nomogram, using the appropriate values of the subsystem's efficiency and the average daily solar radiation, to get the required array size. Alternately, start clockwise from a known PV array size to obtain the amount of water produced for a given total pumping head.

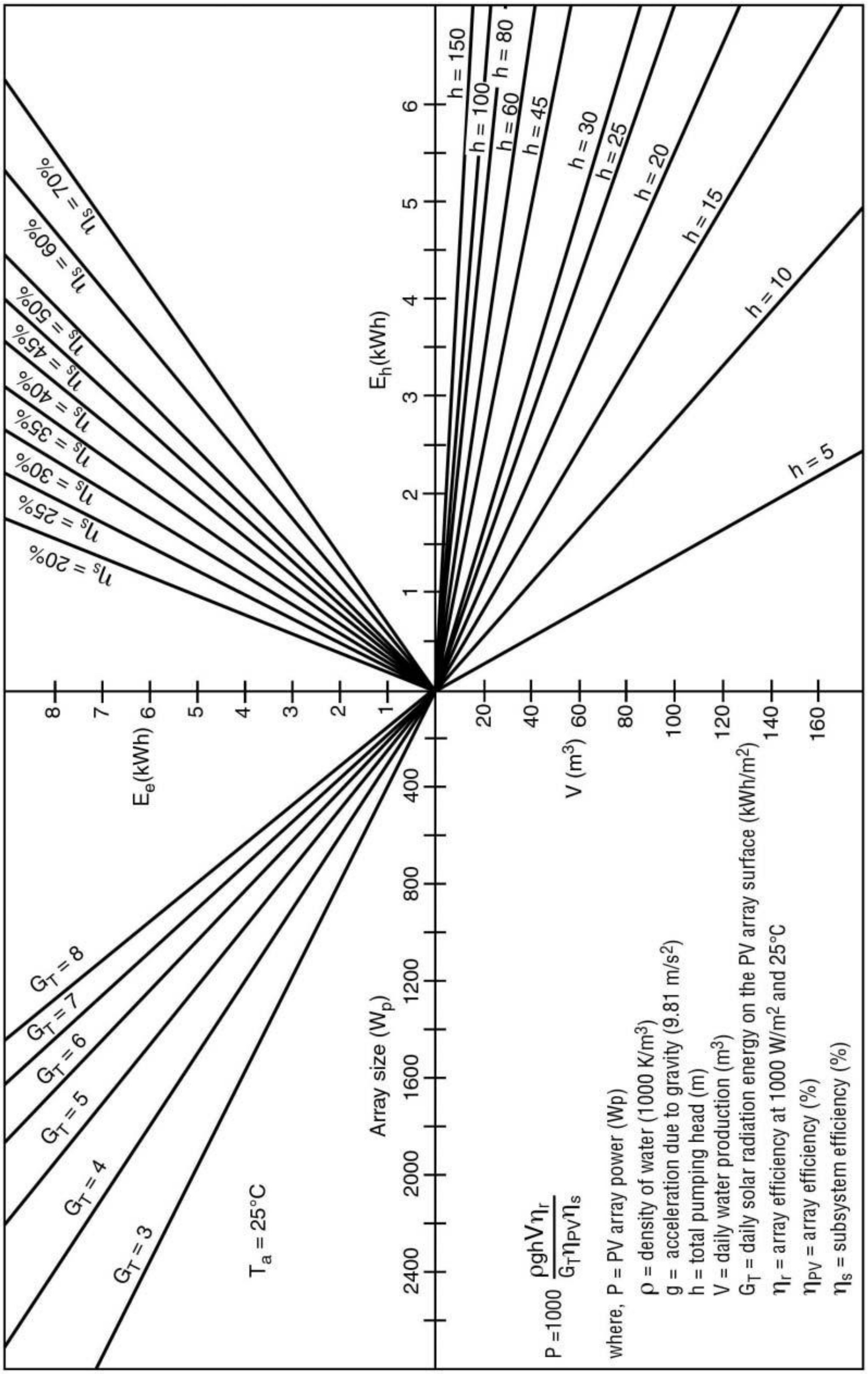


Figure 4.10. Nomogram used to estimate the size of a PV array and daily water production.

4.5 Photovoltaic Pump Evaluation Technique — Load matching

This section discusses the load-matching factor to evaluate the performance of PV water pumps. This approach has been the most effective and simplest in analyzing the performance of heat collectors during the past few decades. The same approach can be adapted for PV systems' performance evaluation.

The load-matching factor is the ratio of energy acquired by the hydraulic load to the maximum PV array power extracted in a one-day period. This could be stated as the ratio of the power that the PV array delivers to the motor–pump subsystem during the day to the maximum electrical power that can be obtained from the array throughout the day. This can also be defined as the ratio of the actual array output used for water pumping to the array output capability. Thus,

$$\phi = \frac{\text{Actual array output used for water pumping}}{\text{Array output capability}} \tag{4.18}$$

This parameter is very useful for assessing how much of a PV array's real power production capability is being used.

The load-matching factor can be determined from theoretical models or from field experimental data (from solar radiation and PV array power output data). Theoretically, from Figure 4.8, the load-matching factor is expressed as:

$$\phi = \frac{P_h}{P} \tag{4.19}$$

where P is the PV array power output, and P_h is the power acquired by the hydraulic load.

The load-matching factor can also be determined graphically from experimental data. Figure 4.11 represents the typical daily average, hourly PV array power output curve. The horizontal line (CD) shows the threshold level of the electrical load on the PV pump. If we take a short time interval (the shaded areas A and B), the total array output capability can be obtained by integrating over a given time. The actual array output used for pumping is then the area of the curve above the threshold line. The area below the threshold line is the power wasted due to friction and other losses. Therefore, the load-matching factor is the ratio of the curve area above the threshold line to the total area of the curve.

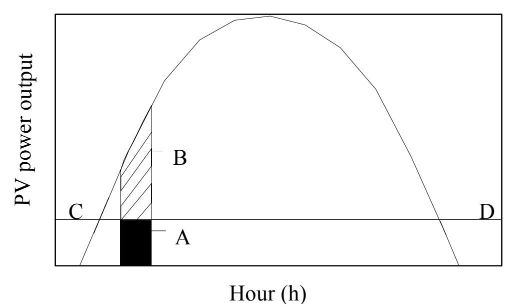


Figure 4.11. A typical daily average hourly PV array power output.

Similarly, the load-matching factor can be determined from the daily average, hourly solar radiation curve. Since the PV array power output depends on the distribution of solar radiation, the solar radiation curve over the day will have a similar shape to Figure 4.11, and the load-matching factor from the solar radiation curve is defined by

$$\phi = \frac{\sum^{N}(G_T - G_C)}{\sum^{N} G_T}, \tag{4.20}$$

where N is the number of daily hour readings, G_C is the critical solar radiation (or the threshold) to start water pumping, and G_T is the solar radiation on the tilted surface of the PV array.

Experimental field data are taken to illustrate how the load-matching factor of a PV pump is estimated. These data were taken from a PV pump in Addis Ababa, Ethiopia. From the data, the solar radiation, PV array power, and the water output were plotted in one graph, as shown in Figure 4.12. In principle, the PV array DC power curve should follow a similar pattern to the solar radiation curve between 8:00 a.m. to 9:00 a.m., but in this case, trees were shadowing part of the array.

At the experiment site, the critical (threshold) solar radiation energy required to start pumping water from the graph is 68 W/m^2 in the morning and 170 W/m^2 in the afternoon. The critical PV array DC power required from the graph is 112 W. In principle, the critical PV power required to start pumping water should always be constant because the threshold power depends on the system components. Because the efficiency of the PV array decreases at higher cell temperatures, the critical solar radiation energy varies over the day, depending on the cell temperature and wind speed of the area. Higher solar radiation energy is required to produce the same amount of DC power at higher cell temperatures.

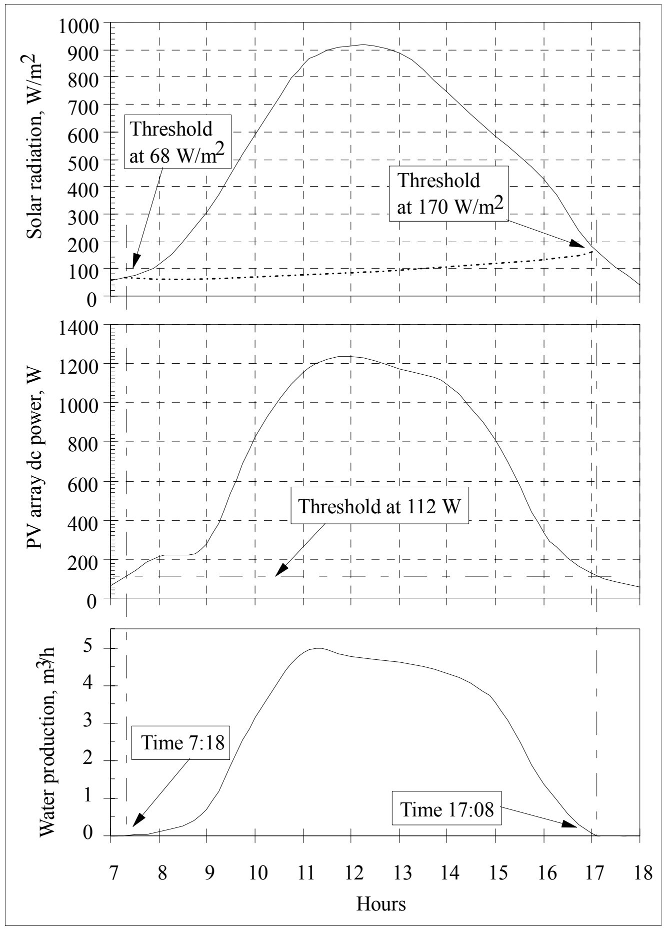


Figure 4.12. Monthly average daily solar radiation energy, DC power output, and water production of a PV pump located at Addis Ababa, Ethiopia, in October 1994.

On the other hand, higher winds will have a cooling effect on the array. Thus, to produce 112 W of DC power, the PV array requires a solar radiation energy of 68 W/m^2 in the morning, or 170 W/m^2 in the afternoon, respectively. The critical solar radiation can vary from day to day, depending on the weather conditions (temperature, wind speed, and other factors). The critical points were found graphically by drawing vertical lines from the beginning and ending points of the water output curve.

The load-matching factor is usually easier to estimate from the PV array power output than from the solar radiation curve. This is because the critical PV array power output is constant, unlike the critical line on the solar radiation curve, which may not be a straight line. The optimum load-matching factor of this PV pump, estimated from the power output curve, is 0.84. This factor could be a bit higher if the trees did not shadow the PV array. This figure is still quite high and shows that the system components are well matched, or properly configured.

The threshold line shifts up or down, depending on the type of motor–pump subsystem, capacity, and weather conditions. Optimum load matching of PV water pumping systems mainly depends on solar radiation and load profiles. Because the load-matching factor is the ratio of the curve's area above the threshold line to the total area of the curve, the load-matching factor for a given PV pump is higher on good solar radiation days than during low solar radiation days. Therefore, the load-matching factor varies from season to season. To maximize the performance of a PV water pumping system, the operation of the load line must be close to the maximum PV array power line throughout the day. Thus, because the load-matching factor is a measure of design quality of the system within the local environment, it has to be as high as possible for all seasons. It is also possible to achieve a higher load-matching factor by carefully selecting the proper size of PV array and the motor–pump subsystem at the best solar radiation locations. The load-matching factor can be close to unity for a well-matched PV pumping system on the best solar radiation day.

The simplest method of measuring a PV pump's performance is to take daily readings of the solar radiation on the PV array's plane, the daily volume of water pumped, and the static head of the well. This allows the hydraulic energy to be calculated, and then the system efficiency can be estimated at different solar radiation energy levels. Appendix D is an example of a simplified daily PV pump recording form for this purpose.

4.6 Design Consideration of Water Tanks

Some of the most important factors to consider in designing water tanks follow.

The power source type. The size of the water tank should be greater for PV- and/or wind-powered water pumping systems than for conventional systems because of the intermittent nature of the power source. Poor solar radiation or windless days create a significant problem in fulfilling the daily water demand. The size of water tanks for conventional systems depends only on the peak and average daily water demands. However, in the case of PV and wind pumps, the size of water tanks depends on those factors and local weather conditions.

The geographical location of the system. Geographical location is very important for a PV/wind pumping system. Sunny and/or windy areas make PV/wind pumps much cheaper and their use ideal in certain locations. Similarly, the size of water tanks can be smaller in such locations. On the other hand, the size of water tanks should be much larger for areas of low solar radiation or low wind conditions.

The type of end users. Unlike those in urban areas, PV/wind pumps installed in rural communities are often designed based on minimum water demand requirements.

The type of application. Water reservoirs designed for irrigation purposes should be very large compared to those for other water supply purposes. Water reservoirs designed for cattle watering and community use typically depend on per capita water consumption. As a rule of thumb, there should be three days of storage for community water supply and five days of storage for cattle watering.

The size of the water distribution networks. Because it can hold a huge amount of water, large water distribution systems also act as water reservoirs. Small distribution networks with water service at only a few points do not have such option. Many of these services are in rural villages where distribution pipes are usually small. In such cases, it is essential to pump water to holding tanks and then on to distribution networks.

Availability of other water resources. Large tanks may be unnecessary if there is a great amount of annual rainfall in the area. Rainwater can be collected and used for cattle watering and for washing clothes in rural areas. Surface water that flows year-round (such as a river) can also provide such services to reduce the need for large-capacity water tanks.

Unlike conventional pumping systems, estimating the proper size of a PV/wind pumping system, including the water tank, requires a detailed evaluation of each component and the system as a whole. As water tanks often cost less than a PV array or wind machine, installing a larger water tank (instead of a larger PV/wind pumping system) allows for the possibility of storing water for low solar radiation or less windy days.

Every means for reducing costs must be considered when designing PV/wind pumping systems. For example, for PV pumping systems, using seasonally adjustable tilt angles can increase the daily water production by 5–10%.

It is also necessary to supply enough water for poor solar-radiation or less windy days, and to use the surplus water produced on days with optimum sun or wind. Consecutive days with poor solar radiation and little wind are especially difficult when trying to meet daily water demand, but can be offset with the surplus.

Water tanks for conventional supply systems are designed to hold 30–40% of the total daily water demand. The bare minimum tank size for any community can be estimated by simulating typical one-year daily weather data and estimating the water balance from daily water demand and production over the year. The water balance is the difference between the daily water production and water demand. Negative water balance demonstrates the extra amount of water required over the day.

The worst consecutive days of poor solar radiation conditions or little wind are reflected on the values of the water balance. The extra amount of water required for these consecutively poor days is calculated by adding the daily water balance of those days with the negative sign. That is equal to the amount of extra stored water required to meet the water demand. Since there may be several consecutive poor days, those days with the largest water requirement are exactly the minimum size of the water tank required to fulfill the community's water demand. In case of hybrid systems, water tanks can be sized like conventional systems because there is a good possibility of getting enough energy to pump water either from wind, sun, or a stand-by diesel system.

5. Installation and Safety

5.1 Wind Pumps

Installing wind pumps can be dangerous if proper safety precautions are not taken. It is very important to follow the manufacturer's installation manual for detailed installation and anchoring instructions. Proper installation includes selecting the correct tower. The tower must withstand the thrust on the wind turbine and the tower itself, and must also support the weight of the wind turbine and those who install or maintain it. In case of hinged towers, the turbine load is distributed on hinges that are guyed, so the weight of maintenance personnel in this particular design is not considered to be important.

Installation of wind pumps varies depending on the types and sizes of the wind machines. There are basically two types of towers: freestanding and guyed (also called *hinged*). Freestanding towers can be divided into three types: truss, pole, and tubular. Freestanding towers are often more expensive than guyed towers and, following assembly on the ground, usually require a crane to erect. assembly on the ground. Truss towers can also be assembled piece-by-piece, starting from the foundation and using a gin pole. Pole towers are primarily used for light wind machines, and tubular towers are built specifically for medium- to high-capacity wind turbines. Guyed towers are designed for small wind turbines. They can be truss or tubular types hinged to the ground by two or more guy levels.

Those possessing basic construction skills can install small wind turbines less than 5 m in diameter. Wind machines with greater diameters present more risk and require special equipment and installation techniques. Experienced installers or contractors should install these.

Three main things should be checked upon receipt of a wind pump (before installation). These include:

1. Verify all documentation is included, specifically the installation and assembly manuals, maintenance and repair manuals, and the manufacturer's warranty;
2. Check to see all items and parts are in the shipment, and all shipping details are correct;
3. Contact the supplier or manufacturer for any missing items before installation.

The most important factor in the installation of mechanical wind pumps, especially for deep wells, is aligning the borehole with the pump rods. Misalignment can rapidly wear the wind pump, and even cause it to malfunction. Rod connectors must be tightened to ensure the pump and the rising-main do not fall into the borehole. Such occurrences can be catastrophic and it can be extremely difficult to recover the pump. At the same time, the couplings that connect the rods must be easily disconnected when raising the pump for maintenance. Other important factors that need to be considered when installing a wind machine are:

- Availability of adequate space for maintenance work.
- Optimum location for wind.

- Adequate room for the concrete foundation to rise 30–50 cm (about 12–20 in.) above the ground to prevent surface water seepage from polluting the groundwater.

Water storage for wind pumps should be sufficient to supply water from three to five days, depending on the local wind regime and continuous daily water demand. Storage tanks can be made from prefabricated plastics, fiberglass, prefabricated galvanized metal sheets, or locally available materials (such as masonry, brick, or concrete). The storage tank can be elevated by using steel structures, concrete beams, or simply being located at a higher elevation. It is also necessary to seal the pump rod at the emerging point of the rising-main to prevent water leakage.

Safety is the most important issue in wind pump installation and maintenance. Life-or-death situations can arise when working with wind machines, so proper follow-up of installation and maintenance is necessary. Proper installation requires thoughtful planning and understanding installation procedures, from foundation work to anchoring to wiring (in case of wind-electric turbines), and on to the installation of subsystems.

Some basic safety precautions to prevent installation and maintenance accidents follow.

1. Before climbing towers, manually furl the wind pump. The wind pump furling mechanism should be checked periodically.

   The furling mechanism tension spring should be adjusted to ensure that furling occurs at the correct wind speed. Adjustment of the furling spring tension should begin with a lighter setting (after installation of the wind pump), so it furls at lower wind speeds. Increasing the tension of the spring can be done once the wind pump runs.

2. Beware of moving parts, especially the blades. Keep fingers and toes away from all moving parts.

3. Avoid standing near or under a wind pump while someone is servicing it.

4. Wear a hard hat, a safety harness, and a safety belt to create safer working conditions when working on a wind machine.

The safety belt will help protect you from falling and to allow free use of the hands is essential. Wearing special boots with firm, hard, nonslip soles, ensures the safety of your feet. Wearing leather gloves can protect hands and provide a better grip.

Electrical safety precautions must be taken to avoid electrical shocks when working on electric wind pumps. Because wind generators produce high voltages, electrical shocks can be fatal. Precautions must be taken when servicing or installing storage batteries. Ventilate the battery storage area to prevent hydrogen accumulation. In addition, wear goggles to protect the eyes whenever working around batteries. Storage batteries must also be protected from discharging.

Fencing the wind pump is important to prevent children from climbing on the tower, or preventing horses and cattle from scratching their backs on the tower edges. Guy cables should be kept away from pathways as much as possible, to prevent vandalism and loosening of tension through normal vibrations.

5.2 Photovoltaic Pumps

Installing PV pumps is usually simpler than installing wind pumps. If the PV pumps use advanced technology; however, they may require the expertise of a professional for proper configuration. Depending on the power requirement of the motor–pump, the array has to be configured for the right current and voltage. The number of modules connected in the series and the strings connected in parallel are determined from the nominal current and voltage requirement of the motor–pump. Once this is designed properly, it is simple to construct the array. The support structure for the PV array can be supplied by the manufacturer or made locally.

As discussed earlier, the tilt angle of PV arrays varies from location to location, but usually is the same as the latitude of the location. The generally acceptable minimum tilt angle for PV arrays located near the equator is 15^{o} from horizontal. In most cases PV arrays in the Northern Hemisphere should face directly south, while those in the Southern Hemisphere should face directly north (that is, the azimuth angle is zero). In some cases, for example for PV arrays installed on rooftops for lighting purposes, it may be difficult to align an array directly south or north. In such cases, it is important to choose the optimal azimuth and tilt angle for optimal use.

Another important factor for optimal use of modules or arrays is to ensure that air circulates from the bottom of the array. For modules installed on rooftops, there may be no possibility for such air circulation. Such conditions increase the cell temperature to an unfavorable degree. Similarly, in some cases, the support structure of PV arrays are made from masonry or are fenced with high masonry or wooden walls located too close to the array. Such arrangements block air circulation and reduce the array's efficiency because of the increase in cell temperature. Ideally a simple steel structure installed about 1 m above the ground should be used, to ensure good ventilation. Such an arrangement creates adequate cooling for the modules and increases the array efficiency and the power output. A typical PV array installation is shown in Figure 5.1.

Fencing must be constructed so that it does not shade the array or block air circulation at any time of day. Another important aspect in site selection is the need to install the PV array away from any shade, including trees, bushes, and buildings. Field experience shows that even the slightest array shading can cause considerable power losses. In addition, the modules composing the array must be identical. Nonidentical cells integrated to build a module are limited by the lowest cell output, and the same effect will occur in nonidentical modules

Cables should be constructed carefully to guard against electrical hazards. Wiring modules can be dangerous on sunny days, unless the array is completely covered. Minimizing cable lengths reduce power losses, especially for DC power cabling. Power-control equipment and all junction boxes need to be shaded and protected from rainwater. Control boxes for small PV systems (up to 2 kWp) usually can be installed under the PV array on the support structure.

All cable connections and seals should be checked for water tightness. A supporting wire should be attached to the motor–pump system if the rising-main pipe is not galvanized steel.

The rising-main should be fixed tightly to the pump, in the case of floating or submersible pumps, or with the rod, in the case of piston and jack pumps. Under no circumstance should the floating devices (the motor/pump units) be lifted or supported by the power-supply cable. Instead, a rope tightened at a suitable place can be used to lower or lift the floating devices.

5.3 Hybrid Systems

Installation, safety procedures, and precautions for hybrid systems vary, depending on the system type. Hybrid systems are usually more complex than individual stand-alone systems. In addition to the stand-alone components of individual systems (PV, wind, etc.), hybrid systems may employ storage batteries, battery chargers, charge controllers, inverters, and back-up generators. Installation of hybrid systems must be done according to the installation and safety guidelines of the individual components, including all the factors considered in the design. Oversized individual systems are usually not necessary for hybrid systems, as is the case with PV or wind pumps; the system is designed to fulfill demand by using two or more stand-alone systems.

6. Operation and Maintenance

Before commissioning a system to the end user(s), basic checks are necessary, and all faults found must be fixed or adjusted within the warranty periods. As with any water pumping system, closely following the operation and maintenance manuals is important for longer operation life and optimal system use.

The levels of maintenance for water pumping systems range from periodic, or preventive activities, to major overhauls. Periodic maintenance based on the manufacturer's recommendations is crucial for efficient and trouble-free operation. In periodic maintenance, every moving part should be examined, and, if necessary, replaced. Anything that requires lubrication should be checked on a regular basis. Depending on the type of system or component types, regular lubrication and oil changes are necessary to maintain transmissions and bearings.

The metal structures of wind pumps need periodic painting to prevent corrosion. Cleaning PV array surfaces must be done regularly, the frequency depending on its location. Dusty sites require cleaning frequently, sometimes even twice a day.

Water storage and distribution networks also need to be regularly examined for water leaks. Steel tanks need regular checkups for rust and should be painted periodically. Similarly, all wiring in PV and electric wind turbine pumps must be checked on a regular basis.

Regular water quality tests are necessary to ensure that a community water supply is safe for drinking. Avoid human and livestock activity near the borehole to prevent groundwater contamination. A good drainage system should be constructed around water distribution points to prevent waterborne diseases, and the surrounding area should be kept as clean and dry as possible.

6.1 Wind Pumps

Trouble-free operation of wind pumps requires periodic maintenance based on the manufacturer's recommendations. Although many wind machines are designed to withstand the worst conditions, components sometimes break or crack. Regularly lubricating and checking all moving parts can prolong a wind pump's life. The pitch of each blade has to be the same and should be checked regularly. A well-maintained wind pump can operate fairly smoothly and quietly.

All moving parts should be checked and tightened after a major overhaul, or when a new wind pump is installed. When required, general system overhauling should be undertaken immediately and should be done in accordance with the manufacturer's recommendations. Major overhauls may be required under the following circumstances:

- System failure because of poor installation or foundation work
- Broken impellers (centrifugal pump) because of silt in the groundwater or corrosion from salt in the groundwater
- Motor failure because of running dry.

Such major breakdowns can happen unexpectedly and a detailed investigation of the cause should be made for reliable, long-lasting pump operation.

Periodic replacement of seals and piston cup leathers in piston pumps is very important for proper operation. It is also recommended that the pump rod seal be replaced at the same time, if it is fitted at the wellhead. If not specified by the manufacturer's recommendations, these items should be replaced every year. Foot valves should also be checked when the seals and piston cups are replaced. The performance of the pump decreases if the foot valve leaks.

Water storage and distribution networks need to be examined routinely for water leaks. All wiring in electric wind turbine pumps should also be checked regularly. Using an electrode is important in an electric wind pump to protect the motor from running dry, thus the electrode should also be checked regularly. Since the water table fluctuates depending on the type of aquifer and the season of the year, it is important to monitor the drawdown of the borehole.

A well-maintained wind pump usually requires fewer repairs than its poorly maintained counterpart. Wind pumps using direct drives require less maintenance than those with transmissions, and mechanical wind pumps require more maintenance than electric wind pumps. On the whole, integrated small wind pumps require far less maintenance than medium-sized ones. Hybrid systems typically have higher maintenance costs than individual systems.

6.2 PV Pumps

PV pumps should not require more than simple maintenance. Because all controllers and inverters are usually integrated in the switchboard, the system functions smoothly without much operator attention. . Some of the features of this integrated control system include surge voltage protection, overload and underload protection, short circuit protection, protection against dry running, MPPT, fault indication, and controlled start-up.

Maintenance of PV arrays is also very minimal. They require periodic cleaning of dust, the frequency of which depending on the location. Modules' glass covers and frames need to be checked regularly for damage and corrosion, and seasonal tilt adjustments might be needed if the array does not have a sun tracker.

The motor–pump subsystem requires periodic check-ups. However, motor–pumps specifically designed for PV arrays are more reliable than other similar systems since they are usually made of stainless steel. Still, it is important to check foot valves, cables and supports, and leaks at the suction and delivery hoses or pipes. With floating pumps, it is important to check for blockages in water strainers and filters.

One of the problems with a stand-alone PV pump system is the size of the water tank. Field experience shows that many of such systems have small-sized tanks that experience water overflows in the daytime and shortages in the evening. Optimal design of the water tanks is based on the water balance of the system from the typical one-year daily solar radiation data. See Section 4.6 for additional information.

Monitoring and evaluation on a systemwide basis is also very important; it can help to further develop the technology, evaluate overall performance, and reduce costs. The three main things to be monitored include the solar radiation on the array plane, the amount of water pumped, and the static water level. In addition, a record of all expenses is necessary for better economic evaluation, and to better understand the long-term real costs and benefits associated with the system.

6.3 Hybrid Systems

For hybrid systems, operation and maintenance is more complex than for single stand-alone systems. Operation of such systems must be in accordance with the integrated system's manual. In these systems, there are more components, such as batteries, inverters, controllers, and backup generators, which require more careful follow-up than a single system (for example, checking a battery's level of charge). Occasionally running the back-up generator is also necessary to keep the generator well lubricated, and to ensure that it will work when it is needed. So a periodic check-up of all components according to the preventive maintenance guidelines of each system is recommended. All meters must also be checked periodically to verify the accuracy of the readings.

7. Economic Evaluation Methods

7.1 General Aspects

Installation of any pumping system requires a long-term financial commitment, and it is important to assess those factors that affect the economic and financial viability of the system. In considering economic viability, a distinction must be made between financial and economic assessments. The economic approach is based on the true value to society as a whole, using benefits and costs free from taxes, subsidies, interest payments, etc. On the other hand, financial viability is a concern from the purchaser's point of view. Financial viability involves evaluation of taxes, subsidies, and loan payments. The long-term effects of the loan should be evaluated by spreading the capital cost over the loan period. Neither the financial or economic approach can convert all relevant factors to monetary terms, so the final decision should be made based on careful consideration of all the technical, economical, financial, and other related external impacts.

In regard to technical aspects, the pumping system must be reliable and must fulfill the water demand. In many cases, the water resource can be the main factor in determining the type of pumping system needed. If the well yield is too low, the only option may be using small pumps (for example, hand pumps or small mechanically or electrically powered pumps). In this case, the well yield is the primary limiting factor.

When a water resource is adequate, the main factor for selecting a mechanized pumping system may be the energy resource, which has an economic aspect. For wind-powered pumps, the determining factor in selection is the availability of wind. For PV pumps, the determining factor is the availability of solar radiation energy. The scarcity of fuel and maintenance personnel in a remote rural village can be also a determining factor for diesel -engine-driven pumps. The economic viability of such systems can be affected because of a lack of fuel and/or maintenance. Days could pass with no pumping capability until a technician can come to fix the system, or until fuel can be brought to the pumping site.

The familiarity of local technicians with the selected system, the frequency and ease of operation and maintenance of the system, and the availability and cost of spare parts are important considerations in the selection of energy systems. PV systems are inherently more reliable and maintenance-free than other types, but spare parts can be scarce and local technicians might be unfamiliar with servicing procedures. Wind pumps are usually the best option for windy areas, as long as the demand is met.

Another important factor is the borehole cost. Drilling is often expensive in remote locations, and it is advisable to use a higher-capacity pump in a high-yield single borehole, rather than a small pump in the same borehole. In such a case, more water can be pumped from the same borehole and the cost of water will be low. So, in this case, the energy source would be the main issue in choosing the type of system (PV, wind, or diesel). Therefore, various factors should be considered in water pumping options during the prefeasibility study.

7.1.1 Financial Versus Economic Viability

Usually, any water pumping system could be acceptable on the basis of meeting the technical requirements. The viability of each pumping option; however, may depend on the acceptability and affordability of the system, and the community's willingness and ability to pay. A complete financial and economic evaluation of alternative systems is recommended before committing to one system.

From a financial standpoint, the purchaser (end user) views the water pump much like any other investment, as the amount of annual loan payments, rather than the lifetime economics of the pumping system. So the purchaser evaluates the financial viability of the system by including all taxes and subsidies associated with it by spreading the loan (investment cost) over the loan period. From the government's point of view; however, the economic approach is used to compare projects over their economic life. Thus, both financial and economic appraisals are equally important and must be used, according to the emphasis given to the project. If the project is part of the distribution of wealth, designed to alleviate poverty in rural areas, an economic appraisal can be more appropriate than a financial assessment. This is because such a project is a part of a government investment project, and adding taxes, subsidies and interests are not important in the assessment. In contrast, a project that is community-initiated and financed in part or in whole by the local users requires a financial appraisal to evaluate various alternative systems.

Whichever approach is used, according to the particular emphasis given to the project, different pumping alternatives have to be evaluated by taking costs and benefits from the system into account throughout the project's lifetime. The economic appraisal method is emphasized in this chapter, because this analysis is relatively easy to convert into a financial evaluation by simply including the appropriate figures (such as taxes, subsidies, and interest payments) in the evaluation.

An economic evaluation is basically a means to identify which alternative pumping option achieves the maximum benefit at the least cost. As stated earlier, all relevant benefits cannot be reduced to monetary terms; the final decision should be based on the technical, economical, and other external impacts combined.

The main difference between the approach of an economic and an external impacts evaluation is the valuing of the factors. An economic evaluation of water pumping systems is based on the monetary values of the system, where all costs (investment, recurrent, and replacement) and income generated from the system are recorded, based on the time value of money. These costs are then evaluated to determine the most viable system from all available alternatives. The external impacts evaluation method applies only to non-monetary values that can directly or indirectly affect the selected pumping system. These two evaluation methods, combined with a technical evaluation, are the main criteria in the selection of the best alternative source of energy for water pumping systems. The selected pumping system can be considered the best choice when the selected system meets these three criteria. The approaches used to evaluate the economic and the external impacts of alternative water pumping options are shown in Section 7.2 and chapter 8, respectively.

7.1.2 Aspects of Economic Evaluation

Economic decision-making includes both generating and evaluating alternatives. Since choosing an alternative always requires a decision, economic decision-making can proceed only if alternatives have been established. The aim of selection must be to find the best possible result for the least possible sacrifice. The task of the evaluator is to find the most profitable among the possible energy alternatives.

In national energy planning, the following three basic policy decisions are usually required for successful energy management.

1. The appropriate level of demand-for-energy requirement that must be served to achieve social goals, such as economic development and basic human needs.

2. The optimal mix of energy sources that will meet the desired demand, based on several national objectives, such as minimum cost, independence from foreign sources, continuity of supply, conservation of resources, elimination of wasteful energy consumption, environmental considerations, and price stability. The analyses are complicated by uncertainties about future trends of demand and supply, relative costs and prices, and incompatibility of different energy sources.

3. A pricing policy based on such criteria as economic efficiency in resource allocation, economic second-best considerations, sector financial requirements, social equity considerations, environmental impacts, and other political constraints.

The process of economic development is closely related to the rapid increase in the quantity of commercial energy consumed. Increased energy consumption and energy efficiency are two conditions necessary for sustained economic development. The complexity of energy–economics interactions indicate that energy sector investment planning, pricing, and management interactions should be integrated with national energy planning. In energy planning and policy analysis, the main emphasis is on the detailed comprehensive analysis of the energy sector, its linkages with the rest of the economy, and the main interactions within the various energy sub-sectors themselves.

The economic evaluation of investments in renewable energy projects should be seen as a technological–economical decision-making process. An investment project, which may not be profitable for an individual business, can be extremely worthwhile for the overall economy when the social benefits it generates are taken into consideration. If we regard economics as the quantitative study of the theory and practices of producing and distributing wealth, and thus the basis for decision-making in social affairs, then "techno-economics" attempts to provide the quantitative basis for decision-making in technical affairs. The essential point is that due attention is given to both technical and economic aspects of the problem. The various effects of all the possible external benefits and costs in the techno-economic evaluation of renewable energy systems can be classified into four levels of decision-making processes.

1. Formulation of criteria for the preliminary selection of the alternative renewable energy system.

2. Formulation and technical optimization of an alternative renewable energy system and selection of the most favorable renewable energy system.

3. Economic evaluation of the conventional and renewable energy system.
4. Determination of the optimal solution based on the criteria of development policy, and social and institutional factors.

Selecting an alternative source of energy for rural areas depends on many factors. The main factors include cost, reliability and quality of service, hours of operation, and convenience of operation. Options for the source of energy include a grid or a decentralized system. In economic evaluation, in order to select the lowest-cost option, each power source alternative must provide an equivalent level of service. Load size and load density are critical factors in selecting between a grid and a decentralized solution. The most common decentralized alternatives to grid supply are diesel generators, small-scale hydropower plants, biomass-based energy sources, wind, and PV systems. Least-cost comparisons between central grid supply and isolated sources are not easy because of the quantity of the supply and the difficulty of quantifying these sources into monetary terms.

On the other hand, investments in long-term projects are characterized by uncertainties regarding project life, operation and maintenance costs, revenues, and other factors that affect project economics. Because future values of these variable factors are usually unpredictable, it is difficult to make reliable economic evaluations. It is also difficult to draw general conclusions regarding the relative desirability of various options. First, both the costs of technology and relative operation vary frequently. Second, sustainability may change depending on the type of end use.

The traditional approach to project investment analysis is to apply an economic evaluation of projects to “best estimates” of project-input variables as if they were certain. Then the results are presented as a single value in deterministic terms. When projects are evaluated based on uncertain inputs, decision-makers will have insufficient information to measure and evaluate the risk of investing in the project. The macroeconomic and social advantages of renewable energy technologies, such as environmental attractiveness, reduction of dependence on imported energy sources, or resource savings, and the hidden costs of conventional energy systems are not adequately represented in microeconomic evaluations. The general market pricing mechanism does not seem to work adequately in such cases. In a distorted market, the government has to compensate by internalizing the external impacts of economic processes. Therefore, efforts to estimate the full costs of energy systems to the society are necessary. Knowledge of the full costs of energy could enable the government or institutions to take corrective action to help the market mechanism achieve an optimal allocation of resources. Although the external impacts of energy systems cannot be adequately quantified and expressed in monetary terms, their inclusion would improve the competitive position of renewable energy sources and later to the extended usage of the system (this issue will be discussed in detail in chapter 8). Therefore, it is necessary to use technically correct and practical methods for evaluating the economic aspects of energy systems.

7.2 Economic Evaluation Methods

A complete compilation of all expenditures and incomes is required for the economic assessment of an investment project. This should include data reflecting the economic conditions where the investment is planned and all associated expenditures and returns, followed by a financial analysis. A quantitative formulation of the idea, together with the decision-making criteria, applicability of the method, and remarks on its limitations should be presented. Various investments and the resulting annual costs and benefits must be indexed according to their time-order of accrual for the proper calculation of financial acceptability.

Some of the traditional methods for analyzing investment costs (some of which will be described in further detail) include

- life-cycle cost (LCC)
- net present value (NPV)
- internal rate of return (IRR)
- benefit-to-cost ratio (BCR) or savings-to-investment ratio (SIR)
- net benefits or savings (NB or NS)
- annuity and cost annuity comparison
- critical value method
- levelized costs (LC)
- payback period.

Life-cycle cost

The LCC method of comparison is a first-order indication when a system is considered for a particular application. LCC is also the most widely used evaluation method. In practice, when the pumping system is to supply drinking water, it is important to establish the comparative LCC of wind or PV versus a diesel pump. This is necessary because the economic benefits of supplying water are difficult to quantify. For example, if each system can reliably furnish the same quality of service, it is safe to assume that they provide equal benefits. In this case, the lowest-cost option is preferred.

In LCC analysis, the NPV of all capital and recurrent costs of the wind or PV pump is compared to the NPV of all the costs of a diesel pump. For example, if the NPV costs of a PV pump are less than the costs of the other alternatives, PV should be the first choice. Mathematical relationships used to calculate the LCC of any investment project are presented in Section 7.2.1.

Net present value

An investment project is only profitable when its NPV is greater than or equal to zero. When there are several alternatives, such as wind, PV, and diesel pumps, the NPVs of different projects should be compared with one another, and the investment with the highest NPV should be selected. NPV can be used to reliably evaluate financially favorable investment projects and compare investment alternatives according to capital yields anticipated to be above the minimum acceptable discount rate.

Internal rate of return

The IRR method is not methodologically accurate when comparing two investment projects with different capital requirements and/or different service lives. A direct comparison of IRRs in such cases can give only an estimate of the alternative projects if it is assumed that additional and follow-up investments can be made at an interest rate equal to the IRR of the original investment.

Benefit-to-cost ratio , savings-to-investment ratio, or net benefits or savings

These three evaluation methods are basically the same. The BCR approach attempts to evaluate projects by measuring the benefits converted into a monetized value, based on market information of the willingness to pay, and the costs, based on market information of the willingness to accept, for the resource sacrificed and undesired items received from the project. The BCR should be greater or equal to 1 in order for the project to be viable. Converting all benefits into monetary terms may be difficult and requires further external evaluation to make decisions. On the other hand, if the alternative options have the same quality of service, the BCR approach can be used to compare alternative projects.

Savings-to-investment ratio (SIR) is the other form of BCR, but this approach is used to make decisions about whether to invest the available money in the project or to save it. In this case, the rate of return of the project must be higher than bank interest in order for the project to be viable. Similarly, net benefits or savings should be positive to favorably consider the project under the net benefits (NB) or net savings (NS) approaches.

Levelized cost

LC is a present-value average of a stream of changing variable costs. All that is involved in this method is to find a single-cost constant (LC) that discounts to the same present value as the stream of variable costs over a period of years being studied.

Annuity and cost annuity comparison

An investment project is considered profitable when its annuity is not negative. If there are several mutually exclusive investment alternatives to be compared, then the alternative with the highest annuity should be adapted, as long as it is greater than or equal to zero. The cost annuity comparison method is a shortened form of the annuity method, without the inclusion of income in the calculation. Using this method, if there are several alternative investment projects, the alternative with the lowest-cost annuity should be selected.

An investment project is considered favorable if the capital invested plus a minimum acceptable rate of interest is recovered by means of anticipated returns within the service life or within a maximum acceptable payback period, as long as the payback period is shorter than the economic life.

Sensitivity analysis

Sensitivity analysis is used to evaluate the effects of uncertainty. It is used to quantify the economic consequences of a potential but unpredictable development in important parameters. Economic parameters include inflation rate, discount rate, equipment capital cost, fuel cost, expected lifetime, quantity of wind and solar radiation energy, etc. Once the LCC of the pumping system is determined, using the common base-case assumption, the economic viability of the pumping system is evaluated in worst- and best-case situations. By varying the economic parameters between the worst and best conditions, the viability limits of different pumping systems can be easily compared. Therefore, sensitivity analysis is used to determine how the NPV life-cycle cost varies from the base case as the economic parameters change. Sensitivity analysis helps to quantify the economic consequences of potential but unpredictable developments in important parameters.

Sensitivity analysis can also be used for more formal risk analysis where probabilities may be assigned to variables. This can enable the decision-maker to tell, at a glance, the choices he or she has made.

Common base-case assumptions should be considered in all these investment cost-analysis methods. The common financial assumptions include salvage value, operating hour, debt service, fuel costs, inflation, and discount rates. The second of these assumptions is where the most important specifications for the typical system in each application are developed. The key technical assumptions common to the base-case analyses include component life (economic life), major maintenance, and engine overhaul. Graphs can be constructed to show the overall best- and worst-case viability of different pumping systems over a given load range. The best-case wind/PV viability graph is developed by compounding the extreme sensitivity limit using the lowest discount and interest rates, the highest fuel cost, the shortest diesel economic life, and the highest wind/solar radiation of the sensitivity limit range. The worst-case is developed using the other extremes of the ranges.

Break-even analysis

Many economic comparisons are forms of break-even analysis. Sensitivity analysis involves an indifference level for a given cash flow element at which two alternatives are equivalent, which is the break-even point of the alternative systems. Break-even analysis shows the point at which alternative pumping systems are equally advantageous, neither system is considered expensive or inexpensive. A break-even comparison detects the range over which each alternative is preferred. The decision-maker only has to choose the most likely preferred system for the required application. For example, in the break-even analysis of wind/PV and diesel pumps, the population size or the pumping head limits for each pumping option can be determined. Break-even analysis can also be used to determine the profitability limit of a single system or product. For example, if the unit water cost of a PV pump is predetermined, based on affordability to the end user(s) or due to some other criteria, the maximum pumping head or population size limits can be estimated using this method.

7.2.1 Life-Cycle Cost

LCC is the sum of all the costs and benefits associated with the pumping system over a given economic lifetime or over a selected period of analysis, expressed in the present value of money, that is the present worth (PW) of the costs and benefits of the system. All the future costs and benefits are discounted to the present-day value and added to the present-day investment costs, and the net present value is the LCC. The LCC, for *n* years' period of analysis, can be expressed mathematically in the form:

$$LCC = \sum_{i=1}^{n} PW_{benefits} - \sum_{i=1}^{n} PW_{costs} \ , \qquad (7.1)$$

where the present-worth costs PW_{costs} are the present worth of the replacement and recurrent costs. The present-worth benefits $PW_{benefits}$ are the present-worth incomes of the pumping system, such as water charges, tariffs, etc. The total PW_{costs} are the sum of total capital costs and PW of replacement and recurrent costs. Similarly, total $PW_{benefits}$ are the sum of all PW incomes.

Equation 7.1 is used to evaluate a single pumping system in terms of its benefits and costs. This method is similar to BCR, SIR, or NB or NS. The only difference between these methods and the LCC is that they use the ratio of present-worth benefits (savings) to present-worth costs (investments). Here, the benefits must be greater than the costs for the pumping system to be worthwhile.

For public projects, such as for a community water supply, the selection of a pumping system should be made based on a comparison with alternative pumping systems. The LCC analysis of a single pumping option by itself cannot be sufficient to make economic decisions. Therefore, it is necessary to compare the system with other alternative pumping systems. For such cases, the present-worth costs of each alternative should be determined and the lowest-cost option considered. There are two ways of comparing alternative water pumping options: (1) to compare the unit water costs of each pumping option, and (2) to compare the per capita capital costs of the systems. Once the total PW is known, the annual equivalent life cycle cost (ALCC) will be determined. The ALCC is the reverse process of discounting (that is, dividing the LCC by the uniform series costs present-worth factor). These factors are shown in the brackets in Equations 7.4 and 7.5.

The present worth of a future single cost or benefit (C_f) payable in n years, which is inflated at a fixed percentage of e each year and discounted at a rate of d, is:

$$PW = C_f \left[\frac{(1+e)^{n-1}}{(1+d)^n} \right] \qquad (7.2)$$

If the real discount rate is used, Equation 7.2 can be written in the form:

$$PW = C_f \left[\frac{1}{(1+i)^n} \right] \qquad (7.3)$$

where i ($i = d\text{-}e$) is the real discount rate. The relations in the brackets in Equations 7.2 and 7.3 are for single-cost (benefit) present-worth factors.

The present worth of a payment or benefit C_a occurring annually for a period of n years inflating at a fixed rate of e per year and discounted at a rate of d is:

$$PW = C_a \left\{ \frac{1}{(d-e)} \left[1 - \left(\frac{1+e}{1+d} \right)^n \right] \right\}, \ \text{for } e \neq d \ , \qquad (7.4a)$$

or, $$PW = C_a\left(\frac{n}{1+e}\right), \quad \text{for } e = d \tag{7.4b}$$

For the real discount rate, where $i = d\text{-}e$, Equation 7.4 can be written as:

$$PW = C_a\left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] \tag{7.5}$$

The equation in the brackets is the uniform series costs (benefits) present-worth factor.

Real discount rates usually can be used in economic calculations. The evaluator has to be careful in using real discount rates, by just directly subtracting the inflation from the discount rate. In a country with hyperinflation, the C_f and C_a factors from Equations 7.2 to 7.5, will be diverted from the real discount rate. Therefore, in such cases, the evaluator needs to use Equations 7.2 and 7.4, instead of Equations 7.3 and 7.5. Figure 7.1 shows comparisons of C_f and C_a for different discount and inflation rates with the real discount rate. At higher inflation, the graph tends to get flatter than the real discount rate and, therefore, Equations 7.3 and 7.5 are not good to use for economic evaluation at higher inflation.

A case study made for economic evaluation of various water pumping systems using life-cycle cost and sensitivity analysis methods is presented in Appendix E.

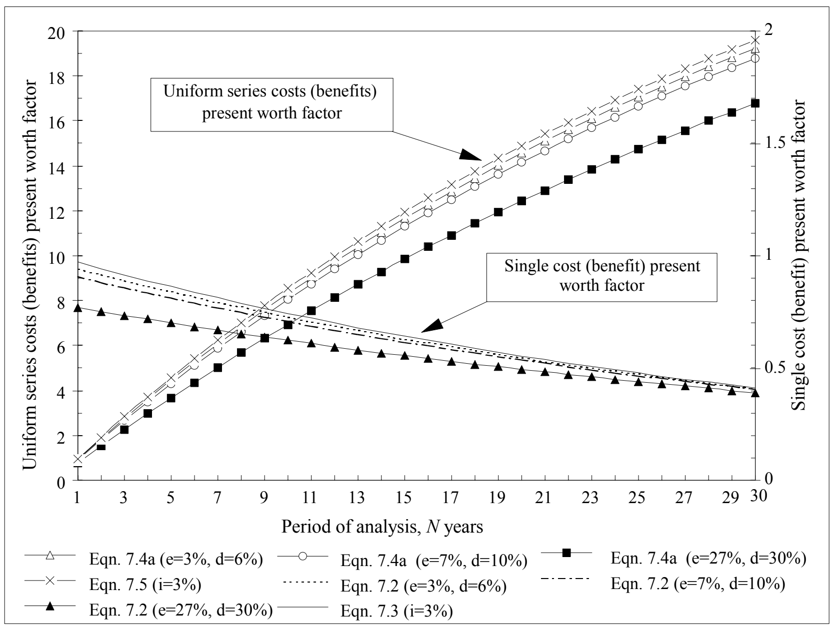


Figure 7.1. Comparisons of C_f and C_a using real discount rate and inflation and discount rates separately using Equations 7.2 to 7.5.

7.3 Cost Appraisal Procedure

The methodologies mentioned in Section 7.2 can be used to identify the lowest-cost pumping system, but the economic evaluation approach by itself is not sufficient to select the optimal system. The lowest-cost solution may not be the best choice, because, as mentioned previously, factors other than cost should also be taken into consideration. Reliability, for example, is a key factor and the user may be prepared to pay more for greater reliability. Thus, cost appraisal is necessary before making the final choice.

Reliability of fuel supply, availability of local maintenance, spare parts, and skilled personnel are the main criteria for economic analysis. For rural villages where there are few roads and unskilled personnel, the ideal power system must not require frequent maintenance visits or refueling. The reliability of fuel supplies and availability of spare parts should be taken into account when considering a diesel pumping option. According to field survey results, diesel-driven pumps operating in developing countries are usually about 10–20% efficient. This is mainly a result of poor maintenance and mismatched subsystems. Such cases impose unnecessary penalties on communities in the form of extra costs.

Mechanical wind pumps could provide a reliable, less-expensive water supply option if wind speed is greater than 3 m/s. Wind speed data are often unreliable; however, and the cost of water produced with a wind pump is very sensitive to the monthly average wind speed. At least three years' of wind speed data collection is necessary before installing wind pumps.

A cost appraisal of different pumping systems can be made using a simple decision chart like the one shown in Figure 4.1. Such a chart helps to screen out possible stand-alone pumping systems unsuitable for the intended purpose. Once the possible power option is selected, the system needs to be properly designed. Then an economic evaluation has to be made to select the best option. Finally, the best pumping system is selected after an external impacts assessment of the selected power source option is completed.

As discussed earlier, the economic hydraulic equivalent load limit for the selection of hand pumps is up to 250 m^4/d, and for diesels above 1,000 m^4/d. (The hydraulic equivalent load is the product of daily water demand V and the total pumping head h). The competitiveness of small electrical and mechanical wind pumps usually depends on the wind regimes.

7.4 Data Collection Procedure for Economic Evaluation

The main parameters needed for economic evaluation are the discount rate, inflation, subsidies, taxes, equipment costs on-site, construction and installation costs, estimation of operation and maintenance, and labor costs throughout the economic life of the system. These parameters vary from country to country and cannot be standardized. The variation depends on several factors, including inflation stability, national policy towards renewable and conventional pumping systems, efficiency of construction companies, level of free competition in the construction business, site accessibility, and location.

The most difficult part of an economic evaluation is not the methodology, but how to collect reliable information for the evaluation. A significant problem is improper recording of expenses by the end users and contractors. In many cases, doing the job quickly is the main priority. As a result, all costs are not properly recorded and lump-sum figures are used. This type of practice distorts the actual investment cost of a project. There is also improper recording of recurrent costs, and projecting recurrent costs over the time span of the economic analysis. Money collection may not be properly made, and actual yearly income not known exactly. Tariffs may not be prepared based on the investment and recurrent costs.

Such problems are not limited to cost recording; there are also similar problems in technical data recording. In many developing countries it is not unusual to find boreholes without a geological log and no recorded well-testing information.. In some cases, there are no water meters connected to the system, thus it is difficult to estimate the daily water output. Water meter reliability can also be a problem.

In economic data collection, one has to understand the following issues. First, the data collector must recognize that precise cost data are not always readily available. The data collector needs to collect all available documentation about the correct costs of the project from archives of end users, contractors, and/or suppliers. Once the actual investment costs are found, the next step is to determine recurrent cost data. These include costs related to operation and maintenance, labor, and replacement. Operation costs are basically operators' salaries, fuel costs, and other associated costs. Maintenance costs includes both preventive and overhaul costs, as well as maintenance personnel expenses (such as daily allowance, travel expenses, and salary for the maintenance period) and spare parts. In many cases, recurrent costs records may not be easily available and it may be necessary to interview operators, end users, water committees, community participation promoters, and/or development workers.

Once the actual investment and recurrent data are collected, the next step is to find the correct discount and inflation rates, subsidies, taxes, and actual fuel costs. Although subsidies and taxes are not relevant to an economic evaluation (they are viewed as transfer of payments or flows of funds to the society as a whole), the data can be used for financial analysis.

The economic opportunity cost of capital is traditionally used as the discount rate in choosing a project among different alternatives, rather than interest rates, because the use of discount rate is more applicable for public projects. The discount rate is "the minimum acceptable rate of return used in discounting benefits and costs occurring at different times to a common time." It reflects the investor's time value of money (or opportunity cost). Real discount rates reflect time value apart from changes in the purchasing power of the money (that is, inflation or deflation) and are used to discount constant money cash flows. Nominal discount rates include changes in purchasing power of the money and are used to discount current money cash flows. Discounting is a procedure for converting a cash flow that occurs over time to an equivalent amount at a common time. The real discount rate i is the nominal discount rate d minus the inflation rate e (that is, $i = d - e$). Usually, the discount rate is used instead of the nominal discount rate, otherwise the term *real discount rate* is used to include inflation or deflation.

The most difficult part of determining the economic opportunity cost of capital is to find the right discount and inflation rates, shadow prices for foreign exchange, and labor costs, because in countries where there is no free market, exchange rates are artificial. Such information is available from the government's economic planning office. Shadow prices are not used unless there is a marked difference in cost between the economic and financial perspectives. In such cases, cost adjustments are necessary for imported items and for those costs that contain a substantial amount of unskilled labor. As a result of the valuation of the foreign exchange and rising taxes and duties, there are alternative valuations of unskilled local labor.

Once the actual investment and recurrent data are collected, and the correct discount and inflation rates, subsidies, taxes, and actual fuel cost information are available, the next step is to estimate the possible income from the project over its economic life. Income can be estimated by either converting monetary values or in-kind values, such as the amount of water production over the project's economic life. To figure such information, one must first determine if there is a water meter installed in the system and if the water meter is working properly. Typically, one-year water output data can be taken and multiplied by the economic life for diesel pumping systems. This assumes that the system efficiency will be the same over its economic life through proper operation and maintenance, thus the water production would also be the same. However, this assumption cannot be true for wind and PV pumps, since the water output depends on the availability of wind and solar radiation energy, and these can vary from year to year. In this case, it is recommended to use typical one-year weather data, describer earlier in this book. This allows for the estimation of the amount of water produced over the system's economic life (simply by multiplying the amount of water produced in one year by its economic life). It is also useful to use average water production data over a few years (the longer the better) to estimate the total water production over the system's economical life.

8. External Impacts Evaluation Techniques

8.1 General

External impacts on pumping systems typically fall into four categories: environmental, social, economic, and political. Examples of environmental impacts include water and air pollution, wildlife protection, soil erosion, and landscape changes. Social impacts include willingness to pay, health, education, unemployment, disability, discrimination, and community cohesion. Economic impacts are those that can be directly measured in monetary units, such as income, taxes, and affordability. Political (institutional) impacts include public access to decision-makers, opportunities for citizen participation, inequalities in the election and selection process, and availability of institutional framework.

Accurate forecasts are needed in planning an external impact evaluation of water pumping systems. Decision-makers at all levels need information to increase their understanding in light of past, present, and future developments. Gaining this perspective requires understanding alternative systems, values, and lifestyles; encourages open dialogue; and seeks to determine the underlying common needs. The following steps are necessary in the planning process:

1. Identify the problem to be addressed
2. Design alternative solutions to the problem
3. Evaluate the alternatives
4. Decide the action to be taken through the appropriate political process and implement it
5. Evaluate the results.

Evaluating a proposed pumping system can be divided into two phases: analysis, where the whole is divided into parts; and synthesis, where the parts are formed into a whole. In more specific terms, the analysis phase defines and estimates the various impacts of the system. This is necessary to gain a detailed understanding of various consequences of a particular system, but at the same time, it poses the dilemma of achieving coherence from various diverse parts. The synthesis phase attempts to solve this dilemma by bringing together the impacts into an integrated view, so a judgment can be formed on whether or not the system should be supported.

The synthesis of impacts to form an opinion can be done informally or formally. Informal review of the impacts can be characterized as judgmental and allows for taking as much time as required to create a distinct impression in the mind. Citizen participation, including experts' involvement in judgmental evaluation of decision-making, is important because it can lead to a qualified judgment of the thing(s) to be evaluated. The formal, or mathematical and additive approach, applies a rating procedure that calculates a composite score of impacts. The informal approach can be both time-consuming and frustrating. The impacts of alternatives are numerous and diverse. Some are desirable and others undesirable. Some can affect an individual directly and others only indirectly (by affecting other people in society). Some occur immediately and others in the distant future; some can be predicted with certainty, others are uncertain. All of these factors should be weighed in reaching a conclusion. Rarely is one alternative clearly superior. Each well-designed alternative typically has disadvantages as well as advantages.

Most evaluation methodologies attempt to overcome these difficulties by taking the formal approach. Using some form of rating system, they calculate a grand index or score, supposedly indicating how the society would be affected by the decision. In effect, they convert all impacts into commensurate units so they can be added up and compared. The various impacts of the action are estimated, then each is assigned a rating; the more important the impact, the higher the rating. If the sum of the ratings for desirable impacts exceeds that for undesirable impacts, then the system would benefit the society and should be supported.

In the design phase of a project evaluation, when a long list of alternatives must be screened, data and budget limits permit few scientifically prepared impact estimates. Even after the alternatives have been narrowed down to a few (or one), some impacts will continue to resist scientific estimation. In that case, human judgment is the alternative.

People think and act on the basis of their view of the world, which is determined by their values, and their knowledge of facts. Human values serve as a guide for personal decision-making, attaching significance and importance to objects and events, directing choices toward those things considered desirable or good, and away from things considered undesirable or bad.

8.2 Evaluation Techniques in Decision-Making

There is no formal evaluation procedure that establishes a citizen judgment methodology. Nevertheless, the contrast between citizen judgment and expert judgment is worth noting, because in principle, any of the expert judgment methods could be applied using citizen inputs exclusively. Asking citizens to determine impacts and assign value weights may not be wise when evaluating those impacts that are best approached from a solid background of scientific knowledge. Establishing and maintaining a citizen judgment process is time-consuming, but forms a useful compliment to expert opinion. Therefore, it seems reasonable to design evaluation processes that include both citizens and experts.

The most common external impact evaluation methods for evaluating public projects are:

- Cost-benefit analysis (CBA)
- Planning balance sheet (PBS)
- Goals-achievement matrix (GAM)
- Energy analysis (EA)
- Land-suitability analysis (LSA)
- East Sussex (ES) and landscape assessment (LA) procedures
- Environmental evaluation system (EES)
- Judgmental impact matrix (JIM)

- Environmental impact assessment (EIA)
- Risk assessment (RA)
- Delphi and impact matrix.

Some of the summarized characteristics of the evaluation methods are shown in Table 8.1.

Cost-benefit analysis

CBA is a comprehensive approach that attempts to solve the evaluation dilemma by using non-technical measurements, applying scientific methods, and calculating a grand index of the social welfare implications of the proposed actions. The ratings that form the index are measured by the willingness-to-pay criterion. Benefits (magnetized value of beneficial impacts) are measured by reference to market information on the willingness to pay to acquire desired items and avoid undesired items. Costs (magnetized value of adverse impacts) are measured by market information reflecting the willingness-to-pay, and sometimes the willingness-to-accept compensation, for resources sacrificed and undesired items received from the project. The CBA also allows for methods of magnetizing social impacts.

Energy analysis

The basic idea of EA is to determine the energy implications of particular actions, so alternatives can be compared with their energy consequences. EA is a completely comprehensive method that should be used instead of CBA on public actions, particularly those having significant environmental consequences. It is a comprehensive method to evaluate alternative plans for energy conservation and development, and an evaluation tool for assessing the energy resource implications of energy conservation and development programs and projects. EA has a great deal of force, but as a comprehensive evaluation method, it is more an idea than a developed methodology.

Environmental evaluation system and judgment impact matrix

The EES and JIM methods of evaluation are more quantitatively orientated and use the Delphi procedure for systematically obtaining and processing expert judgments. Impact categories are presented by the EES method to be used in all applications, and the impacts are estimated by scientific procedures wherever possible. The rating system calculates a composite score of environmental impacts by rescaling the impacts and multiplying them by a set of constant-value weights based on expert judgment. A positive net score obtained by subtracting the adverse from the beneficial impacts reflects favorably on the project, whereas a negative score reflects unfavorably.

The unique contribution of JIM is the way it subdivides the impact estimation problem into a large number of needed bits of information that, once obtained, can be hooked up by a computational procedure. There are two basic stages to impact estimation. First, the impacts of the project or system on the environment are estimated; then the consequences of the environmental impacts (things of more direct concern to society) are estimated. JIM estimates the impacts of each component separately. The advantage is that, since a component might be used in several alternative designs, its impact needs to be estimated only once and used for each alternative in which it appears.

Environmental impact assessment

From the technical point of view, EIA can be thought of as a data management process. It has three components. First, the appropriate information necessary for a particular decision to be taken must be identified and possibly collected. Second, changes in environmental parameters resulting from implementation must be determined and compared with the situation likely to occur without the proposal. Finally, actual changes must be recorded and analyzed. The objective of EIA is not to force decision-makers to adopt the least environmentally damaging alternative. Environmental impact is one of the issues addressed by decision-makers as they seek to balance the often-conflicting demands of development and environmental protection.

Table 8.1. Characteristics of Different Evaluation Methods That Can Be Used in the External Impact Evaluation of Various Water Pumping Systems *(adopted and modified from McAllister, 1982).*

Characteristics	CBA	PBS	GAM	EA	LSA	ES, LA	EES	JIM
1. Type of measure:								
Technical					☒	☒	☒	☒
Non-technical	☒	☒		☒				☒
Either			☒					
2. Method of estimating impact:								
Scientific	☒			☒				
Judgemental						☒		☒
Either		☒	☒		☒		☒	
3. Determining of ratings:								
Source								
Expert judgement		☒			☒	☒	☒	☒
Market prices	☒	☒						
Physical characteristic				☒				
Not specified			☒					
Measurement unit								
Money	☒	☒						
Points or votes			☒		☒	☒	☒	☒
Energy				☒				
Types of rating								
Simple					☒	☒		
Constant value weight			☒	☒				☒
Re-scaled impacts							☒	

Planning balance sheet

The PBS method stresses the importance of recording all impacts, whether monetizable or not, and analyzing the distribution of impacts among different community groups. The PBS, like the CBA, seeks to assess social as well as private costs and benefits. Impacts are measured in non-technical terms and estimated wherever possible by scientific methods. PBS has wide latitude in making judgmental estimates, because it seeks to determine impacts at a more detailed level.

Landscape assessment and East Sussex

The LA method serves a variety of purposes, including the preparation of landscape preservation plans, the preparation and evaluation of general land use plans, and the measurement of aesthetic impacts. The method makes no attempt to measure factors other than aesthetics. The ES method uses a subjective measurement scale that helps to systematize its procedures without being analytical.

Risk assessment

The RA method is of particular interest in many respects, as it parallels EIA. Both are concerned with the likely consequences of environmental change. RA is frequently used to assess the probability and likely consequences of a particular catastrophic event. It tends to be a highly numeric appraisal; essentially it is a statistical analysis of likely events based upon certain probabilities of occurrence.

There are several ways of analyzing risks. The most common methods are decision analysis and social welfare; utility functions, or utility outcome; total utility, or composite environmental quality index (EQI) and project alternative ranking order; and expected utility. All of these methods have similar approaches. They all use weighted values, either in the form of probability or rating in ranking order. The EIA, and CBA and RA evaluation methods are easy ways of determining the institutional, social, and environmental impacts for a socioeconomic evaluation of public investments.

In principle, any of the above methods can help to make a proper decision. However, the main factor that affects the final decision is how the experts prepare (collect) the inquiry (data).For particular problems, models are only of limited use as they provide solutions with a reduced accuracy, credibility, or even predictability.

Delphi and impact matrix methods

A developing technology may require a detailed external impact assessment of the system, along with the technical and economical viability assessments, to determine its role in solving energy problems. An external impact assessment may be accomplished by using an inquiry method based on questionnaires completed by interested parties, analyzed by experts, and treated statistically. The most common methods used in such cases are the Delphi and impact matrix inquiry. The Delphi method is based on the collection of opinions from a selected group of experts through preliminarily prepared questionnaires. Answers are weighted according to the expertise of specialists. A comparison of different opinions through a follow-up questionnaire permits an expert to compare his or her opinions with others, and reconsider his or her earlier judgments in light of new or different ideas.

An individual expert may have an incomplete, simplified, and perhaps distorted image of the system. Without consideration of how all parts relate within a system, the influence of reciprocal relationships between variables can be over- or underestimated. Such interdependence problems are treated by the impact matrix, which uses a sharper statistical evaluation method.

The impact matrix method attempts to predict a future scenario through experts' assumptions and opinions. This is accomplished by estimating and logically presenting relationships between the relevant variables. All the possibilities must be considered using any variety of different procedures, such as brainstorming, establishing checklists, etc. Once the variables (internal and external) have been defined and a basic construction of the present completed, the system under investigation will be described with a set of questions. The first step will be listing the systems under investigation and defining the context (all the technical, economical, institutional, and social aspects of the systems). This leads initially to a classification of variables by differentiating between the endogenous (internal) and exogenous (external) variables, and allows for the construction of a matrix establishing the different influences. The idea is to establish a structural matrix where each variable corresponds to a line or column. If a relation exists between relevant variables (or if one variable has any influence on another variable), it will be indicated by binary notion (0 or 1).

8.3 Common External Impacts Evaluation Methods of Water Pumping Systems

Many proposed public projects are complex actions, entailing numerous potential consequences of interest and concern to the public. Understanding their possible implications as a whole is very difficult, thus it is necessary to divide the whole into parts, or impacts, and evaluate them systematically using an analytical method. Once the impacts are analyzed, they need to be synthesized to form a whole.

There are several evaluation techniques that can help in reaching decisions. The impact matrix method is the best evaluation tool, especially for newly introduced technology. CBA, RA, and EIA are the simplest and most comprehensive evaluation methods for public investment projects. The quantification of complex public projects by such methods may result in a precise answer, but it may not make the final judgment more accurate or objective. Human judgments combined with such methods are believed to provide an effective means of evaluating the external impacts of such projects, including alternative water pumping options. Three of these evaluation methods are presented in the following sections.

8.3.1 Cost-Benefit Analysis

CBA is a comprehensive approach that helps to evaluate public projects, such as water pumping systems, by allowing for measurements in non-technical terms and estimating them scientifically. The number of separate impacts to be identified in the evaluation can be quite large. To gain a quick visual impression of the quantity of information that might be generated by an impact analysis, consider the table, or matrix, shown in Table 8.2. Various beneficial and adverse impacts are listed separately, and these are further subdivided according to the beneficiaries or interest groups on which they fall. If impact information is organized in tabular form as here, a separate table of information is needed for each option to be evaluated. Considering the potentially large number of impact types, time periods, people or interest groups, and alternatives, the number of bits of information can be sizable. When information on a proposed public action is as detailed as that, decision-makers are able to gain keen insights into its advantages and disadvantages.

It is fundamental to this way of thinking that a variety of potential solutions be generated through brainstorming before the evaluation takes place. This helps to avoid the common impulse to latch on to the first seemingly agreeable idea and close one’s mind to other possible solutions.

Using CBA, both the beneficial and adverse impacts of alternative water pumping options are listed separately and graded based on the weighted value of the individual impacts. Then the scores of the beneficial and adverse impacts are added separately. Finally, a grand index for each pumping system is calculated by subtracting the sum of all adverse impacts from the sum of all beneficial impacts. The positive grand index with the highest value shows the best choice option among the listed water pumping technologies. A case study is included in appendix F using both the CBA and RA methods.

Table 8.2. Table of Disaggregated Impacts.

	Beneficiaries or interest groups			
Impacts	1	2	3	. . .
1				
2				
3				
.				
.				
.				

Impacts	Rating (Value weight)
1	
2	
3	
.	
.	
.	

8.3.2 Risk Analysis

The external impacts of alternative water pumping options can be also evaluated mathematically by using the RA method. The idea behind this technique is to devise a formula or equation that can summarize all the criteria for accepting or rejecting the proposal impacts in a single score or grand index. If the score for beneficial impacts exceeds that of adverse impacts, the grand index is positive, indicating that the action should be supported; if the grand index is negative, it should not.

Problems can be represented in matrices, where the columns represent the criteria (impacts) *C* and the rows the various types of water pumping technologies *S*, as shown in Table 8.3. It is convenient to formulate types of pumping systems and impacts so they form mutually exclusive and exhaustive sets. Thus, only one impact can be selected or can occur, and one must be selected or must occur. This can be easily performed by Boolean expansion for any set of elements. For example, if there are two impacts that are not exclusive and exhaustive, it is possible to form four composite impacts with the following properties:

Table 8.3. Problem Representation in Matrix Form.

Pumping systems \ Criteria (impacts)	c_1	c_2	c_3	– –	c_j	– –	c_n
s_1							
s_2							
s_3							
¦							
s_i							
¦							
s_m							

C_1: c_1 and c_2 occur
C_2: c_1 occurs but not c_2
C_3: c_2 occurs but not c_1
C_4: neither c_1 nor c_2 occurs

If there are *n* impacts, then the Boolean expansion will usually yield 2^n composite impacts. One of the most popular RA methods is the expected utility, or the project alternative ranking order, method. The general formula for determining expected utility *EU* of any pumping system, using the Boolean expansion is:

$$EU(S_i) = \sum_{j=1}^{n} P(C_j | S_i) \; U(C_j, S_i), \quad (8.1)$$

where S is the type of pumping technology, C is the criteria (impacts), and $P(C_j / S_i)$ is the probability of each impact. The expected utility for each pumping technology is determined by listing the beneficial impacts. Then, according to their importance, probability will be assigned for each impact, so the sum of the assigned probabilities for whole impacts will be 100% (or 1 point). The expected utility for each pumping option is calculated using Equation 8.1. The highest expected utility value is normally accepted as the best choice pumping option for the expected application, and is also considered the least risky water pumping system.

8.3.3 Critiques and Limitations of Decision-Making Approaches

The purpose of presenting these critiques is not to suggest that decision-making approaches have little value, but to provide the user with an awareness of the limitations of the analyses. Such methodologies can help indicate when certain approaches can be appropriately applied, how much precision and reliability can be expected in the results, the nature of any existing controversy surrounding the use of an approach, and what questions should be asked about the methodology in examining the results of any application.

Asking citizens to determine impacts and assign weights to values has an obvious disadvantage; the citizens may be unqualified to judge impacts best approached from a scientific background. Another disadvantage is that establishing and maintaining a citizen judgment process may be inconvenient. Scheduling meetings for citizen groups involves inevitable timing and location conflicts. If the task is time-consuming and prolonged, the size of the group may dwindle. Nevertheless, the contrast between citizen and expert judgments is worth noting, because, in principle, any of the expert judgment methods could be applied using citizen inputs exclusively.

In the absence of sound information on the consequences of alternatives, planning debates can easily break down into purely rhetorical contests in which the side that can talk the loudest and longest has the most influence. On the other hand, Banuri (1990) points out that the pursuit of self-interest in economic matters may be desirable, if everyone follows a recognized moral code, has a shared sense of justice, and there are sufficient internal constraints.

According to Merkhofer (1987), critiques of formal approaches are summarized into four groups. The first is fundamental criticism, where limitations of existing theory with respect to characteristics inherent in social decision-making make available approaches incapable of identifying an alternative. The second is operational criticism. These are practical considerations that limit or subvert an approach's value in actual applications. The third is the institutional incompatibility, in which characteristics of approaches are at odds with existing institutions and processes. The fourth is criticism based on ethical grounds.

Some of the fundamental criticisms concern the impossibility of finding a socially optimal decision rule, destruction through decomposition, inherent incompleteness, and inability to account for the costs of irreversibility. According to Howard (1980), decision analysis is a very clear method (paradigm) suitable only for the individual decision-maker, thus is not applicable for public policy decisions.

The execution of several disaggregated tasks, including structuring the problem, determining probabilities of risk-event outcomes, interpreting those outcomes in terms of impacts, and valuing those impacts, will divert from more creative approaches to problem-solving. Decomposition may oversimplify the problem. The model of a decision situation can never be an absolutely complete representation of reality. Any complex real-world problem will always have more dimensions than a model can capture. Therefore, the results derived from an approach based on an incomplete model may not apply to the real world for which the model is meant to approximate.

Even if decision-making approaches could in theory identify an optimal social alternative, practical problems may still prevent this capability from being realized in real-world applications. Some of the practical limitations that critics claim reduce or subvert the values of formal approaches, according to Merkhofer (1987), are omissions and inaccuracies, the difficulty of measuring benefits and costs, biased assessment, modeling and analysis, and misinterpretation and susceptibility to misuse.

Incompleteness resulting from omissions of important considerations is likely to be responsible for the largest errors in applications of decision-making approaches. The four sources of omissions, according to Fischhoff (1977), are human errors, failure to anticipate human response to safety measures, failure to consider unanticipated changes in the environment, and failure to appreciate large-scale interactions and dependencies.

The creative and judgmental nature of decision-making approaches ensures that they will be prone to distortion because of human limitations. On the other hand, approaches may be misused by the end users and/or the results may be misinterpreted, even if analysts do not manipulate their results. There are a number of ways in which end users might misuse analysis. Because formal approaches clearly identify unknown factors, these factors might be employed as an excuse for delay or inaction. Howard (1980) observes that in many instances, assessments seem to be commissioned not to aid in an impartial decision-making, but rather to advocate a particular position. Another way in which an analysis can be misused is by selective omission of results or caveats.

The other criticisms are focused not on whether or not formal decision-making approaches are capable of working as they are designed, but rather on if they are acceptable in view of established institutions, procedures, and social norms. Institutions can and do change, and might well do so in response to new technologies, such as decision-making approaches. Thus, incompatibilities with current practices do not negate an approach's value. Some of the incompatibilities, according to Merkhofer (1987), relate to organizational structure and processes, social norms, constitutional and legal principles, and principles of democratic decision-making. Some critics argue that formal decision-making approaches run significantly counter to existing social attitudes, preferences, and practices, and consequently, regardless of their potential value, will not gain any real acceptance. Issues discussed in this category include the reluctance of society to quantify environmental and health amenities, and the unwillingness of decision-makers to admit that the basis of decisions is largely subjective and inconclusive.

The principal sources of ethical criticisms are the inability of formal approaches to provide solutions to questions like “Under what conditions is someone in the society entitled to impose a risk on others for the sake of a supposed benefit to yet others?” and “Should social risk decisions be the responsibility of a technical elite, or should they be approached through the democratic process?” Ethical problems that have been the source of criticisms of formal approaches include equity distribution, intergenerational effects, and the regard for humans as the most important and central point (anthropocentricity).

All public policy decisions result in a distribution of benefits and burdens; some gain and others lose from the distribution. The decision from the formal approach does not fairly and equitably distribute the costs and benefits of policies. Long and Ploeg (1989) noted that policy implementation issues should not be restricted to the case of top-down, planned interventions by governments, development agencies, and private institutions, because local groups actively formulate and pursue their own development projects that often clash with the interests of central authority.

It appears there is currently no available formal decision-making approach for risk decisions that is free from criticism. Furthermore, available approaches have different strengths and weaknesses.

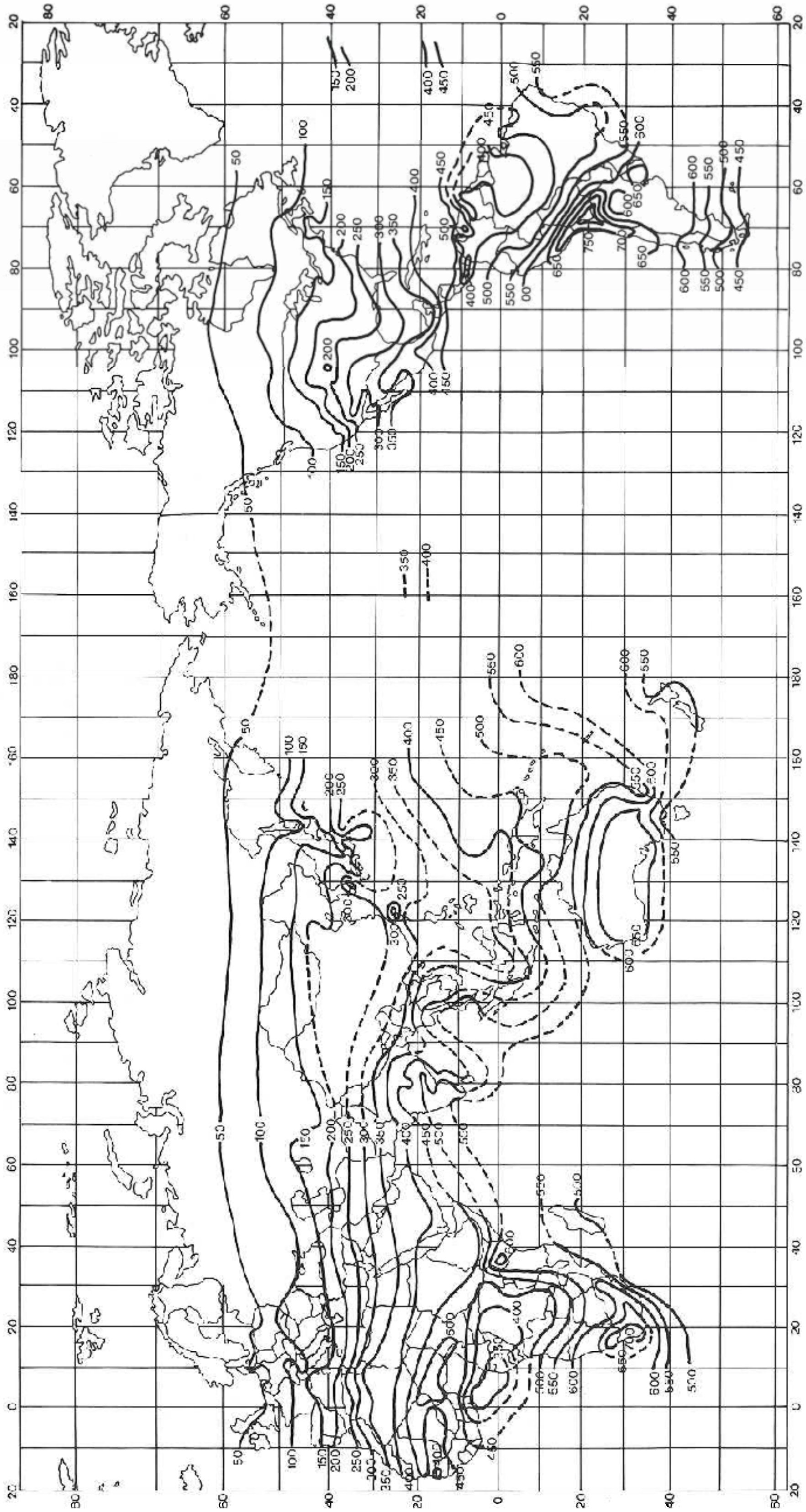
Whichever decision-making approach is used, the first step is usually problem characterization. This involves examining three aspects relating to technical, organizational, and perceptual factors. The technical characteristics of the problem determine the usefulness of different approaches. The organizational aspects relate to issues that influence the acceptability and applicability of approaches. Perceptual characteristics influence people's reactions to the likely outputs of the analysis. The second step is to consider alternative approaches. The spectrum of available procedures and techniques is much wider than the options, which are apparent at first glance. Analysts and sponsors of formal analysis must resist the temptation to choose those approaches with which they are most familiar. The selection and development (and ultimately the interpretation of the results) of an approach should be conducted with attention given to specific evaluation criteria, including logical soundness, completeness, accuracy, practicality, and acceptability.

Finally, it is important to note the value of the debate between opponents and proponents of formal decision-making approaches, for this leads to improved methods for making difficult decisions on how to best locate the scarce resources available in our finite world.

Appendix A: Wind and Solar Radiation Energy Maps of the World

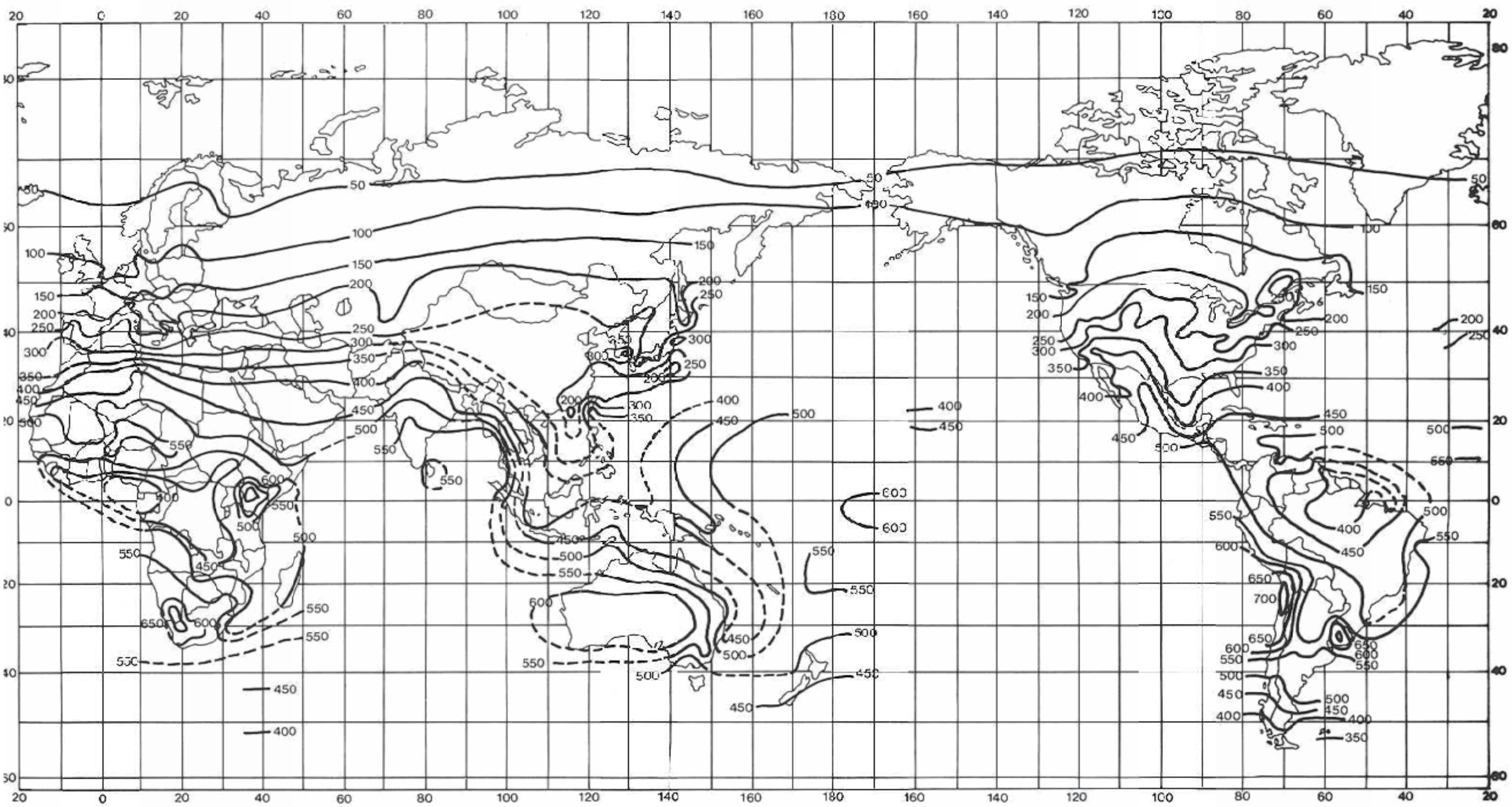
Source: World Solar Energy Atlas, Note: 1 cal/cm^2/d = 1 langley = 11.63 Wh/m^2/d

SOLAR RADIATION MAP JANUARY



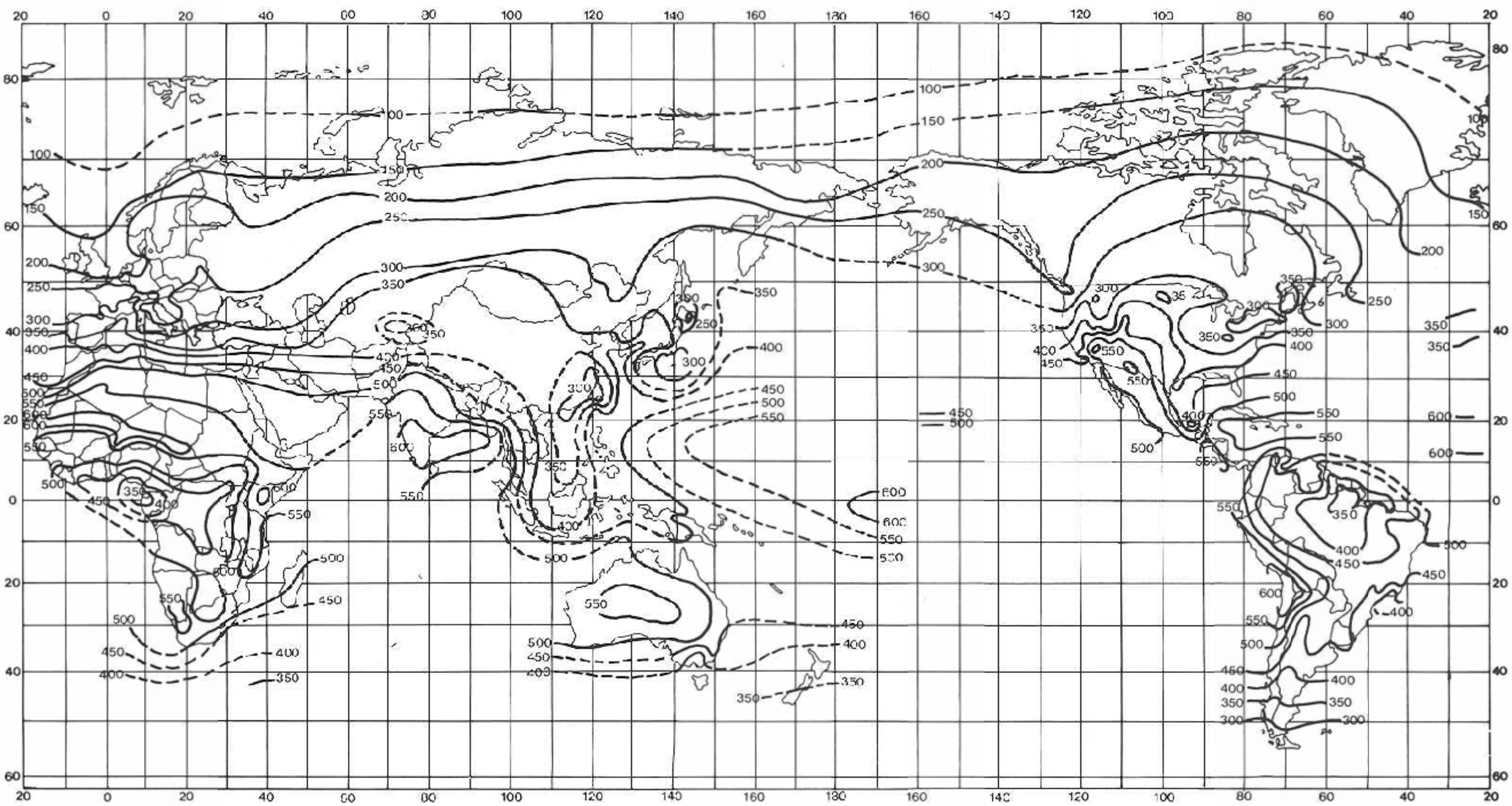
Daily means of total solar radiation (direct+diffuse). Incident on a horizontal surface in cal/cm² day.

SOLAR RADIATION MAP FEBRUARY



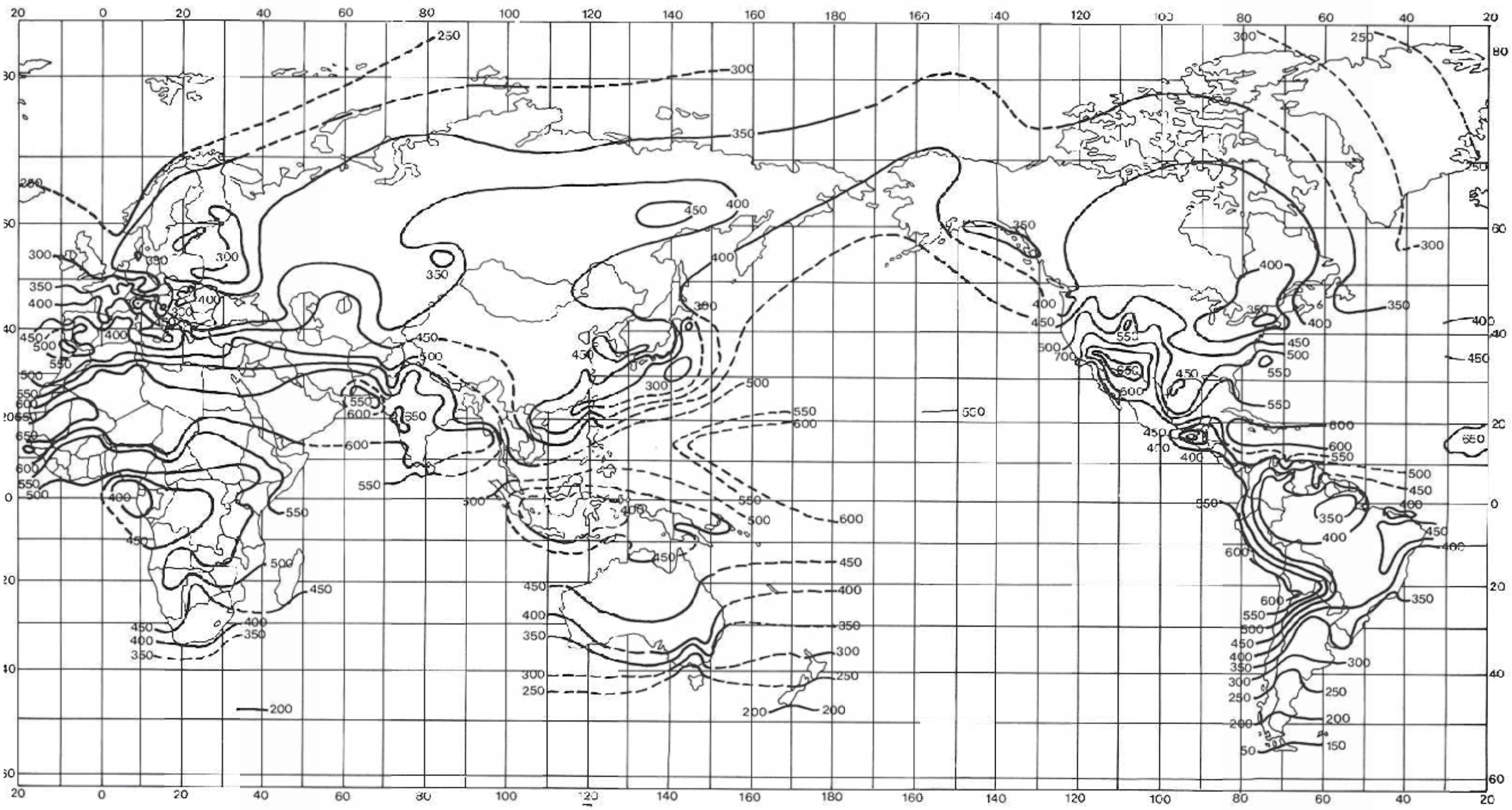
Daily means of total solar radiation (direct+diffuse).
Incident on a horizontal surface in cal/cm² day.

SOLAR RADIATION MAP MARCH

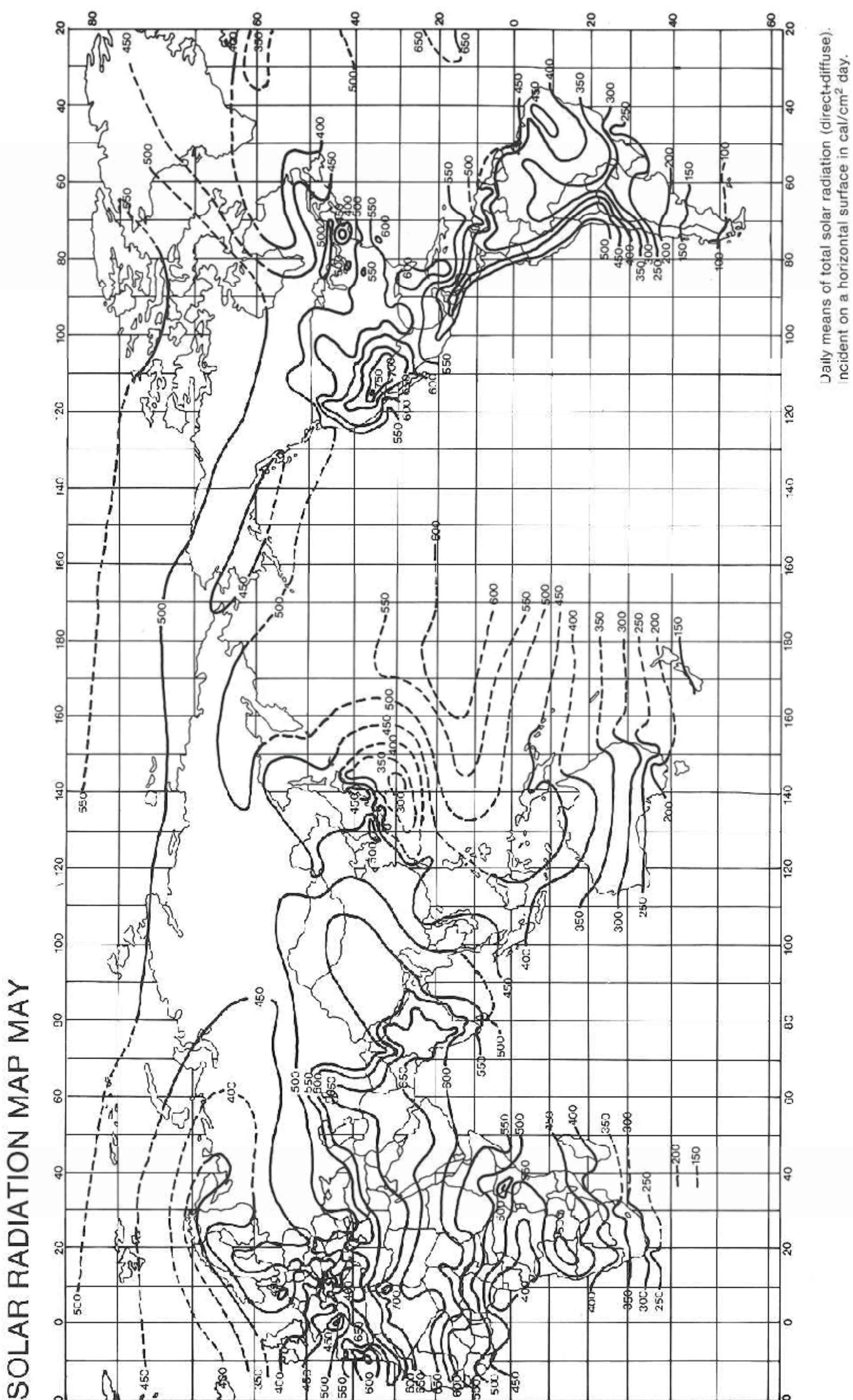


Daily means of total solar radiation (direct+diffuse). ncident on a horizontal surface in cal/cm² day.

SOLAR RADIATION MAP APRIL

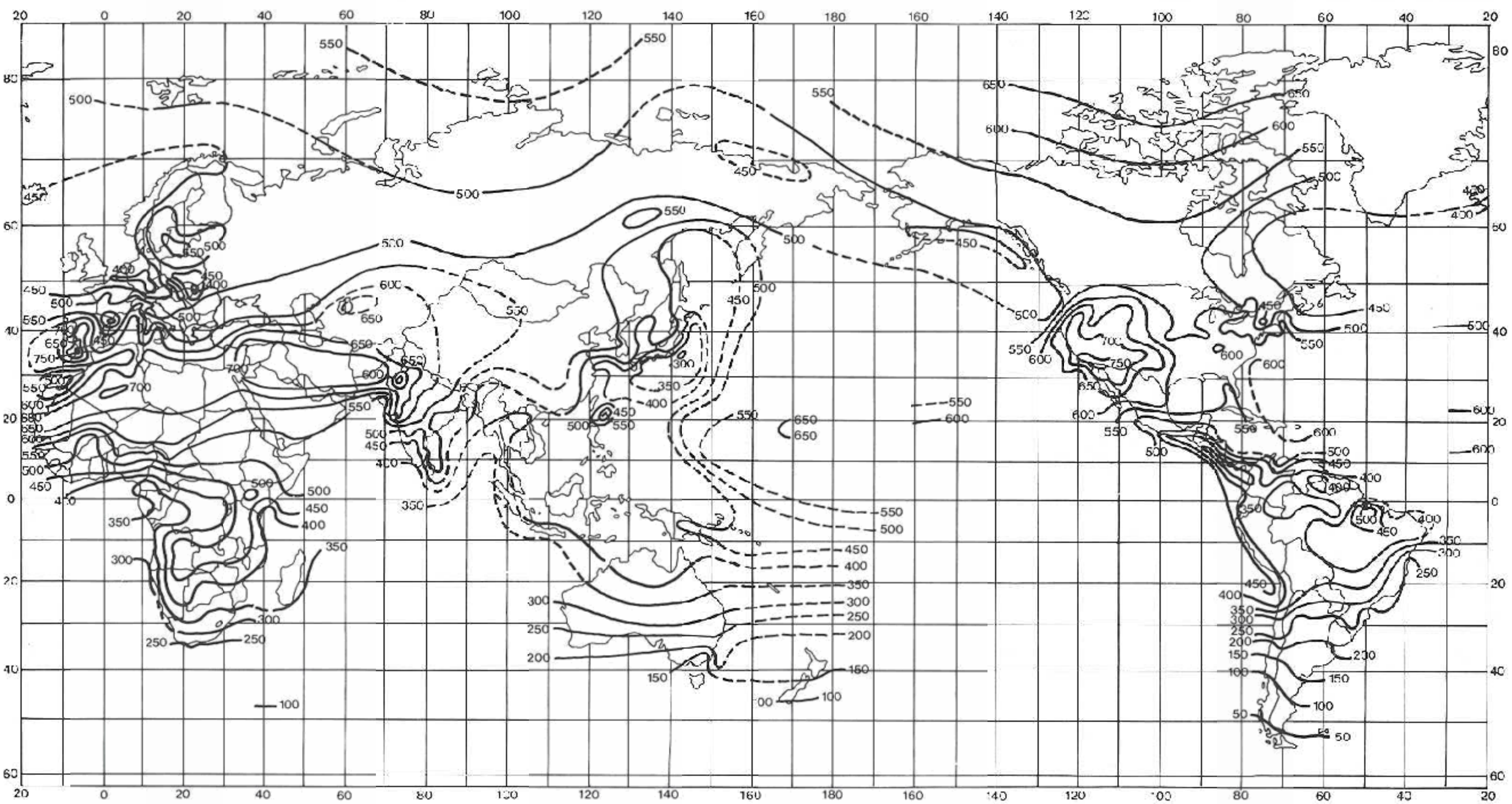


Daily means of total solar radiation (direct+diffuse). Incident on a horizontal surface in cal/cm² day.



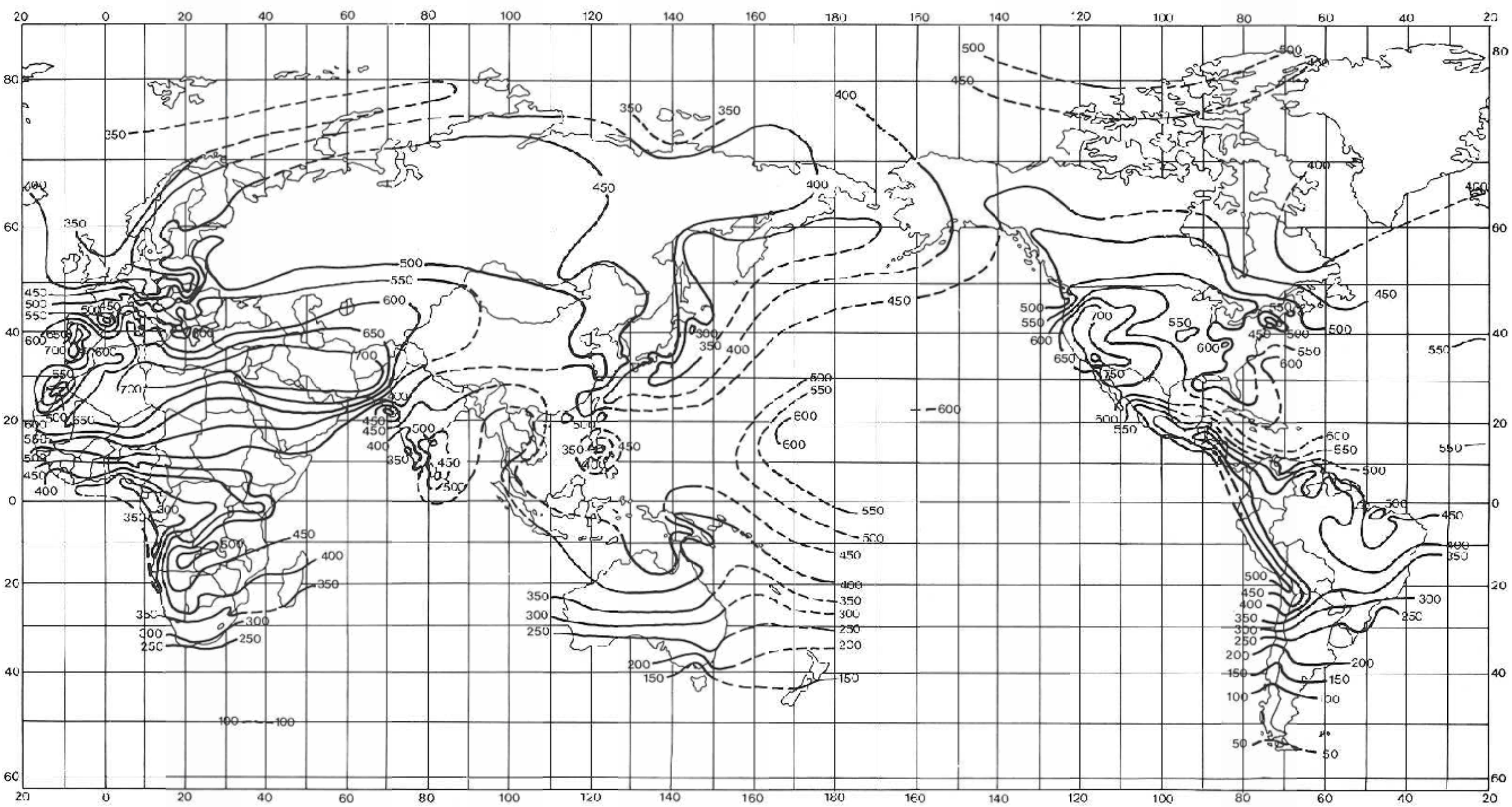
Daily means of total solar radiation (direct+diffuse). Incident on a horizontal surface in cal/cm^2 day.

SOLAR RADIATION MAP JUNE



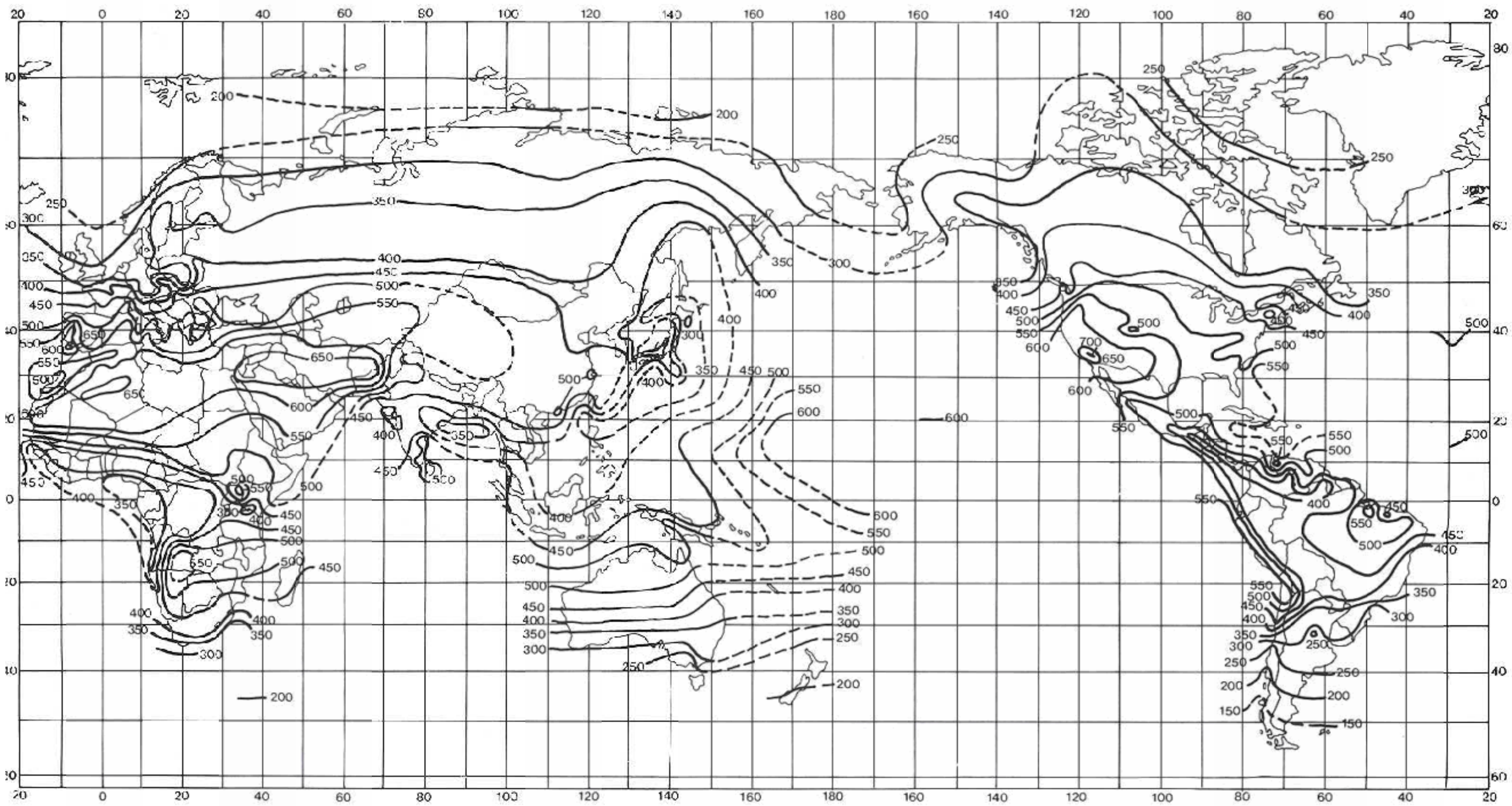
Daily means of total solar radiation (direct+diffuse). Incident on a horizontal surface in cal/cm² day.

SOLAR RADIATION MAP JULY



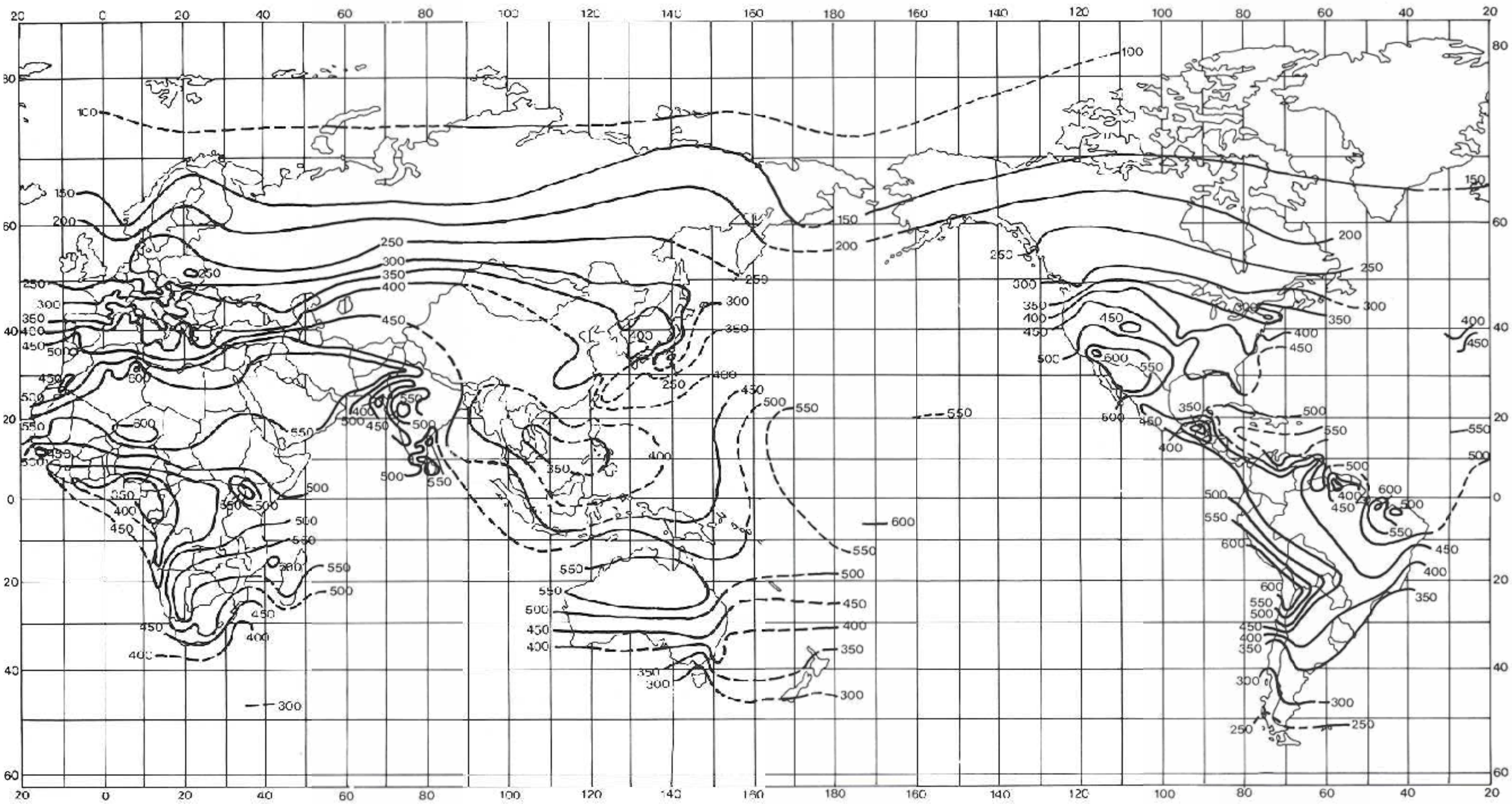
Daily means of total solar radiation (direct+diffuse).
Incident on a horizontal surface in cal/cm² day.

SOLAR RADIATION MAP AUGUST



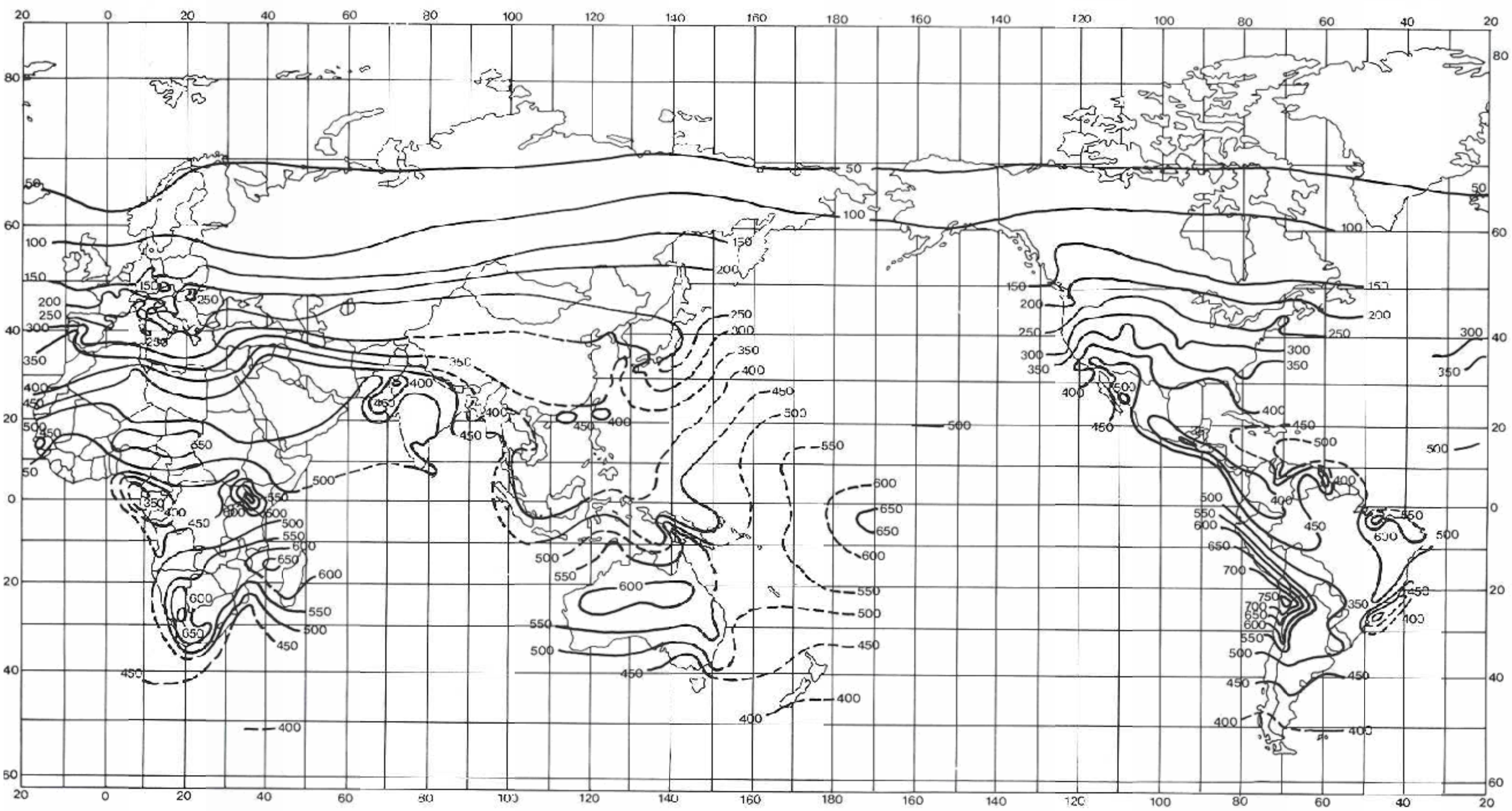
Daily means of total solar radiation (direct+diffuse).
Incident on a horizontal surface in cal/cm² day.

SOLAR RADIATION MAP SEPTEMBER



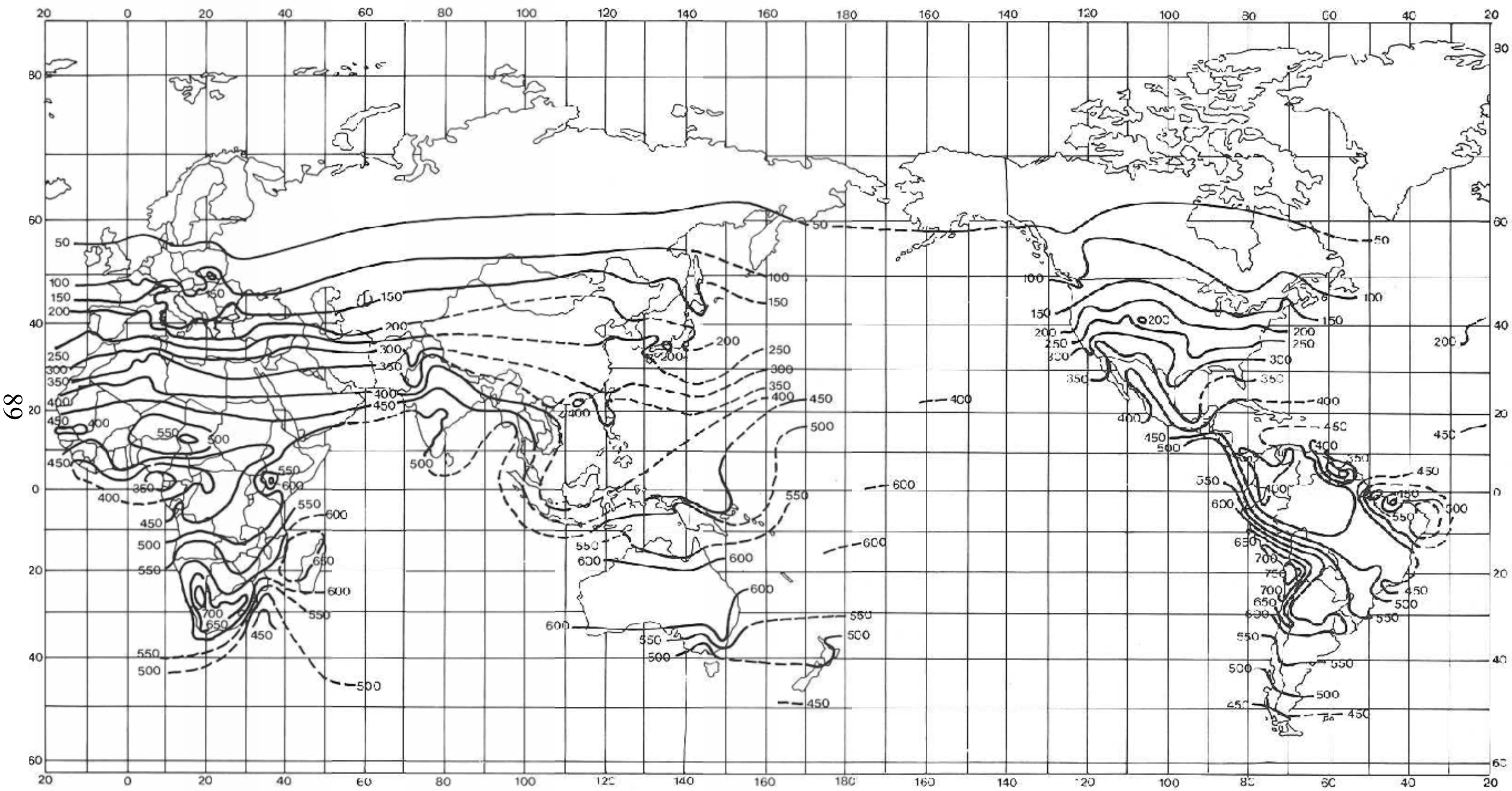
Daily means of total solar radiation (direct+diffuse).
Incident on a horizontal surface in cal/cm² day.

SOLAR RADIATION MAP OCTOBER



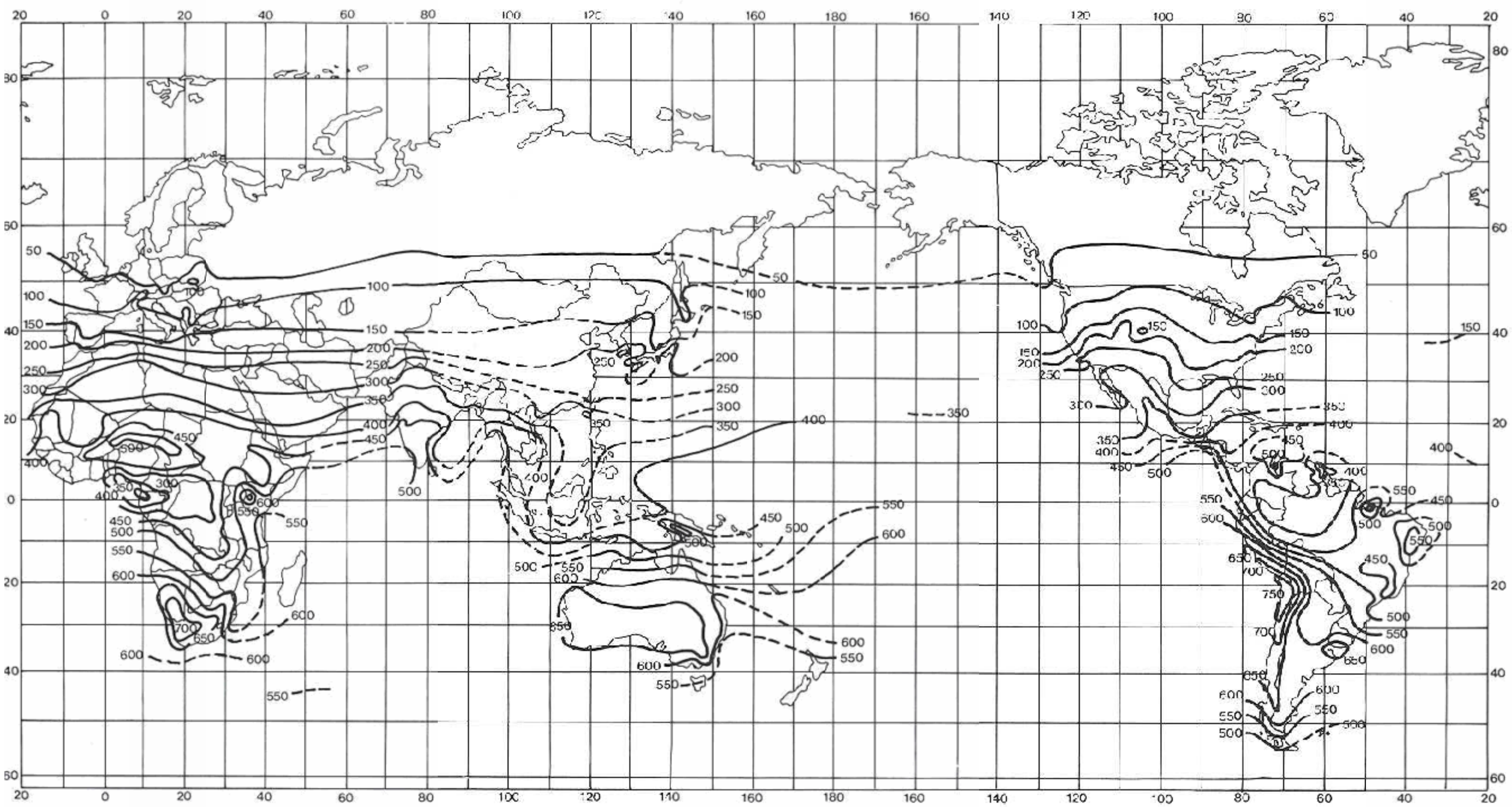
Daily means of total solar radiation (direct–diffuse). Incident on a horizontal surface in cal/cm² day.

SOLAR RADIATION MAP NOVEMBER



Daily means of total solar radiation (direct+diffuse). Incident on a horizontal surface in cal/cm² day.

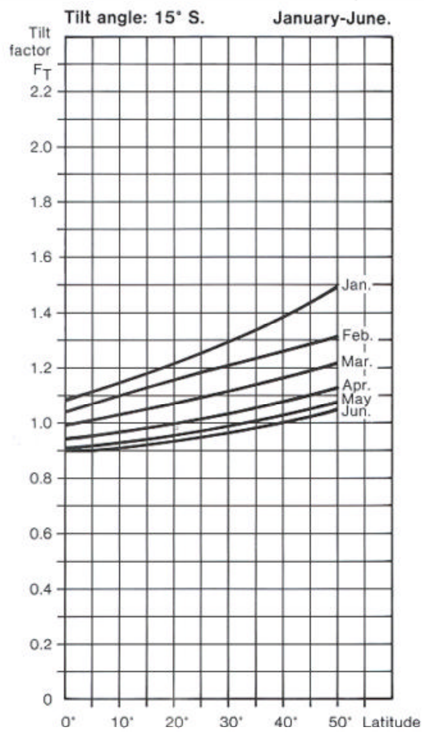
SOLAR RADIATION MAP DECEMBER

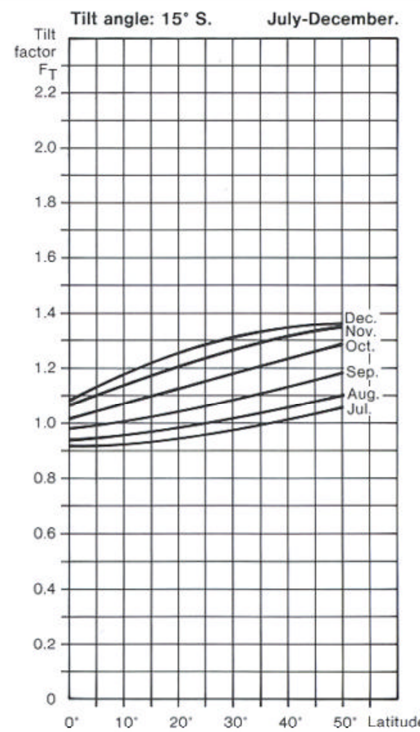


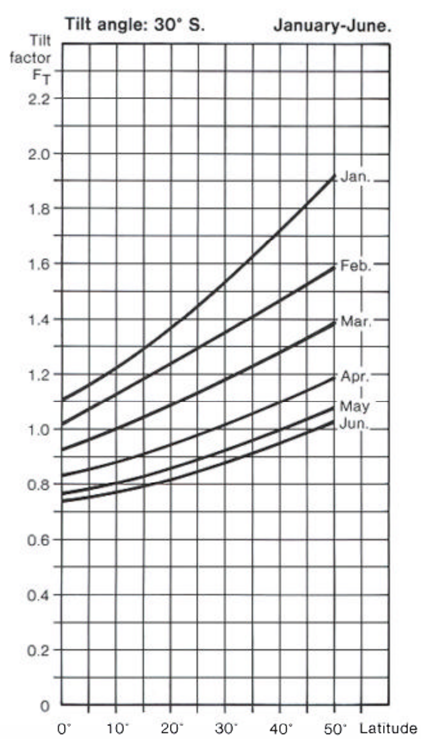
Daily means of total solar radiation (direct+diffuse).
Incident on a horizontal surface in cal/cm² day.

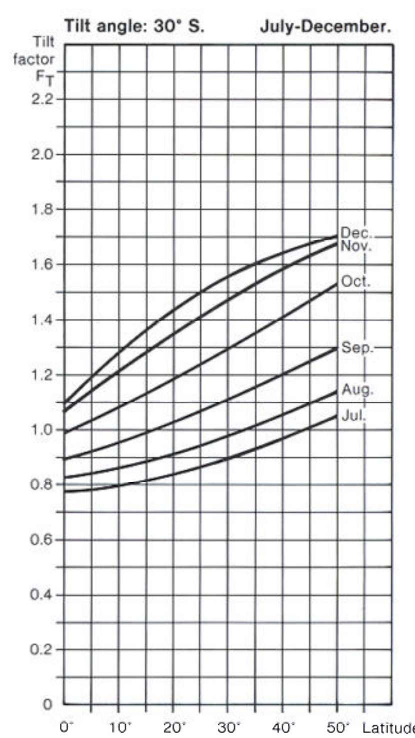
Appendix B: Tilted Factor, F_T

NORTHERN HEMISPHERE









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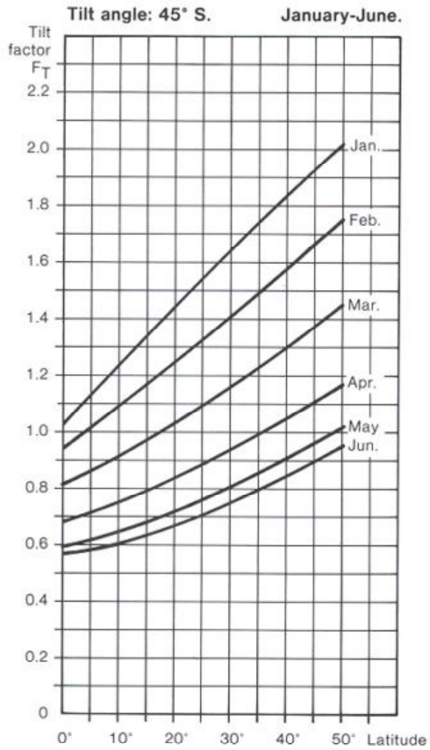
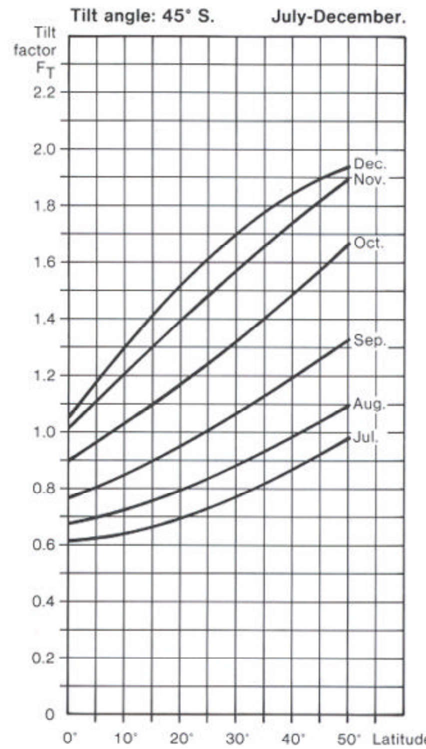
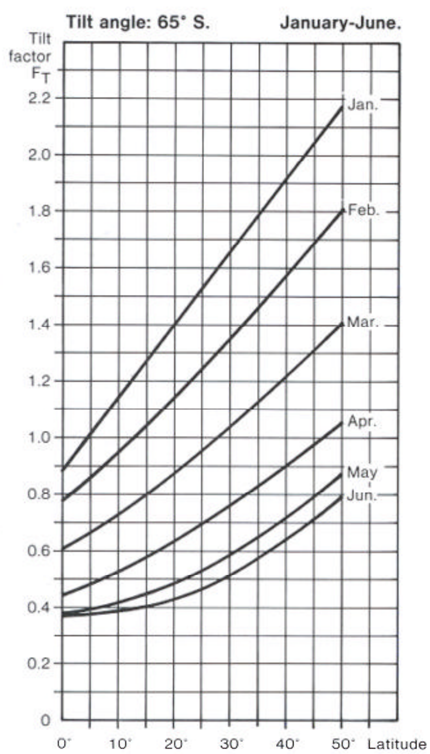
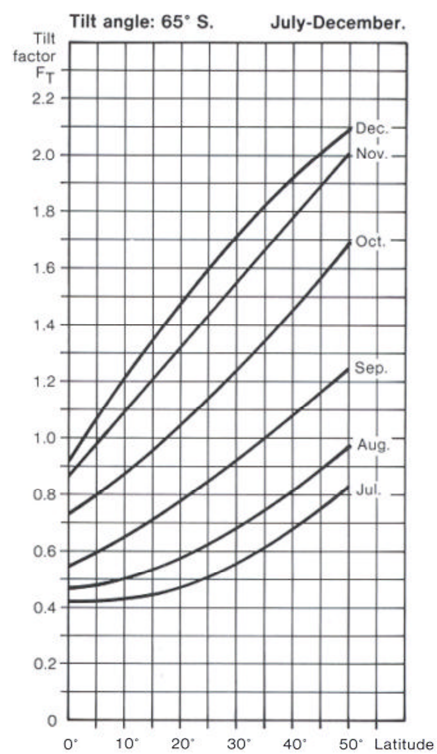
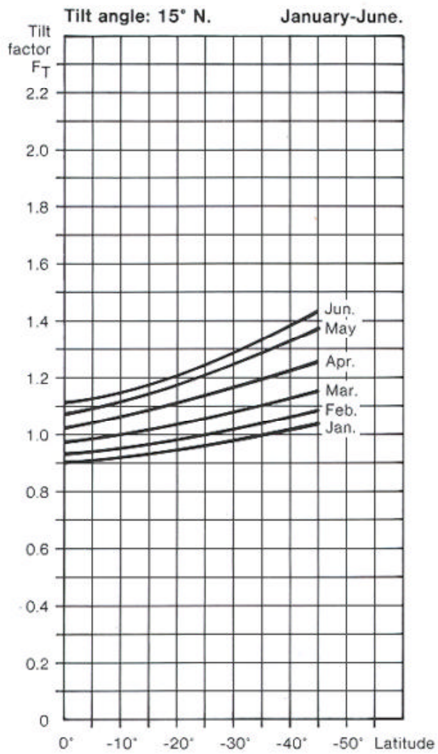


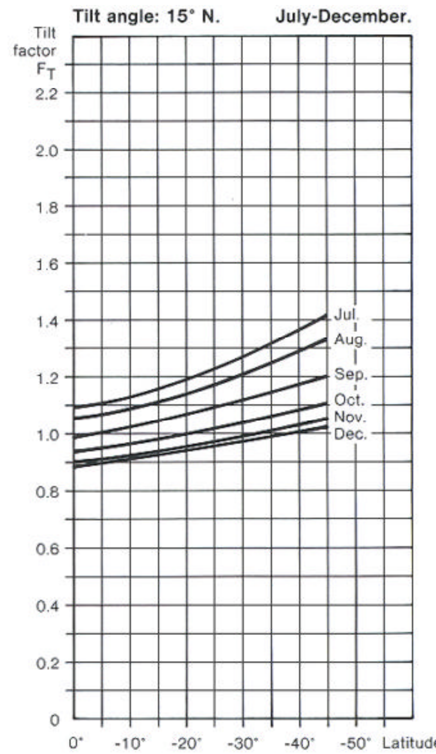


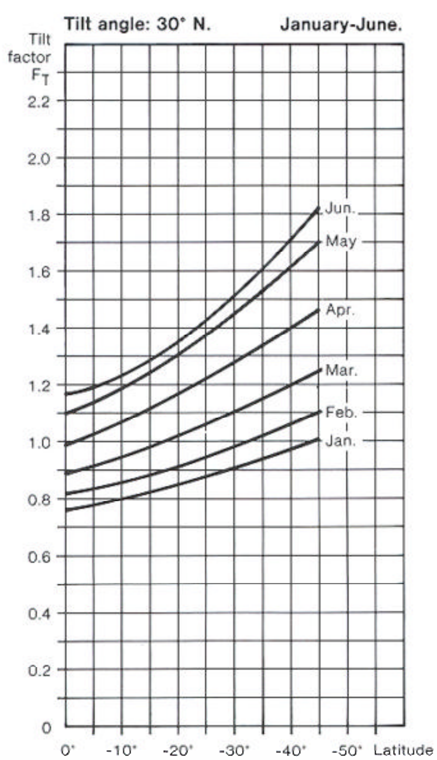


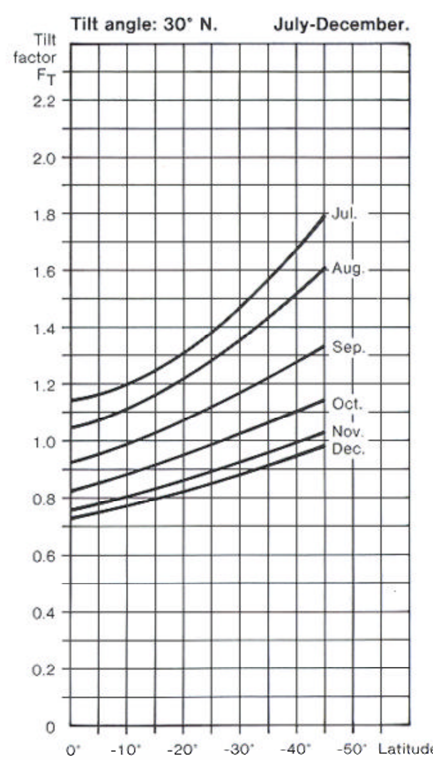


SOUTHERN HEMISPHERE









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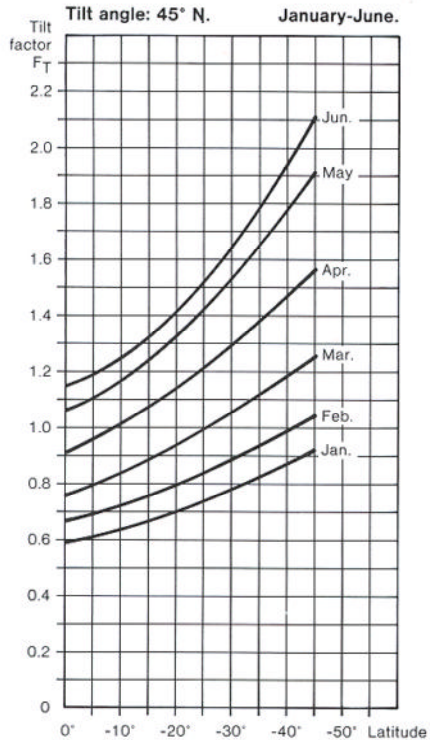

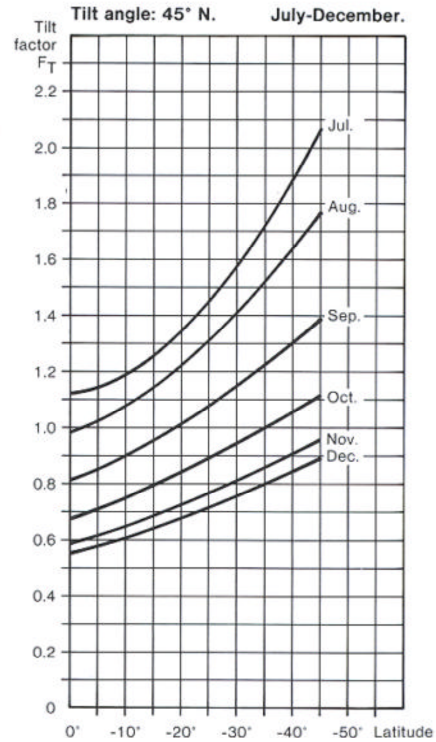

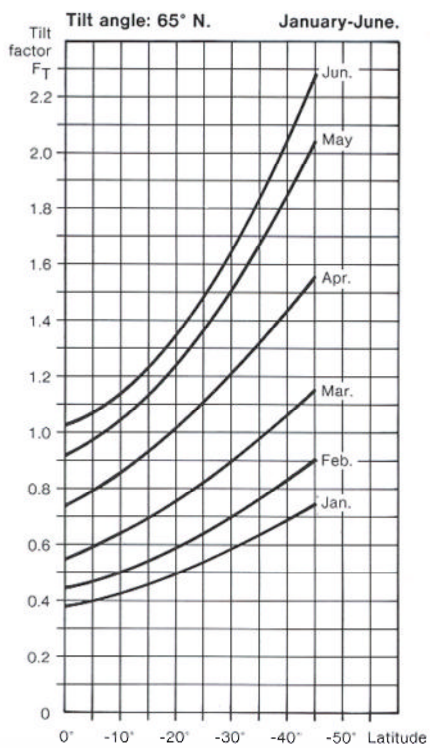

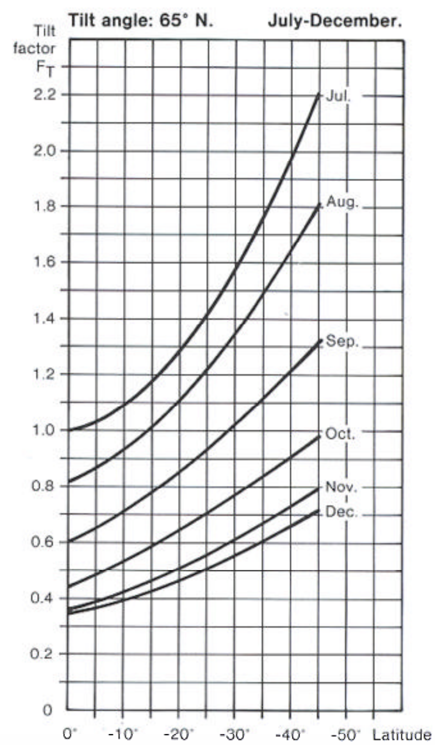

Appendix C: Daily Photovoltaic Pump Monitoring Format

Date__________________

Recorded by__________________________

Location__________________________ District__________________________ Region________________

Latitude__________________________ Longitude_______________________ Elevation____________(m)

Pump type_________________________ Pump discharge___________(m^3/d) Motor type____________________

Nominal motor power_____________(W) PV array type____________________ PV cell type___________________

PV array peak watt_____________(kWp) No. of panels_________(s)______(p) Inverter made by_______________

Inverter type___________________ Inverter power capacity_________(kW) Total well depth______________(m)

Pump setting___________________(m) Static water level______________(m) Dynamic water level__________(m)

Reservoir distance from pump____________(m) Reservoir height_________(m) Reservoir capacity___________(m^3)

Hours of the day (*h*)	Pyrano-meter reading (mV_{DC})	PV (shunt) reading (mV_{DC})	Inverter (shunt) reading (mV_{AC})	Actual PV voltage (VDC)	Actual inverter voltage (VAC)	Air temp (ºC)	Cell temp (ºC)	Water reading (m^3)	Solar radiation (W/m^2)	Actual PV current (*A*)	Actual inverter current (*A*)
7.00											
7.30											
8.00											
8.30											
9.00											
9.30											
10.00											
10.30											
11.00											
11.30											
12.00											
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13.30											
14.00											
14.30											
15.00											
15.30											
16.00											
16.30											
17.00											
17.30											
18.00											
18.30											

Appendix D: Simplified Daily Photovoltaic Pump Recording Format

Recorded by: __________________ Month: ________

Location: _____________________ District: _______ Region: _______________

Latitude: ______________ Longitude: ____________ Elevation: ___________m

Pump type: ____________ Motor type: ____________ PV cell type: ___________

PV array peak watt: ___________kWp No. of panels: _______S by _____ p

Inverter type: _______________ Made by: ______________ Pump setting: ___________m

Dynamic water level: _____________m Reservoir distance from pump: _______m

Height from ground: ______________m Capacity: ____________m^3

Well yield: __________ l/s Total well depth: ___________m Total pumping head: _________m

Days	Pyranometer readings (W/m^2)	Static head (m)	Volume of water pumped (m^3)	Remarks	Initials of recorder
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
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25					
26					
27					
28					
29					
30					
31					

Appendix E: Case Study: Economic Evaluation of Water Pumping Systems

In this case study, 10 PV water pumping stations, 6 diesel/gasoline pumps, and several windmills and wind turbines are used to evaluate the economics of various water pumping options. Eight of the PV pumping systems and four of the diesel systems are located in Ethiopia. One of the PV pumps is used for irrigation purposes; this system has a 600-Wp capacity DC motor and a floating pump. The other seven PV systems are for community water supplies and livestock watering; each of these systems has a 1.6-kWp capacity PV array, coupled with an AC submersible Grundfos motor/pump. The seven PV pumping systems and the four diesel-driven mechanical pumps are used to supply from 2,000–4,000 people and have fairly large water distribution systems. The other two PV systems are located in Mexico and have 848- and 800-Wp capacity arrays coupled with Grundfos SP3A-10 and Solarjack types of pumps, respectively. These pumping systems use DC motors. The systems are used for livestock watering and irrigation purposes and have no water distribution networks. The four diesel pumps are Model TS2 Lister diesel engines with a capacity of 11.2 kW each, coupled with Mono-lift pumps. The capacity of each pump is 10.8 m^3/h at a manometeric head of 100 m. The other two systems located in Mexico are a 15-kW diesel genset and a 6-kW gasoline pump.

The wind machines are located at the USDA Agricultural Research Service in Bushland, Texas. The types of wind machines used for the evaluation are the Bergey-1500 wind turbine, and the Aermotor, Dempster, and Dutch-Delta windmills. These wind machines are mainly used for livestock watering. The hub height of the Bergey-1500 type of wind turbine is 18 m (60 ft). The hub height for the Aermotor windmill is 10 m (33 ft). The rotor diameters of the Aermotor, Dempster, and Dutch-Delta windmills are 2.44 m (8 ft), 2.44 m (8 ft), and 4.88 m (16 ft), respectively, with a maximum strokes of 32, 32, and 38 strokes/min, respectively. The stroke lengths of the Aermotor, Dempster, and Dutch-Delta are 190, 180, and 165 mm, respectively. The number of steel blades for the Aermotor, Dempster, and Dutch-Delta windmills are 18, 15, and 32, respectively. The Dutch Delta has delta wing-shaped blades, but the Aermotor and Dempster blades are curved, inverse-tapered, wing-shaped blades.

The seven PV pumps supplying community water in Ethiopia were installed from late 1993 to early 1994. The PV irrigation pump was installed in 1990. The two PV pumps installed in Mexico were operational in 1997 and 1998, respectively. The wind turbines in Bushland, Texas, have been monitored for five years since 1992. Similarly, the USDA Agricultural Research Service also extensively monitored the windmills for long periods. The cost information of these systems used for economic evaluations are projected into 1998 prices and evaluated for a 20-year economic life from the beginning of 1998.

Life-cycle cost and sensitivity analyses of these technologies were made and the results are presented below. The graphs are made based on 1998 prices and analyze 20 years of economic life. The economic life of the PV modules, wind turbines, the windmill, and the tower are taken as 20 years, and the economic life for the windmill pumps and the cylinder is 5 years. Similarly, the economic lives of the motor–pump subsystem and the leading-edge tape of the blades for the Bergey-1500 type of wind turbine are assumed to be five years. The economic life of the furling cable for Bergey-1500 is assumed to be 10 years. The diesel generator installed in Mexico is assumed to have a 10-year economic life and all the rest of the diesel/gasoline engines and the pumps are assumed at five years' economic life. The motor–pump subsystem for the PV pumps is assumed at 10 years. The real discount rate for wind pumps installed in Bushland, Texas, is 4.1%, and for pumping systems installed in Ethiopia and Mexico is assumed at 7%.

The cost information for the PV pumps installed in Ethiopia is actual field data found from the archives of donors, contractors, owners, and end users. The wind machines' cost information was obtained from the USDA Agricultural Research Service. The cost information of the PV and diesel/gasoline pumping systems installed in Mexico was obtained from New Mexico State University. The operation and maintenance costs of the two PV pumps installed in Mexico is assumed to be 1% of the initial capital cost, and the diesel generator/gasoline pumps are based on a flat rate of $200/year.

Labor cost [basically operator(s) salaries] varies from place-to-place, depending on the type and size of the pumping system. Diesel pump operators are usually paid more than PV pump operators because diesels require more skilled labor. Real fuel prices are used in the evaluation. The cost of fuel for diesel pumps installed in Ethiopia is $0.35/l (US), based on the 1998 price. The cost of fuel varies from place to place depending on transportation costs. The oil and lubrication costs for the four diesel-driven mechanical pumps are $2.42/l (US). The fuel, oil, and lubrication consumption is based on the manufacturer's guide. The cost of fuel for the diesel genset and gasoline pumps installed in Mexico are $0.51/l (US) and $0.47/l (US), respectively. There is no subsidy for any of the systems used in this evaluation. Taxes are also not included in the evaluation. The economic evaluation of the diesel engines stationed in Ethiopia is based on seven-hour-a-day operation, and the economic life is estimated based on the recommended operating hours of the manufacturer.

Based on field investigations, the operation and maintenance costs of PV pumps depend on whether or not the system has a distribution network. PV arrays typically represent 30–40% of the total investment costs. The next largest cost is well drilling, at about 20% of the total. The third largest cost is the motor–pump subsystem. Equipment and material take 60–70% of the total investment costs, and construction and installation

Table E-1. Percentage of PV Pumping System Components Compared to the Total Investment Costs of the System for AC PV Pumping Systems.

No	PV pumps by cost type	With water distribution (%)	Without water distribution (%)
A	INVESTMENT COST		
1	Equipment and material costs		
1.1	PV array	33.0	36.8
1.2	Motor-pump subsystem (including inverter, support structure and accessories)	16.2	18.1
1.3	Pipes and fittings	13.5	12.5
	Subtotal	**62.7**	**67.4**
2	Construction and installation		
2.1	Well drilling	21.7	20.7
2.2	Plumbing work	6.6	2.9
2.3	Reservoir plus installation	6.7	7.7
2.4	Transportation and loading and unloading costs on site (10% of civil work)	2.3	1.3
	Subtotal	**37.3**	**32.6**
	Total investment cost	**100**	**100**
B	ANNUAL RECURRENT COST		
1	Operation	1.4	0.5
2	Maintenance cost, @$15/month	0.3	0.2
	Subtotal	**1.7**	**0.7**
C	REPLACEMENT COST (motor-pump set, inverter and others)	**7.8**	**8.7**

share 30–40%, depending on whether or not the system has a distribution system. The cost of operation and maintenance for PV systems without a distribution network is nearly 1% of the total investment cost; with a distribution network, about 2%.

Replacement costs depend on the type of motor–pump subsystem. AC systems tend to be more expensive than DC systems because AC PV pumps require an inverter and a special control system. Table E-1 shows the percentage of PV pumping systems' components against the total investment cost of the system. This table, prepared for PV pumps with AC motors, uses actual field data from several PV pumping systems. Table E-2 shows the percentage of diesel-driven mechanical pump components versus the total investment costs of the system. This table was prepared using actual field data from the four diesel pumping stations in Ethiopia.

Table E-2. Percentage of Diesel-Driven Mechanical Pumping System Components Versus the Total Investment Costs of the System, Based on Four Pumping Stations in Ethiopia.

No	Diesel pumps cost by type/site name	Station 1 (%)	Station 2 (%)	Station 3 (%)	Station 4 (%)	Average (%)
A	INVESTMENT COSTS					
1	Equipment and material costs					
1.1	Pipes and fittings	19.9	12.6	19.2	12.0	15.9
1.2	Complete TS2 type diesel engine with P631 type Mono pump and drive head	26.1	30.3	25.2	31.7	28.3
1.3	FOB charge and packing	2.9	3.3	2.9	3.6	3.2
1.4	Accessories	3.6	4.1	3.5	4.4	3.9
	Sub total	**52.5**	**50.4**	**50.7**	**51.7**	**51.3**
2	Construction and installation					
2.1	Foundation work (10% of 1.2)	2.6	3.0	2.5	3.2	2.8
2.2	Well drilling	23.4	31.5	29.5	28.3	28.2
2.3	Plumbing work	8.5	5.4	6.9	10.3	7.8
2.4	Reservoir plus installation	9.6	7.7	7.3	4.8	7.3
3	Transportation costs on site	3.4	2.0	3.0	1.8	2.6
	Sub total	**47.5**	**49.6**	**49.3**	**48.3**	**48.7**
	Total investment costs	**100**	**100**	**100**	**100**	**100**
B	ANNUAL RECURRENT COSTS					
1	Operation	3.1	3.6	2.7	7.1	4.1
2	maintenance cost, @36 man-year	6.8	7.4	6.2	9.2	7.4
3	Fuel, oil and lubrication: (fuel @23 l/d, oil @0,59 l/d, lubrication @0,05 l/d)	7.9	8.9	7.7	7.5	8.0
4	Spare-parts for one year	5.6	5.8	5.4	6.2	5.7
	Subtotal	**23.4**	**25.7**	**22.0**	**30.0**	**25.3**
C	REPLACEMENT COSTS (Diesel engine, pump and accessories)	**29.7**	**34.4**	**28.7**	**36.1**	**32.2**

As indicated in Tables E-1 and E-2, the equipment and materials cost is about 65% for PV pumps, while diesel pumps cost a little over 50%. On the other hand, the construction and installation cost for diesel systems is quite high compared to PV systems. The operation and maintenance costs of diesels are also high, about 25% of the total investment costs. This demonstrates that the cost of keeping diesel pumps running is too high, and in the long run, that PV systems can offset investment costs that are higher than for diesels. The other noticeable percentage is the replacement cost for diesel pumps. As will be discussed in greater detail, these costs make PV pumps even more attractive. Figure E-1 provides an economic comparison of the Aermotor, Dempster, and Dutch-Delta windmills, and the Bergey-1500 electrical wind turbine, which are all located at the USDA-Agricultural Research Service in Bushland, Texas, and aıE-5 exposed to the same environment.

The economic comparison shows that Aermotor and Dutch-Delta windmills, using the 70-mm inside diameter pump, perform at a lower unit water cost at a well depth of about 45 m. The Aermotor windmill with a 48-mm inside diameter pump, and the Dempster windmill with a 70-mm inside diameter pump, perform as well as the Bergey-1500 wind pump at about 45 m pumping head (see Figure E-1). Different results; however, occur when the wind regime changes. At higher wind-speed locations, the Bergey-1500 wind turbine performs better than the windmills. This can be seen from a sensitivity analysis of these wind pumps at various wind speeds, as shown in Figures E-2 and E-3. Figure E-2 uses average wind speed and flow rate data, based on Weibull distribution (k = 2). Figure E-3 is based on the specific wind speed and flow rate data without using Weibull distribution. These two figures show that mechanical wind pumps can attain optimum performance at lower wind speeds than electrical wind turbines.

From Figure E-2, the optimum wind speed (the lowest unit water cost) occurs at 8 m/s for windmills and at 13 m/s for the Bergey-1500 electrical wind turbine. The optimum wind speeds in Figures E-2 and E-3 are the same for both mechanical wind pumps and electrical wind turbines. However, the unit water cost curves in Figure E-2 (using Weibull distribution) are shifting up while the curves in Figure E-3 (without using Weibull distribution) are shifting down. This shows that an evaluation of mechanical and electrical wind pumps, with specific wind speed data (without using wind distribution), can mislead users because wind speeds can fluctuate highly over the day, season, and year. In general, both figures confirm that electrical wind turbines require higher wind speeds than mechanical wind machines, as the cut-in wind speed for the Bergey-1500 electrical wind turbine is higher (at 5–6 m/s) than the mechanical wind pumps

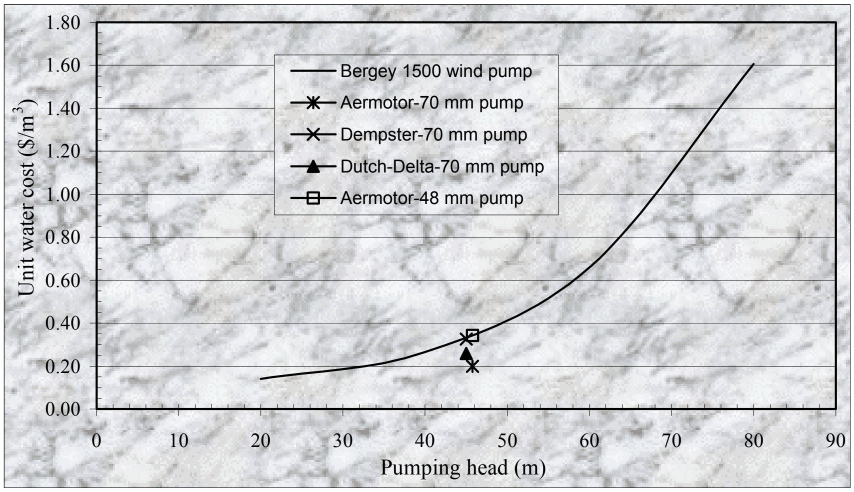


Figure E-1. Unit water cost versus total pumping head for various kinds of wind machines at an average wind speed of 5.65 m/s, installed at the USDA-Agricultural Research Service in Bushland, Texas.

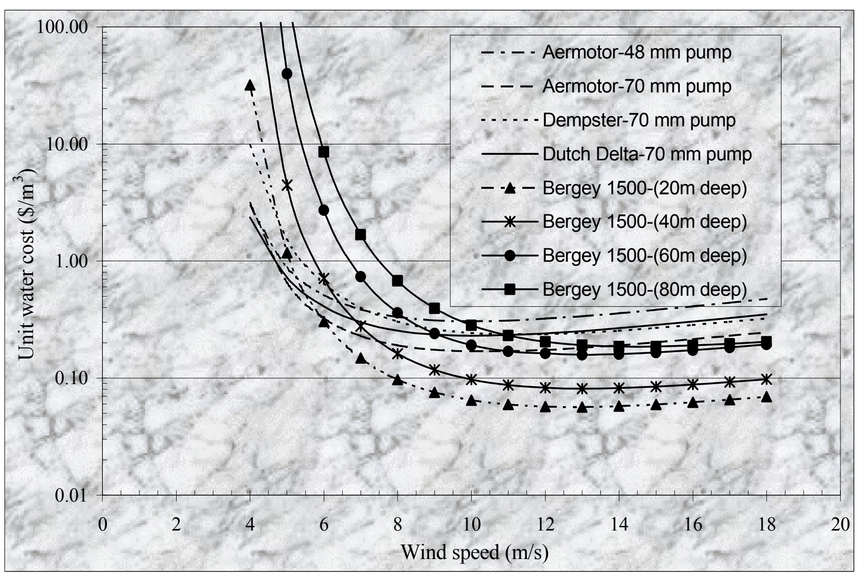


Figure E-2. Sensitivity analysis of mechanical and electrical wind pumps based on average flow rate and wind speed data using Weibull distribution (at K=2).

(at 3.5 m/s).

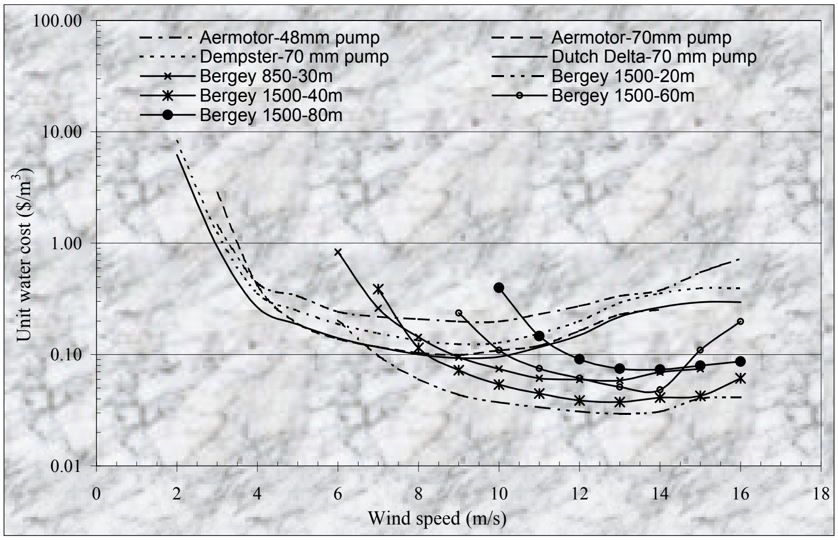
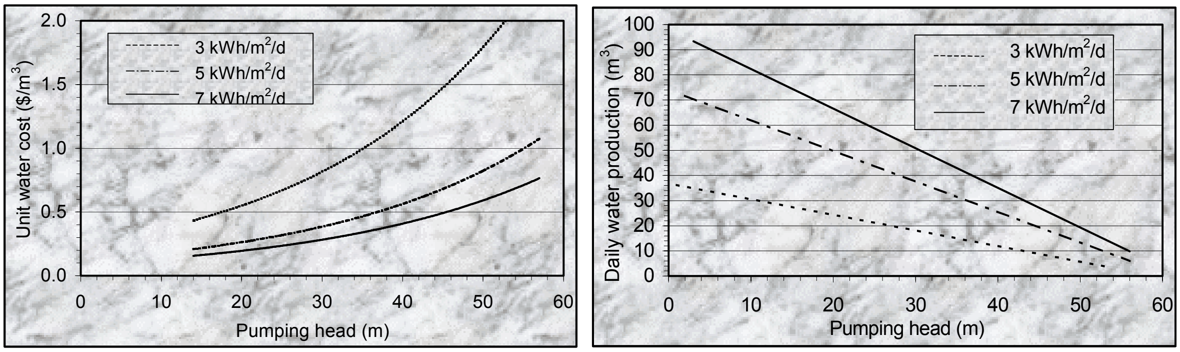


Figure E-3. Sensitivity analysis of mechanical and electrical wind pumps based on specific flow rate and wind speed data.

The approximate unit water cost of the Bergey-1500, installed at 20 m well depth and with an average wind speed of 5.65 m/s (based on five years' operational data between 1992 and 1997) is $0.14/m^3. If installed at the optimum wind speed location (13 m/s), the unit water cost of this wind pump could be $0.06/m^3. This shows that the system is not fully utilized at its optimum capacity. On the other hand, a location with an average wind speed of 13 m/s is not readily available in many parts of the world. Therefore, it might be interesting (and challenging) for wind turbine manufacturers to lower the optimum wind speed, while keeping the performance of the system at its optimum level.

Figures E-2 and E-3 show the unit water costs of the Bergey-1500 (at different pumping heads) tend to be lower, while the mechanical wind pumps tend to be higher at higher wind speeds. This shows that electrical wind turbines perform better (have lower unit water costs) at higher wind speeds, than mechanical wind pumps. On the other hand, windmills are better options for water pumping at low wind speeds than electrical wind turbines. Therefore, it is erroneous to generalize that electrical wind pumps are cheaper or better than windmills. Such a conclusion should be made based on the average wind speed of the location where the system operates, as it is apparent that the unit water costs of systems depends closely on the availability of wind. Therefore, it is important to identify the wind regime of the location before selecting the type of wind machine for a water pumping application. Figure E-2 shows that windmills are cheaper up to about 6 m/s wind speed, and the Bergey-1500 begins to become cheaper above 6 m/s.

A sensitivity analysis of AC PV pumping systems (1.6-kWp PV arrays) were made at various pumping head and solar radiation energies (3, 5, and 7 kWh/m^2/d), and the results are presented in Figures E-4 and E-5. The figures show that a slight change of solar radiation energy, which is the main source of energy for PV pumps, changes the unit cost and the amount of water production.



a) Unit cost versus pumping head.

b) Daily water production versus pumping head.

Figure E-4. Unit cost of water and daily water production for PV pumps at 3, 5, and 7 kWh/m²/d.

From this sensitivity analysis, the hydraulic equivalent load limits are related to the availability of solar radiation energy. The hydraulic equivalent load limit for annual average solar radiation energy of 3 kWh/m²/d is up to 500 m⁴/d, for 5 kWh/m²/d is up to 1,000 m⁴/d, and for 7 kWh/m²/d is up to 1,400 m⁴/d (see Figure E-5).

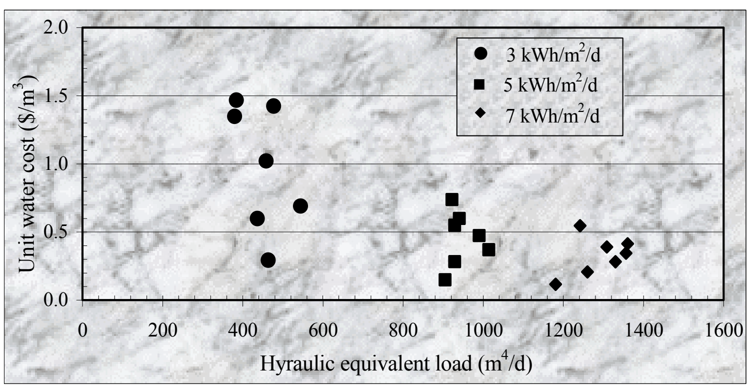


Figure E-5. Hydraulic equivalent load limits of PV pumps at annual average solar radiation energy of 3, 5, and 7 kWh/m²/d.

Results of an economic comparison of the Bergey-1500 wind pumps, AC and DC PV pumps, diesel-driven mechanical pumps, a diesel generator pump, and a gasoline pump are presented in Figures E-6, E-7, and E-8. The comparison shows that small DC PV pumps are the lowest-cost option for small applications. Such systems are ideal for hydraulic equivalent loads up to about 600 m⁴/d, as shown in Figure E-7. The Bergey-1500 wind pump is the second-lowest-cost pumping option. It is competitive with diesel-driven mechanical pumps up to about 60 m total pumping head, based on five years' wind regime data (1992–1997) from Bushland, Texas. The Bergey-1500 wind pump installed in Bushland is also competitive with the DC PV pumps, up to about 25 m total pumping head.

The diesel generator unit water cost is high and should not be used as a representative value. This is because the system is probably underutilized. New Mexico State University provided the data and the author has no control of the information. This is included simply to show readers how such errors can alter results. This diesel genset was in use and was substituted by the 848-Wp PV pump; hence, the same daily water production is used in the evaluation. All the cost information is assumed to be correct; however, and the pump's daily operational hours might be underestimated. Consequently, the economic life of the diesel generator pump should be longer than the values used in this evaluation.

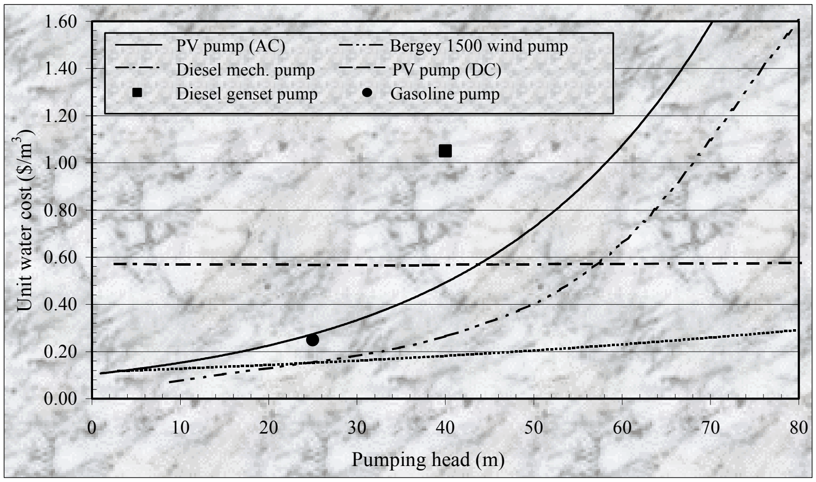


Figure E-6. Economic comparisons of wind, PV, and diesel/gasoline pumping systems. The evaluation is based on the average wind speed of 5.65 m/s for the Bergey-1500 wind pump, and the fuel cost of $0.35/l for the diesel-driven mechanical pumps (located in Ethiopia), $0.51/l and $0.47/l for diesel genset and gasoline pumps (located in Mexico), respectively. The average annual solar radiation used for this evaluation in Ethiopia is about 5.5 kWh/m^2/d and in Mexico is 5.8 kWh/m^2/d.

Gasoline driven mechanical pumps are usually less expensive than diesel-driven mechanical pumps for smaller applications, such as for small community water supplies or small irrigation projects. Diesel-driven mechanical pumps are normally competitive for higher water demands and deeper wells. AC PV pumps are currently ideal for medium water demands (up to a maximum hydraulic equivalent load of about 1,500 m^4/d) and medium pumping heads (up to about 45–50 m) in locations where wind regime is low (see Figures E-5 and E-7). Note that the hydraulic equivalent load generally depends on the capacity of the system; the higher the capacity, the higher the hydraulic equivalent load. In case of PV pumps, the hydraulic equivalent load depends mainly on the solar radiation energy as well as the size of the PV array and the subsystem. However, in the case of wind pumps, the competitive hydraulic equivalent load mainly depends on the average wind speed, the size of the turbine, and the subsystem. For a given size, the hydraulic equivalent load increases with the wind speed (until the wind machine furls), as is shown in Figure E-8. The maximum hydraulic equivalent load of the Aermotor (with 48-mm and 70-mm pump inside diameter) and Dutch-Delta wind pumps occur at about 500, 750, and 900 m^4/d, and for the Dempster occurs at hydraulic equivalent load of 700 m^4/d. The maximum hydraulic equivalent load for the

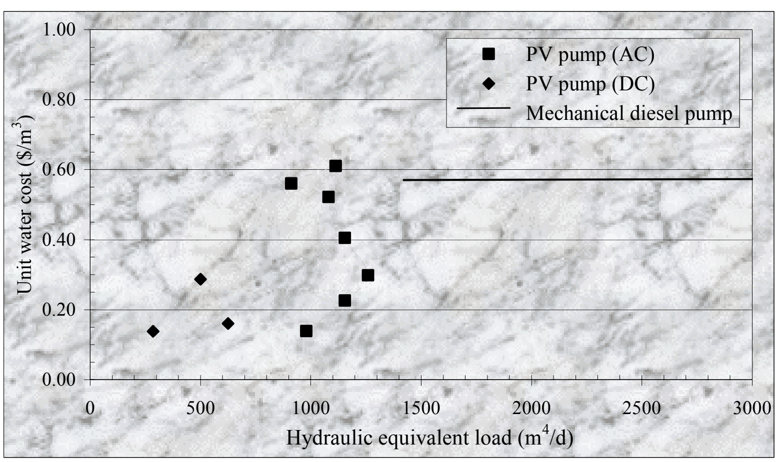


Figure E-7. Hydraulic equivalent load limits of PV pumps (DC and AC systems) and diesel-driven mechanical pumps (mono). The evaluation is based on the fuel cost of $0.35/l for the diesel-driven mechanical pumps (located in Ethiopia), $0.51/l and $0.47/l for diesel genset and gasoline pumps (located in Mexico), respectively. The average annual solar radiation used for this evaluation in Ethiopia is about 5.5 kWh/m^2/d and in Mexico is 5.8 kWh/m^2/d.

Bergey-1500 wind pump is up to 2100 m^4/d, depending of the size of pumps used.

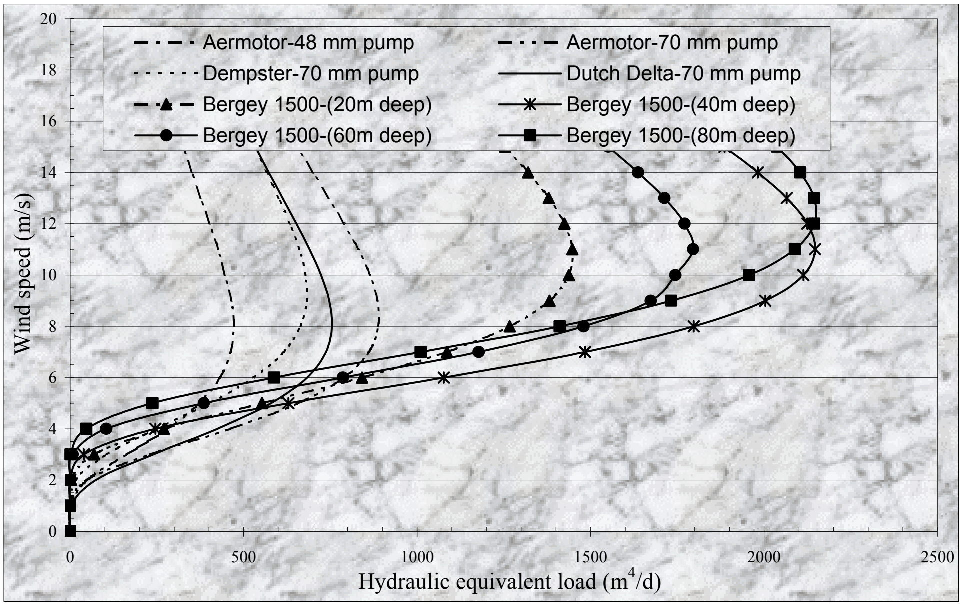


Figure E-8. Hydraulic equivalent load of electrical and mechanical wind pumps at various average wind speeds using Weibull distribution (at k=2).

Appendix F: Case Study: External Impacts Evaluation of Water Pumping Systems in Ethiopia

Sample data collection approaches used for external impact evaluation

A field survey was conducted to evaluate the external impacts of eight PV pumping stations and other wind, hand, and diesel pumping stations in Ethiopia. The sample survey was intended to cover all interest groups, and included sample interviews with end users, institutions in charge of construction and maintenance, nongovernmental organizations (NGOs), operators, and community leaders (water committees, farmers' associations, etc.). The survey, shown in appendix G, was made based on the environmental, social-economical, and institutional aspects of these pumping options. Detailed evaluations of the beneficial and adverse impacts of these pumping systems were determined from the surveys and the evaluation results are presented below.

This survey was made to get a clear picture of different interest groups' preferences, and to assess the socio-cultural acceptability, technical reliability, and institutional set-up requirements of the wind, PV, hand, and diesel water pumping systems. Lister-Peter diesel pumps and locally made wind and hand pumps were used in the evaluation. Seven of the PV pumps use Kyocera-made multicrystalline modules (32 modules) with 1.6-kWp capacity and Grundfos-made SA1500 type inverters coupled with various kinds of Grundfos pumps. There is also one DC PV irrigation pump with a capacity of 600 Wp, made by Kyocera (12 modules) coupled with a KSB type of floating pump. The sample survey was made using 20 randomly selected villagers, 10 water committee members, 12 operators, 15 professional government and NGO employees, and 5 qualified pump technicians. Their responses were recorded using the three questionnaires in appendix G. Then their responses were analyzed and sorted into two groups, the beneficial and adverse impacts, and collected on the fourth page of appendix G. Next, copies of that page were given to 15 professional experts to evaluate the impacts. Ten responses were received back. Based on the responses, the pumping options were evaluated according to their importance, and scores were given to each pumping technology. An external impacts evaluation of these pumping options was made based on the cost-benefit analysis (CBA) and risk analysis (RA) methods mentioned in chapter 8.

An external impact evaluation using a cost-benefit analysis

The beneficial and adverse impacts of the systems described above were listed separately and graded based on the weighted values of the individual impacts of each water pumping technology. Then, the scores of the beneficial and adverse impacts were added up separately. Finally, a grand index for each pumping system was calculated by subtracting the sum of all adverse impacts from the sum of all beneficial impacts. The grand index with the highest positive value indicates the best choice option.

The opinions of various interest groups are listed in terms of beneficial and adverse impacts for these pumping options, according to the format shown in Table 8.2. These opinions were summarized and sorted out, then weighted and scored. The value weights are from 1 to 15, and scores are from 0 to 5. The higher the number the impact scored, the higher the importance of that impact. The value weights and scores of both beneficial and adverse impacts of the four pumping systems are shown in Tables F-1 and F-2, respectively.

Table F-1. Value weights and scores for the beneficial impacts of the four pumping systems.

No.	Beneficial impacts (Criteria)	Value weights (1-15)	Scores (0-5) PV Pumps	Diesel Pumps	Wind Pumps	Hand Pumps
1	Equipment reliability	15	5	4	3	1
2	Fuel reliability	15	5	1	5	5
3	Spare-parts availability	15	2	2	3	3
4	Weather change flexibility	15	1	5	1	4
5	Operational safety	15	4	3	3	4
6	Ground water reliability	14	4	4	4	3
7	Easy maintainability	14	4	2	2	5
8	Installation convenience	14	4	2	1	5
9	Local maintenance personnel availability	13	1	1	1	4
10	Impact on community development	13	5	5	5	3
11	System expansion possibility	13	5	1	1	4
12	Social acceptability of using the system	12	4	4	4	3
13	Affordability (water charge based on service)	12	4	3	4	5
14	Time saving because of using the system	12	4	5	4	2
15	Service quality in fetching water (human labor involvement)	10	5	5	5	1
16	Changes in the quality of life of individuals	10	4	4	4	2
17	Operational simplicity by age-groups and gender	10	5	1	4	1
18	Possibility of using the system for other purposes (such as irrigation, cattle watering, electricity, etc.)	9	5	4	4	1
19	Impact on environmental protection	8	5	2	4	3
20	System familiarity	6	2	4	3	4
21	Wild-life protection	6	5	4	1	5
	Total	251	83	66	66	68

The beneficial and adverse impacts are graded based on the relative value weights of the individual impacts and the relative scores given for each pumping system. The value weight (0 to 15) shows the maximum possible points that each impact can score relative to the rest of the impacts. Scores from 0 to 5 are given according to the relative importance of each pumping system to the rest of the systems. The scores are then multiplied by the corresponding value weights of each impact and added separately for each pumping system in both beneficial and adverse impacts. A higher score indicates less risk in the case of beneficial impacts. Similarly, a higher score indicates a higher risk in the case of adverse impacts.

For example, the score given to diesel pumps for fuel reliability is 1 in the case of beneficial impacts in Table F-1. This score is given because fuel supply for remote Ethiopian villages is poor. Even if the diesel system is not broken, the unavailability of fuel was a basic factor for the scorers. At one time, the community was without water for weeks, thus the villagers' score was very low. On the other hand, the remaining pumping options do not need fuel and can score full points. Similarly, PV and wind pumps are more dependent on weather changes and, therefore, receive minimum scores. The effect of weather is insignificant for diesels because the borehole is relatively deep and recharge will be relatively fast. For hand pumps, the well is typically shallow and recharging the borehole can take more time in the dry season than in the rainy season, depending on the aquifer type and the location. Scores are given for the remaining impacts based on the extent of impacts on each pumping option and based on the evaluation of various interested groups.

Table F-2. Value Weights and Scores for the Adverse Impacts (risks) of the Four Pumping Systems.

No.	Adverse impacts (risks)	Value weight (1-15)	Scores (0-5)			
			PV Pumps	Diesel Pumps	Wind Pumps	Hand Pumps
1	Exposition to possible accident during installation and operation	15	2	3	4	1
2	System failure due to weather dependency	15	5	1	5	2
3	System failure due to fuel supply shortage	15	0	4	0	0
4	System failure due to spare-parts shortage	15	2	3	3	4
5	System unreliability	15	1	2	3	4
6	Site accessibility problem in construction and Maintenance of the system, fuel transport, etc.	14	1	5	5	1
7	Installation inconvenience	14	2	4	4	1
8	Long delays in repair in case of breakdowns	13	3	4	3	2
9	Local maintenance skills requirement	13	2	3	3	5
10	Difficulty in maintaining the system	12	2	3	4	1
11	Skills requirement for operating the system	12	1	4	2	0
12	Inconvenience of system expansion	11	1	5	5	1
13	Inconvenience of equipment replacement in case of breakdowns	10	2	4	5	1
14	Water pollution possibility	9	1	3	1	4
15	Users credibility to the system	9	3	3	3	4
16	System capacity limitations	8	2	1	2	4
17	Operational inconvenience by different age-groups and gender	8	1	4	2	4
18	Non-versatility (not adapted to other use, such as electricity, irrigation, etc. purpose)	7	0	2	2	4
19	Time spend in fetching water	7	1	1	1	4
20	Unwillingness to pay for water	6	2	2	2	1
21	Land use	5	4	3	3	2
22	Unfamiliarity of system	5	3	2	2	1
23	Possibility of system abandoning due to the community's inability to pay for water	5	1	2	1	0
24	Upland game birds	4	0	1	4	0
	Total	247	42	69	69	51

Once the value weights are assigned to all impacts and the scores given for each pumping system separately, the maximum scores for each impact and pumping system are determined from the products of the scores and the corresponding value weights of each impact for each pumping system. Finally, the total maximum scores for each pumping option are computed by adding up the maximum scores of each impact for each pumping system. The results for the beneficial and adverse impacts are shown in Tables F-3 and F-4, respectively.

The grand index for each of the four pumping systems is calculated from the corresponding total scores of the beneficial impacts minus the corresponding total scores of the adverse impacts. The results are shown in Table F-5.

Table F-3. Maximum Possible Value Weights of the Impacts and Maximum Scores Given to Each Dumping Option for Beneficial Impacts Evaluation of the Four Pumping Systems.

No.	Beneficial impacts (Criteria)	Maximum value weight (15*5)	Maximum scores for PV Pumps	Diesel Pumps	Wind Pumps	Hand Pumps
1	Equipment reliability	75	75	60	45	15
2	Fuel reliability	75	75	15	75	75
3	Spare-parts availability	75	30	30	45	45
4	Weather change flexibility	75	15	75	15	60
5	Operational safety	75	60	45	45	60
6	Ground water reliability	70	56	56	56	42
7	Easy maintainability	70	56	28	28	70
8	Installation convenience	70	56	28	14	70
9	Local maintenance personnel availability	65	13	13	13	52
10	Impact on community development	65	65	65	65	39
11	System expansion possibility	65	65	13	13	52
12	Social acceptability of using the system	60	48	48	48	36
13	Affordability (water charge based on service)	60	48	36	48	60
14	Time saving because of using the system	60	48	60	48	24
15	Service quality in fetching water (human labor involvement)	50	50	50	50	10
16	Changes in the quality of life of individuals	50	40	40	40	20
17	Operational simplicity by age-groups and gender	50	50	10	40	10
18	Possibility of using the system for other purposes (such as irrigation, cattle watering, electricity, etc.)	45	45	36	36	9
19	Impact on environmental protection	40	40	16	32	24
20	System familiarity	30	12	24	18	24
21	Wild-life protection	30	30	24	6	30
	Total	1255	977	772	780	827

According to the Ethiopian conditions, the result shows that PV pumps are highly beneficial and their use in the community water supply is preferred over the other three pumping options. Based on this evaluation, hand pumps could be a second option for shallow wells and small-community use. Locally made wind pumps can be another option for locations where the minimum monthly wind speed is greater than 3 m/s. Diesel pumps are ideal for high water demands and more accessible areas. Unreliable fuel supplies, and lack of local maintenance and spare parts in remote villages of Ethiopia may prevent the use of diesel pumps much of the year.

External impacts evaluation using risk analysis

The external impacts evaluation of the four water-pumping options can be tested using the RA method. The evaluation can be made mathematically by either devising a formula (equation) that can summarize all the impacts in a single score, or by using a grand index in which a simple criterion can be applied to accept or reject the proposal.

There are many ways of analyzing risks. The most common method is the expected utility, or the project alternative ranking order, method. The expected utility method shows the ranking order of different alternative water pumping options. In this method, the highest expected utility value is usually the best choice water pumping option for the desired application, and it is also considered the least risky pumping system.

Table F-4. Maximum Possible Value Weights of the Impacts and Maximum Scores Given to Each Pumping Option for adverse Impacts (risks) Evaluation of the Four Pumping Systems.

No.	Adverse impacts (risks)	Maximum value weight (15*5)	Maximum scores for PV Pumps	Diesel Pumps	Wind Pumps	Hand Pumps
1	Exposition to possible accident during installation and operation	75	30	45	60	15
2	System failure due to weather dependency	75	75	15	75	30
3	System failure due to fuel supply shortage	75	0	60	0	0
4	System failure due to spare-parts shortage	75	30	45	45	60
5	System unreliability	75	15	30	45	60
6	Site accessibility problem in construction and Maintenance of the system, fuel transport, etc.	70	14	70	70	14
7	Installation inconvenience	70	28	56	56	14
8	Long delays in repair in case of breakdowns	65	39	52	39	26
9	Local maintenance skills requirement	65	26	39	39	65
10	Difficulty in maintaining the system	60	24	36	48	12
11	Skills requirement for operating the system	60	12	48	24	0
12	Inconvenience of system expansion	55	11	55	55	11
13	Inconvenience of equipment replacement in case of breakdowns	50	20	40	50	10
14	Water pollution possibility	45	9	27	9	36
15	Users credibility to the system	45	27	27	27	36
16	System capacity limitations	40	16	8	16	32
17	Operational inconvenience by different age-groups and gender	40	8	32	16	32
18	Non-versatility (not adapted to other use, such as electricity, irrigation, etc. purpose)	35	0	14	14	28
19	Time spend in fetching water	35	7	7	7	28
20	Unwillingness to pay for water	30	12	12	12	6
21	Land use	25	20	15	15	10
22	Unfamiliarity of system	25	15	10	10	5
23	Possibility of system abandoning due to the community's inability to pay for water	25	5	10	5	0
24	Upland game birds	20	0	4	16	0
	Total	1235	443	757	753	530

The expected utilities of these pumping options are estimated using Equation 8.1. In this evaluation method, all the beneficial impacts are listed according to the relative importance of each impact, and each is assigned a percentage probability in such a way that the sum of the assigned probabilities for the whole impact is 100%. According to the usability of each pumping option, a utility value from 0 to 1 is given for each impact, as shown in Table F-6. Utility is measured on a scale of 0 to 1, where 1 is the highest utility and 0 is the lowest. For example, if political instability exists in the country, a critical fuel shortage may occur and diesel pumps cannot operate, thus the utility can be 0, even though the equipment is in good condition.

Table F-5. The Grand Index for Each of the Four Pumping Systems.

Total impacts	Total value weight	PV Pumps	Diesel Pumps	Wind Pumps	Hand Pumps
Beneficial	1255	977	772	780	827
Adverse	1235	443	757	753	530
Grand Index	20	534	15	27	297

Table F-6. Probabilities and Utility Values of the Beneficial Impacts for the Four Water Pumping Options Using the Risk Analysis Approach.

No.	Beneficial impacts	Probability (%)	Utility (0-1)			
			PV Pumps	Diesel Pumps	Wind Pumps	Hand Pumps
1	Equipment reliability	6.0	1.0	0.8	0.6	0.2
2	Fuel reliability	6.0	1.0	0.2	1.0	1.0
3	Spare-parts availability	6.0	0.4	0.4	0.6	0.6
4	Weather change flexibility	6.0	0.2	1.0	0.2	0.8
5	Operational safety	6.0	0.8	0.6	0.6	0.8
6	Ground water reliability	5.6	0.8	0.8	0.8	0.6
7	Easy maintainability	5.6	0.8	0.4	0.4	1.0
8	Installation convenience	5.6	0.8	0.4	0.2	1.0
9	Local maintenance personnel availability	5.2	0.2	0.2	0.2	0.8
10	Impact on community development	5.2	1.0	1.0	1.0	0.6
11	System expansion possibility	5.2	1.0	0.2	0.2	0.8
12	Social acceptability of using the system	4.8	0.8	0.8	0.8	0.6
13	Affordability (water charge based on service)	4.8	0.8	0.6	0.8	1.0
14	Time saving due to the use of the system	4.8	0.8	1.0	0.8	0.4
15	Service quality in fetching water (human labor involvement)	4.0	1.0	1.0	1.0	0.2
16	Changes in the quality of life of individuals	4.0	0.8	0.8	0.8	0.4
17	Operational simplicity by age-groups and gender	4.0	1.0	0.2	0.8	0.2
18	Possibility of using the system for other purposes (such as irrigation, cattle watering, electricity, etc.)	3.6	1.0	0.8	0.8	0.2
19	Impact on environmental protection	3.2	1.0	0.4	0.8	0.6
20	System familiarity	2.4	0.4	0.8	0.6	0.8
21	Wild-life protection	2.4	1.0	0.8	0.2	1.0
	Total	100 %	16.6	13.2	13.2	13.6

The probability assigned to each impact is then multiplied by the corresponding utility value of each pumping system to determine the expected utility value for each impact, as shown in Table F-7. Then the expected utility values of each impact, for each pumping option, are added to estimate the expected utility for each pumping system.

Similarly, the expected utility can also be estimated from adverse impacts of each pumping system. However, in this case, the best choice pumping system would be the smallest expected value, since this value indicates the less risky water pumping option.

Using RA, the external impact evaluation of the four water pumping options shows that PV pumps are less risky than the other systems. According to this evaluation, locally made hand pumps are the next less risky pumping option, followed by diesel pumps and locally made wind pumps.

An external impact evaluation of the four water pumping options using both CBA and RA concludes that PV pumps should remain as the first option, followed by the locally-made hand and wind pumps, and diesel pumps. The final decision; however, is made based on the technical, economical, and the external impacts among alternative systems. From the economic evaluation in appendix E, AC PV pumps presently are competitive for medium-sized communities (up to a maximum hydraulic equivalent load of about 1,500 m^4/d) and for a total pumping head up to 50 m. DC PV pumps are recommended for small water demands up to about 600 m^4/d. Diesel-driven mechanical (mono) pumps are competitive for higher water demands, above 1,500 m^4/d. Wind pumps are the least- expensive option for windy locations. Hand pumps (as determined from earlier work by the author) are competitive for individual and small-sized community use (in the range of 130–260 m^4/d) and for shallow wells. Therefore, based on these combined analyses, PV pumps are recommended as the best option for medium-sized communities. Hand pumps are recommended for individual use and small-sized communities, and diesel pumps are the best choice for large communities. Recommendations for using wind pumps depends on the availability of wind in the area.

Table F-7. The Expected Utility Values of the Four Water Pumping Options.

No.	Beneficial impacts (Criteria)	Expected utility value for each impact			
		PV Pumps	Diesel Pumps	Wind Pumps	Hand Pumps
1	Equipment reliability	6.2	5.0	3.7	1.2
2	Fuel reliability	6.2	1.2	6.2	6.2
3	Spare-parts availability	2.5	2.5	3.7	3.7
4	Weather change flexibility	1.2	6.2	1.2	5.0
5	Operational safety	5.0	3.7	3.7	5.0
6	Ground water reliability	4.6	4.6	4.6	3.5
7	Easy maintainability	4.6	2.3	2.3	5.8
8	Installation convenience	4.6	2.3	1.2	5.8
9	Local maintenance personnel availability	1.1	1.1	1.1	4.3
10	Impact on community development	5.4	5.4	5.4	3.2
11	System expansion possibility	5.4	1.1	1.1	4.3
12	Social acceptability of using the system	4.0	4.0	4.0	3.0
13	Affordability (water charge based on service)	4.0	3.0	4.0	5.0
14	Time saving due to the use of the system	4.0	5.0	4.0	2.0
15	Service quality in fetching water (human labor involvement)	4.1	4.1	4.1	0.8
16	Changes in the quality of life of individuals	3.3	3.3	3.3	1.7
17	Operational simplicity by age-groups and gender	4.1	0.8	3.3	0.8
18	Possibility of using the system for other purposes (such as irrigation, cattle watering, electricity, etc.)	3.7	3.0	3.0	0.7
19	Impact on environmental protection	3.3	1.3	2.7	2.0
20	System familiarity	1.0	2.0	1.5	2.0
21	Wild-life protection	2.5	2.0	0.5	2.5
	Expected utility	81.1	64.1	64.7	68.6

Appendix G: Sample Survey Formats Used for External Impacts Evaluation

QUESTIONNAIRE FOR WATER COMMITTEE LEADERS AND COMMUNITY PARTICIPATION PROMOTERS

Date_________________________

Recorded by__________________________
Location______________________ District________________ Region________________
Total population served_____________________ Total number of household____________________
Water pumping system type_________________ Other water source(s)________________________
Water system installed by___________________ Date of installation?_________________________
Administered by_____________________________________
How was the committee created?____
Who constructed the new system?_____________ What was your contribution?________________
What was the community involvement towards the new system?___________________________
Did you have money collected from the community for the construction of the system?_____________
If yes, how much?____________________________________
Do you have a ledger/notebook for recording expenses?_________________________________
If yes, are the notebook entries up to date?_______ Where do you keep the money (bank, treasurer)?____
For which purpose are you using the money (please check in front of the blank line)?
1) Operator salary_____________________ 2) Buying spare parts_______________
3) Paying repairperson_________________
4) Buying replacement pump____________________ 5) Savings________________________
Roughly how much you are saving every month?_________________________($)
How much is your monthly collection?_________________________________($)
Where do you use the savings?_____________ Do you have plans to have additional systems?_______
Who decides where the money will be used (e.g., government agent, water committee chairman, treasurer, committee members, or other)?____
Who pays the operator's salary and the operation and maintenance: the water committee or other?________
What is the role of the water and environment administration office with regard to the system?__________
____
Other institutions, if any____
What is your estimate of the average yearly income per household?___________________________($/yr.)
What is the mode of payment for water? ____
Is it based on a flat rate, meter reading, or according to family size?_________________How much does each household pays?___________($/month),______($/household), or_______________($/m^3)
Do you have an equity system where the poor pay less and the rich more?_____________
If yes, how much do the poor pay?_______________________ How about the rich? _______________
Is the water tariff affordable?_______________ If not, what would be affordable in your opinion?____
What are the most common diseases in this community?___________________________________
How has the health situation changed since the new system has been put in use?______________________
Remarks____
____
____
____

QUESTIONNAIRE FOR OPERATORS AND TECHNICIANS

Date________________________

Recorded by_________________________

Location_____________________ District_____________ Region________________

Total population served____________________ Total number of household___________________

Water pumping system type_________________ Other water source(s)________________________

Water system was installed by_______________ Date of installation__________________________

Administered by____________________________________

Who pays your salary?______________ Who pays for operation and maintenance?_______________

As a pump caretaker, what are your responsibilities (check if he/she does)?

1) Daily checking of the system____________________ 2) Water selling____________________

3) Cleaning of panels and sanitation measures_________ 4) Money collection_________________

5) Report to repair man in case of breakdown_________ 6) Purchasing of fuel________________

7) Purchasing of spare parts_______________________ 8) Other__________________________

Have you received any kind of training to become the caretaker?_________________________________

Did you receive any tools?_______ Can you show me (check the types he/she has)?________________

What means of communication do you use with the repairperson in case of breakdown?_______________

Who pays for this (transportation cost, telephone, etc.)?____

Do you think this is enough?____________ What is your proposal?______________________________

Are all the community members using the new water system?_______________

If not, what types or sources are they using?____

Why are they not using the new system?____

Which source of water (the new system or the traditional) is near to the village?______________________

Does the system provide sufficient water for all needs in all seasons?______________________________

If not, which month(s) has (have) a shortage of water?_______ Which is the best season?____________

Does the community use the new system for other than household purposes?_________________________

If so, for what purposes?____

How many times has the system failed to operate since it was installed?_______________

What was the reason?________________________ How long did it take to repair?________________

Who repaired it?_____________________________ Who paid for the repair?______________________

Is there a plan for system extension?____________ If so, who initiated it?________________________

Who is going to pay?_______________ How much of that will be covered by the community?______(%)

How much is each household expected to pay?____($/month),_____($/household) or lump-sum_______$

Who will pay for the replacement of equipment, if needed?_______________________________________

Remarks____

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QUESTIONNAIRE FOR RANDOMLY SELECTED VILLAGERS

Date____________________________

Recorded by___________________________

Location______________________ District________________ Region____________________

Total population served______________________________ Total number in household__________

How much is your family average yearly income____________________($/yr.)

What is your main income source?____

How many family members do you have?_________________________

Water pumping system type_____________________________ Other water source(s)____________

Which water system do you prefer?_______________________ Why?__________________________

How was the test of the traditional water source?_____________ How about the new system?__________

How much time did you spend to collect water every day with the old system?______________________(h)

Had you been informed before this pumping system was installed?___________________________________

If yes, did you agree?_______________________ If yes, what made you agree?____________________

How much contribution was proposed?_______($/month), ________($/household) or lump-sum________$

If not, who made the decision for the construction of the new system?_______________________________

Were you willing to pay?________________ Why?____

How much are you paying now?_________($/month),___________($/household) or lump-sum_________$

Did you have a higher priority than the new water pumping system?__________________________________

What is your opinion now towards the new system?____

How many liters of water per day you are using for household purposes?___________________(liters/day)

How much each household pays?_________($/month),____________($/household), or___________($/m^3)

For what purposes other than household are you using the new system?______________________________

Does the new system provide sufficient water for your needs in all seasons?__________________________

Since the installation of the pump, has the system broken down?________ If yes, how many times?______

How long did it take to fix?___________ Were you using the old system until the new system was fixed?__

If yes, how did you find it?____

What are the most common diseases in this community?____

How has the health situation been since the new system was installed?______________________________

Remarks____

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EVALUATION FORM FOR TECHNICIANS, GOVERNMENT INSTITUTIONS, AND NGOs ON THE BENEFICIAL AND ADVERSE IMPACTS OF VARIOUS WATER PUMPING SYSTEMS

No.	Impacts	Value weights (1-15)	Scores (0-5)			
			PV Pumps	Diesel Pumps	Wind Pumps	Hand Pumps
A	*Beneficial impacts*					
1	Equipment reliability					
2	Fuel reliability					
3	Spare-parts availability					
4	Weather change flexibility					
5	Operational safety					
6	Ground water reliability					
7	Easy maintainability					
8	Installation convenience					
9	Local maintenance personnel availability					
10	Impact on community development					
11	System expansion possibility					
12	Social acceptability of using the system					
13	Affordability (water charge based on service)					
14	Time saving because of using the system					
15	Service quality in fetching water (human labor involvement)					
16	Changes in the quality of life of individuals					
17	Operational simplicity by age-groups and gender					
18	Possibility of using the system for other purposes (such as irrigation, cattle watering, electricity, etc.)					
19	Impact on environmental protection					
20	System familiarity					
21	Wild-life protection					
	Total					
B	*Adverse impacts (Risks)*					
1	Exposition to possible accident during installation and operation					
2	System failure due to weather dependency					
3	System failure due to fuel supply shortage					
4	System failure due to spare-parts shortage					
5	System unreliability					
6	Site accessibility problem in construction and Maintenance of the system, fuel transport, etc.					
7	Installation inconvenience					
8	Long delays in repair in case of breakdowns					
9	Local maintenance skills requirement					
10	Difficulty in maintaining the system					
11	Skills requirement for operating the system					
12	Inconvenience of system expansion					
13	Inconvenience of equipment replacement in case of breakdowns					
14	Water pollution possibility					
15	Users credibility to the system					
16	System capacity limitations					
17	Operational inconvenience by different age-groups and gender					
18	Non-versatility (not adapted to other use, such as electricity, irrigation, etc. purpose)					
19	Time spend for fetching water					
20	Unwillingness to pay for water					
21	Land use					
22	Unfamiliarity of system					
23	Possibility of system abandoning due to the community's inability to pay for water					
24	Upland game birds					
	Total					

Glossary

Airfoil - A blade or solid?, curved in such a way that it produces lift when placed in airflow.

Alternating current (AC) - Electric current in which the direction of flow oscillates at frequent, regular intervals.

Altitude - The angle between the horizon (a horizontal plane) and the sun, measured in degrees.

Amorphous silicon - A thin-film PV silicon cell having no crystalline structure.

Anemometer – An instrument for measuring wind speed, basically driven by drag forces of wind on small revolving cups.

Annual equivalent life-cycle cost (ALCC) (annualized cost) - The equivalent annual cost of a project if the expenses are treated as being equal each year.

Aquifer – A naturally occurring layer of water-bearing soil, rock, or sand.

Array - A mechanically integrated configuration of PV modules and support structure designed to form a DC power-producing unit.

Azimuth - Angle between true south and the point directly below the location of the sun, measured in degrees.

Balance of system (BOS) - Components of a PV system other than the PV array.

Battery - Two or more cells electrically connected for storing electrical energy.

Battery bank - An energy storage capacity (ampere-hour).

Borehole - A hole drilled through the ground to reach water. Borehole diameters vary depending on the required size of the system. Standard borehole sizes are 4–6 in.

Capital cost - Initial investment of a project.

Centrifugal pump - A pump that delivers water centrifugally using impellers by producing a pressure difference.

Charge controller (battery charger) - A device that controls the charging rate and/or state of charge for batteries.

Concentrator - An optical component of a PV array used to direct and increase the amount of incident sunlight on a solar cell.

Conversion efficiency - The ratio of the electric energy produced by a PV/wind turbine to the energy from incident sunlight/wind.

Crystalline silicon - A type of PV cell made from a single crystal or polycrystalline slice of silicon.

Current - The flow of electric charge in a conductor between two points having a difference in potential (voltage).

Cut-in speed - The minimum wind speed at which a particular wind turbine will produce energy.

Cut-out speed - The speed at which a particular wind turbine will reduce its power output in order to protect itself from excessive wind speeds. Most small wind turbines do this by tilting out of the wind.

Darrieus – A vertical axis rotor with airfoil-shaped blades. The blades often are Troposkien–shaped.

Days of autonomy - The number of consecutive days a stand-alone system will meet a defined load without energy input.

Design month - The month having the lowest renewable energy (RE) production to load ratio.

Diffuse radiation - Solar radiation scattered by the atmosphere.

Direct radiation - Solar radiation transmitted directly through the atmosphere.

Direct current (DC) - Electric current flowing in one direction.

Disconnect - Switch gear used to connect or disconnect components in a stand-alone system.

Discount rate - Rate at which the value of money changes relative to general inflation.

Drag force - Force on a body in airflow acting parallel to the flow.

Drawdown - The distance below the water table that the water level in a well falls to when steady state pumping is in progress.

Drip irrigation – A type of irrigation method that uses rows of perforated pipes through which water drips on the irrigated field.

Efficiency - The ratio of output power to input power, expressed in percent.

Electric circuit - A complete path followed by electrons from a power source to a load and back to source.

Electric current – The magnitude of the flow of electrons.

Flatplate - An arrangement of solar cells in which the cells are exposed directly to normal incident sunlight.

Footvalve – A one-way valve at the base of a pump through which water is sucked by the pump up-stroke.

Furling - A mechanism that helps to stop or slow wind pumps (either by turning the whole rotor head out of the wind or by rotating each blade individually).

Global solar radiation - The sum of diffuse and direct solar radiation incident on a horizontal surface.

Grid - The network of transmission lines, distribution lines, and transformers used in central power systems.

Hub height - The distance from the ground to the center of the rotor (hub) of a wind machine.

Hydraulic equivalent load - The product of the daily amount of water produced by the pumping head.

Hydraulic energy - The energy necessary to lift water.

Incidence angle - Angle that refers to the sun's radiation striking a surface. A normal angle of incidence refers to the sun striking a surface at a 90° (or perpendicular) angle.

Inverter - A solid-state device that converts a DC input to an AC output.

Jack pump - A reciprocating pump in which the motor is on the surface and the pump is in the borehole. This type of pump is mainly used for high pumping head applications.

Kilowatt (kW) - One thousand watts.

Kilowatt hour (kWh) - One thousand watt hours.

Life-cycle cost - An estimate of the cost of owning and operating a system for the period of its useful life; usually expressed in terms of the present value of all costs incurred over the lifetime of the system. The sum of the capital cost and the present worth of the recurrent, salvage, and replacement costs.

Lift force - Force on an airfoil acting in a direction perpendicular to the airflow across the airfoil.

Load - The amount of electrical power being consumed at any given moment. Also, any device or appliance that is using power.

Load matching - The process of matching the load with the input power source to maximize the power transfer to the load.

Load-matching factor - A non-dimensional factor defined by the ratio of energy acquired by the hydraulic load to the maximum power extracted from the power source in a one-day period. It can also be the ratio of the actual power output used for water pumping to the power source output capability.

Maximum power point tracker (MPPT) - The impedance-matching electronics used to operate a PV array output at its maximum power.

Module (Panel) - A predetermined electrical configuration of solar cells laminated into a protected assembly.

Net present cost (NPC) - All project expenses converted into the current value of money.

Nominal voltage - A reference voltage used to describe batteries, modules, or systems (e.g., a 12-volt or 24-volt battery, module, or system).

Nomogram - A diagram that can be used to perform calculations or design a system by graphical means only.

Orientation - Placement according to the cardinal points (N, S, E, and W); azimuth is the measure in degrees from true south.

Panel - See module.

Payback period - The number of years (periods) required for the income (benefit) from a project to equalize its investment cost.

Peak hour demand - The maximum amount of water required in an hour. In most cases, peak hour can refer to noon and/or evening water consumption.

Peak watt (Wp) - The amount of power a PV device will produce during peak solar radiation periods when the cell faces directly towards the sun.

Photovoltaic (PV) cell - A cell that generates electrical energy when incident solar radiation impinges on it.

Photovoltaic (PV) system - An integrated system composed of a PV array, power conditioning, and other subsystems, such as the motor–pump.

Polycrystalline silicon - Silicon that has solidified at a rate such that many small crystals have formed.

Positive displacement pump - A type of water pump that can lift water from a borehole by means of a cavity or cylinder of variable size. Also called a *volumetric pump*.

Power conditioning - The electrical equipment used to convert power from a PV array into a form suitable to meet the power supply requirements of more traditional loads. It is a collective term for inverter, transformer, voltage regulator, meters, switches, and controls.

Power curve - A graphical representation of a wind turbine's power output as a function of wind speed.

Present worth - The value of future costs or benefits expressed in the current value of money (present-day money).

Prime mover - The source of power for running any given load.

Progressive cavity pump - A type of positive displacement pump that has a helical cavity between the rotor and stator. As the rotor rotates, the cavity progresses upward carrying the water with it.

Pumping head - The height of a water column that would produce the pressure that the pump experiences.

Reciprocating pump - A type of pump that has a pull/push motion, rather than rotation.

Remote site (location) – A site that is not located near a utility grid.

Renewable energy (RE) - Energy produced by non-fossil fuel or nuclear means. Includes energy produced from PV, wind turbines, hydroelectric, and biomass.

Rising main - The pipe used to lift water from the borehole.

Rotor - The rotating central section of a motor or a pump.

Single-crystal (monocrystalline) silicon - A material formed from a single silicon crystal.

Solar thermal electric – A method of producing electricity from solar energy by concentrating sunlight on a working fluid that changes phase to drive a turbine generator.

Solidity - Ratio of the total blade widths to the circumference of the rotor.

Stand-alone system - A system that operates independently of utility lines. It may draw supplementary power from the utility but is not capable of providing power to the utility.

State of charge - The available capacity in a cell or battery expressed as a percentage of rated capacity. For example, if 25-ampere-hours have been removed from a fully charged 100-ampere-hours cell, the new state of charge is 75%.

Static head - The height over which water must be pumped. Static head may vary due to seasonal changes in well recovery rates, fluctuations of groundwater levels, etc.

Stator – The outer stationary component of a motor or a progressive cavity pump.

Stroke – The maximum extent of travel of the pump rod and the piston.

Subsystem - In water pumping systems, typically refers to the motor–pump sets.

Sucker rod – Another name for a pump rod.

Tilt angle - Angle of inclination of a PV array as measured in degrees from the horizontal surface. Usually equal to the latitude of the PV array's location.

Tilted Factor - The ratio of the incidence solar radiation on a tilted PV array surface to the global solar radiation.

Tip-speed ratio - Ratio of the blade tip speed to the wind speed. Tip-speed ratio is higher for lower rotor solidity.

Village water supply (rural water supply) - Water supply for drinking and other domestic purposes [such as livestock, and backyard (micro) irrigation for a small garden]. This term does not include water for irrigation.

Volt (V) - A unit of measurement of the force given to electrons in an electric circuit; electric potential (voltage).

Water table (static water level) - The level below the ground at which the natural water level can be found.

Watt (W) - Measure of electric power. Watts = volts x amps.

Watt hour (Wh) - A quantity of electrical energy when one watt is used for one hour.

Weibull distribution - A mathematical means of describing various possible statistical wind speed distributions at different sites.

Weibull distribution coefficient, *k* - The coefficients used in the Weibull equations that define the shape of the wind speed distribution.

Wind turbine - A general term used to describe a wind-powered electric generator; a device that converts wind energy into electricity.

Yawing - The motion of the rotor head about its vertical pivot to point into the wind.

Zenith angle - The incidence angle to a horizontal surface.

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	July 2004
2. REPORT TYPE	Subcontract Report
3. DATES COVERED *(From - To)*	April 2001 - September 2001
4. TITLE AND SUBTITLE	Renewable Energy Water Pumping Systems Handbook; Period of Performance: April 1--September 1, 2001
5a. CONTRACT NUMBER	DE-AC36-99-GO10337
5b. GRANT NUMBER	
5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)	Neway Argaw
5d. PROJECT NUMBER	NREL/SR-500-30481
5e. TASK NUMBER	WER4.7001
5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	Neway Argaw 12180 Applewood Ct. Broomfield, CO 80020
8. PERFORMING ORGANIZATION REPORT NUMBER	RAM-1-31224-01
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393
10. SPONSOR/MONITOR'S ACRONYM(S)	NREL
11. SPONSORING/MONITORING AGENCY REPORT NUMBER	NREL/SR-500-30481
12. DISTRIBUTION AVAILABILITY STATEMENT	National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, VA 22161
13. SUPPLEMENTARY NOTES	NREL Technical Monitor: Larry Flowers

14. ABSTRACT *(Maximum 200 Words)*

Water is one of the most basic necessities for rural development. This book provides valuable information on how renewable energy technologies can be used for irrigation, livestock watering, and domestic water supplies. This report emphasizes wind and solar energy resources, and hybrid water pumping systems.

15. SUBJECT TERMS

Water pumping; renewable energy; wind; solar; photovoltaic; rural development; developing countries

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPONE NUMBER** *(Include area code)*
Unclassified	Unclassified	Unclassified	UL		

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18