# UNIVERSITY OF NAIROBI

# DEPARTMENT OF MECHANICAL AND MANUFACTURING ENGINEERING

## FINAL YEAR PROJECT REPORT

**PROJECT CODE: QBM 01/2012**

**PROJECT TITLE:**

**DESIGN OF A WIND/SOLAR HYBRID SYSTEM FOR WATER PUMPING**

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**A FINAL YEAR PROJECT SUBMITED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE IN BACHELOR OF SCIENCE IN MECHANICAL AND MANUFACTURING ENGINEERING.**

# DECLARATION

The content of this document is the original work based on our own research and to the best of our knowledge it has not been presented elsewhere for academic purposes.

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This report is submitted in partial fulfillment of the requirements for the award of a Bachelor of Science degree in Mechanical and Manufacturing Engineering.

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# DEDICATION

This project is dedicated to our dear parents for educating us and giving us the chance to realize the importance of education and that nothing in this life is impossible if much effort is put in it. This dedication is also for the realization of the discipline that education brings to a person's life for being a student.

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Our utmost thanks to the staff and students of the department of Mechanical and manufacturing Engineering for creating a conducive research environment and the University of Nairobi as a whole for providing the research facilities for the project activities within and out of the campus.

Humble appreciation also goes to our dear parents for the consistent and unconditional financial and moral support throughout our life in campus, and more specifically during the research of this project.

Great thanks to the Almighty God for giving us the intellect so used in this project. Moreover, we extend our gratitude to all other parties not mentioned here, who in one way or another contributed to the successful completion of this project.

# ABSTRACT

The main objective of this project was to analyze and design of a wind/solar hybrid system for water pumping. The compilation of this project report involved a variety of information research being gathered and geared towards achieving the objective.

The study involved analysis of the wind and solar as renewable sources of energy and their application to water pumping. A comparison of these two to other alternative sources of energy for water pumping was evaluated and the benefits and limitations noted. The alternative sources were fuels, energy stored in water, nuclear energy, tidal power, geothermal energy and thermoelectric power. Information on these sources of energy in the country was obtained from the internet as well as data obtained from visits to the Ministry of Energy, Meteorological Department and the Ministry of Water.

With the establishment of the available wind and solar resources in the country, their distribution and utilization was recorded in form of wind and solar maps respectively which were obtained from the Ministry of Energy website as well as earlier publications of the same. A visit to the Ministry of Water resulted to information on boreholes in possible areas in Kenya where the project is suitable for water pumping to supply to the surrounding community. The Meteorological Department provided information on wind rosettes of possible areas where the project would be applicable, namely, Bubisa in Marsabit where the collective information was used to match the hybrid system and work out a viable solution.

An evaluation of the cost (economy) of such a project was done and a conclusion was made. The most important factor to be noted was that despite the initial high capital cost of the hybrid system, it would be a feasible project in the long run and in line with Kenya’s vision 2030. The wind/solar hybrid system is environment friendly and its source of energy, although fluctuating, is freely available and non-depletable.

## OBJECTIVES

The objectives of the project were:

- To study the history and developments in wind power exploitation.
- To study the history and developments in solar power exploitation.
- To identify the various challenges facing wind and solar power exploitation.
- To design an efficient solar/wind hybrid system for water pumping.

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# INTRODUCTION

Wind is the product of the movement of air. Air has a certain density and surrounds the earth for a layer of approximately 64km in altitude. Air exerts a downward pressure, which is referred to as Atmospheric pressure. The pressure on the earth's surface is one atmosphere at sea level. As the earth rotates on its axis, gravity forces this relatively heavy air near the earth's surface to spin around with it. However the air higher up is less affected. The difference between the speed at which air moves close to the surface and the speed of air up forms vortexes or whirlpools. This mixing causes variations in air speed, and, consequently 'wind' is generated at the earth's surface. Additionally, the sun warms the earth and the atmosphere. Heating is greater at the equator than at the earth's poles. Warm air is less dense than cold air. Warm air rises while cold air sinks. Therefore, there is always a series of pressure differentials in the air caused by the earth's rotation and by differential temperature on the earth's surface. These two factors account for the earth's "wind".

Wind energy is rightfully an indirect form of solar energy since wind is induced chiefly by the uneven heating of the earth's crust by the sun. Winds can be broadly classified as planetary and local. Planetary winds are caused by greater solar heating of the earth's surface near the equator than near the northern or southern poles. This causes warm tropical air to rise and flow through the upper atmosphere toward the poles and cold air from the poles to flow back to the equator nearer to the earth's surface. The direction of motion of planetary winds with respect to the earth is affected by the rotation of the earth. The warm air moving toward the poles in the upper atmosphere assumes an easterly direction (in both the northern and southern hemispheres) that results in the prevailing westerlies (winds are named according to the direction they come from). At the same time, the inertia of the cool air moving toward the equator nearer the earth's surface causes it to turn west, resulting in the northeast trade winds in the northern hemisphere and the southeast trade winds in the southern hemisphere. Local winds are caused by two mechanisms. The first is differential heating of land and water. Solar insolation during the day is readily converted to sensible energy of the land surface but is partly absorbed in layers below the water surface and partly consumed in evaporating some of that water. The land mass becomes hotter than the water, which causes the air above land to heat up and become warmer than the air above water. The warmer lighter air above the land rises, and the cooler heavier air above the water moves in to replace it. This is the mechanism of shore breezes. At night, the direction of the breezes is reversed because the land mass cools to the sky more rapidly than the water, assuming a clear sky. The second mechanism of local winds is caused by hills and mountain sides. The air above the slopes heats up during the day and cools down at night, more rapidly than the air above the low lands. This causes heated air during the day to rise along the slopes and relatively cool heavy air to flow down at night. Although solar energy is cyclic and predictable, and even dependable in some parts of the globe, wind energy, however, is erratic, unsteady, and often treacherous except in very few areas. it does, however, have a place in the total energy picture, particularly for those areas with more or less steady winds, especially those that are far removed from central power grids, and for small, remote domestic and farm needs (Ref. 1).

Wind is one of the greatest sources of natural energy. It is free and is available day and night for the production of economical power to pump water or to generate electricity. A wind pump needs no fuel and little maintenance and will last 20 years and more. The cost of financing a wind pump compares very favourably with any conventional pumping system. Using a wind pump can immediately help your cash flow. Provided local wind conditions are adequate, a wind pump will always produce water more cheaply and with less trouble than an engine. When the next fuel shortages occur, the wind pump will be immune to the problem. The major advances in the design of the wind pump took place towards the end of the 19$^{th}$ century in the USA. The technology was taken up and developed by the early pioneers or settlers who needed a method of lifting ground water for irrigation, for watering of livestock and later for providing water for steam locomotives which began to spread across the country. But the glory of the wind pump was short-lived. With the advent of cheap fossil fuels in the 1950's and 1960's and the development of pumping technology the wind pump became almost obsolete. Nowadays, with regular fuel crises and rising prices there has been a revival of interest in wind power but the wind pump has yet to regain the status it held during its heyday (Ref. 2).

## 1.1 SOURCES OF ENERGY

The various sources of energy (Ref. 3) are:

1. Fuels (solids, liquids and gases)
2. Energy stored in water
3. Nuclear energy
4. Wind power
5. Solar energy
6. Tidal power
7. Geothermal energy
8. Thermoelectric power

### 1.1.1 Fuels

Fuels may be nuclear or chemical. Fuels can be classified according to whether:

1. They occur in nature called primary fuels or are prepared called secondary fuels
2. They are in solid, liquid or gaseous state.

**Table 1.1: Types of Fuels (Ref. 3)**

| Type of fuel | Natural(primary) | Prepared(secondary) |
|---|---|---|
| Solid | Wood | Coke |
| | Peat | Charcoal |
| | Lignite coal | Briquettes |
| Liquid | Petroleum | Gasoline |
| | | Kerosene |
| | | Fuel oil |
| | | Alcohol |
| | | Benzol |
| | | Shale oil |
| Gaseous | Natural gas | Petroleum gas |
| | | Producer gas |
| | | Coal gas |
| | | Coke-oven gas |
| | | Blast furnace gas |
| | | Carbureted gas |

### 1.1.2 Energy stored in water

The energy stored in flowing streams of water is a form of mechanical energy. It may exist as the kinetic energy of a moving stream or as potential energy of water at some elevation with respect to a lower datum level.

Water power is quite cheap where water is available in abundance. Although capital cost of hydroelectric power plants is higher as compared to other types of power plants yet their operating costs are quite low.

### 1.1.3 Nuclear Energy

One of the most outstanding facts about nuclear power is the large amount of energy that can be released from a small mass of active material. Complete fission of one kg of uranium contains the energy equivalent of 4500 tonnes of coal or 2000 tonnes of oil. The nuclear power is not only available in abundance but it is cheaper than the power generated by conventional sources.

Economic advantage of nuclear power can be realized only if one can ensure a guaranteed base load of about 75%. The number of electro-chemical processes (fertilizer plants), desalination of water and use of electricity for pumping water from tube wells assure a constant base load (Ref. 3).

### 1.1.4 Wind Power

The principal services of this nature are the pumping of water into storage tanks and the charging of storage batteries. Windmill power equipment may be classified as follows:

1. The multi-bladed turbine wheel – it is the foremost type in use and its efficiency is about 10 percent of the kinetic energy of the wind passing through it.
2. The high-speed propeller type.
3. The rotor.

The propeller and rotor types are suitable for the generation of electrical energy, as both of them possess the ability to start in very low winds. The propeller type is more likely to be used in small units such as the driving of small battery charging generators, whereas the rotor, which is rarely seen, is more practical for large installations.

Modern windmills are capable of working on velocities as low as 3-7 km/hr while maximum efficiency is attained at 10-12 km/hr. A normal working life of 20 to 25 years is estimated for windmills.

### 1.1.5 Solar Energy

For developing solar energy, two ways have been explored: the glass lens and the reflector. These devices concentrate the solar rays to a focal point which is characterized by a high degree of heat which can be utilized to boil water and generate steam. The reflector is the better of the two methods due to the convenience with which it can be manufactured in different shapes and sizes.

### 1.1.6 Tidal Power

The rise and fall of tides offers a means for storing water at the rise and discharging the same at fall. Of course the head of water available under such cases is very low but with increased catchment area considerable amounts of power can be generated at a negligible cost.

### 1.1.7 Geothermal Energy

It is efficient and its power plants have low emissions. It has low cost after the initial investment and very minimal environment impact. Geothermal fields are found in few areas of the world and have expensive start-up costs, while their wells could eventually be depleted.

### 1.1.8 Thermoelectric Power

Different metals do not necessarily contain the same number density of conduction electrons. If two metals are placed in contact, the conduction electrons diffuse across the boundary, showing a net flow in a direction determined by the work functions of the metals concerned. The resulting potential difference across the boundary, which is equal to the difference of the work function potentials, prevents further diffusion and so a dynamic equilibrium is reached (Ref. 3).

## 1.2 HISTORY OF WIND POWER EXPLOITATION

Human beings have always dreamt of converting wind power to mechanical and, more recently, electric power. Wind, more than any other renewable energy source, has intrigued serious and amateur inventors over the ages. It is said that more patents for wind systems have been applied for than any other device to date. In ancient times the kinetic energy of the wind was used to propel ships by sails. Windmills, however, are more recent, having been used for a little over a thousand years. The earliest reference to windmills appeared in Arab writings from the ninth century A.D. that described mills that operated on the borders of Persia and Afghanistan some two centuries earlier (Ref. 1).

The use of wind energy can be traced back long before America was discovered. In American history, it can be traced from the time of Columbus. Wind energy became useful on the tobacco farms and sugar plantations and has been a part of America's agriculture from its conception. However, wind energy did not get the proper attention throughout America's history. Long before the 1980's when the idea of using wind was all the rage, early American ranchers living on the prairies in Nebraska and Kansas bridled the wind to work the water-pumps on their land.

Since early recorded history, people have been harnessing the energy of the wind. Wind energy propelled boats along the Nile River as early as 5000 B.C. By 200 B.C., simple windmills in China were pumping water, while vertical-axis windmills with woven reed sails were grinding grain in Persia and the Middle East. And just as the wind has been harnessed to propel boats swiftly across the world’s oceans and to pump water and grind grain, so too has it been captured to fuel the comparatively modern invention of electricity.

The wind has been used as a source of power for over 2000 years; the giant livestock industries of Australia and the USA were, and still are, dependant on wind pumps by the million. Today, with oil and engine prices constantly rising, wind power is enjoying a big revival and is set to make a major contribution to our energy needs in the 21st century. Wind power is therefore both a technology of the past and a new technology for the future. It combines experience with promise. There are manufacturers in several developing countries now producing wind pumps. The uptake of wind machines for water pumping, however, has been generally very slow even though the technology is well suited to the demand of many regions of Africa, Asia and Latin America. Where they are used, the demand is for one of the following end uses:

- village water supplies
- irrigation
- livestock water supplies

Water pumping is one of the most basic and widespread energy needs in rural areas of the world. It has been estimated that half the world's rural population does not have access to clean water supplies (Ref. 6).

The wind systems that exist over the earth's surface are a result of variations in air pressure. These are in turn due to the variations in solar heating. Warm air rises and cooler air rushes in to take its place. Wind is merely the movement of air from one place to another. There are global wind patterns related to large scale solar heating of different regions of the earth's surface and seasonal variations in solar incidence. There are also localized wind patterns due the effects of temperature differences between land and seas, or mountains and valleys.

Wind pumps are very sensitive to wind speed; a slight increase in mean wind speed produces a marked increase in output of water. For example, only a 25% increase in wind speed results in a 100% increase in energy availability. The wind energy captured is in proportion to the area of the wind pump rotor. Therefore a machine with a rotor twice as big in diameter as another will actually produce over four times as much water under given operating conditions.

Wind speed data can be obtained from wind maps or from the meteorology office. Unfortunately the general availability and reliability of wind speed data is extremely poor in many regions of the world. However, significant areas of the world have mean wind speeds of above 3m/s which make the use of wind pumps an economically attractive option. It is important to obtain accurate wind speed data for the site in mind before any decision can be made as to its suitability.

Modern wind turbines generally consist of a rotor with three blades; a nacelle, which typically contains a gear box, generator, brake, yaw motor, and yaw drive; and an anemometer. As the wind pushes the blades, power is transferred from the rotor to the gear box and generator and is eventually deposited into an electrical grid, which then distributes power to consumers. The efficiency with which a wind turbine is able to capture wind power and transfer it to a grid depends on several design elements. For example, rotor blades can be built with a subtle twist, which allows for maximum wind power capture. Other elements, such as a large generator and large-diameter rotor, enable the capture of large amounts of energy but also have higher energy costs than turbines that use smaller rotors and generators.

## 1.3 LIMITATIONS OF WIND PUMP TECHNOLOGY

Some of the limitations of the wind pump technology are:

- Minimum wind requirements for wind pumps - It has shown that, typically, wind pumps require an average "least windy month" wind speed of about 2.5m/s to begin to be economically competitive. Because of the cube relationship between wind speed and energy availability, which is true for any optimally matched wind pump, and wind regime, the economics of wind pumps are very sensitive to wind speed. Therefore, wind pumps are one of the most cost-effective options (compared with engines or any other prime-movers) for pumping in locations with mean wind speeds exceeding about 4m/s, but, conversely, they are not at all cost-competitive where mean wind speeds are significantly below 2.5m/s.

- Variation of wind speed with height - The speed of the wind increases with height. The rate of increase is dependent partly on the height and partly on the nature of the ground surface. This is because rough ground, with many uneven trees, bushes or buildings, causes turbulence, while a flat and unobstructed surface like the sea or a flat grassy plain allows the air to flow smoothly which results in higher wind speeds nearer to the surface.

- Effects of Obstructions - Any obstruction to the wind has a wake extending up to 20 or 30 diameters (of the obstruction) downwind. The wake is depleted of wind energy compared with the surrounding wind, and is turbulent. Sharp edged and irregular obstructions such as rock outcrops, cliffs and escarpments, or large buildings can cause violent turbulence which, apart from depleting the energy available, can cause damage to a windmill located nearby.

- Investment Cost - Although the lifetime cost of wind is often less than diesel or petrol-powered pumps, the investment cost of purchasing a wind pump is usually higher than that of diesel pumps. Groups purchasing water supplies often have limited funds and cannot take a long-term view toward the technology.

- Maintenance and Service - Technicians and buyers are often unfamiliar with wind pump technology, and pumps in remote locations often break down because of a lack of servicing, spare parts, or trained manpower to administer them. In reality, wind pumps are less maintenance intensive than diesel pumps. However, the wind pump technology is "strange" to many people and there is a need to train maintenance staff where pumps are installed.

- Need for water storage - Because wind pumps only supply water when the wind is blowing, there is almost always a need to build storage tanks to avail water when the wind is not blowing.

- Low output - With wind speeds between 2.5-5 m/s, average sized wind pumps will deliver between 10 to 50 $m^3$ at 10m depth or 2 to 20 $m^3$ at 50m depth. Such outputs may be too low for large communities or irrigation requirements.

## 1.4 USE OF WIND TURBINES IN EGYPT

Water access is a critical need in Rural Egypt today. The Egyptian economy depends highly upon agricultural production which accounts for over 15% of its GDP. Water is essential for agriculture but not every village there has access of the water from the Nile and so Diesel fuel was used to pump water out of the ground. Some of these communities though are in remote areas and transporting diesel fuel is quite a costly affair, making wind power an economical option.

Overall, Egypt has fairly good electricity access rates- an estimated 94% of the population has access to electricity, but this still leaves an estimated 4 million Egyptians, mostly living in remote areas without access. Wind energy could be an effective way to provide electricity in areas that may not receive grid connections any time soon. The Egyptian Solar Energy Society implemented two projects between September 1995 to September 1997 that involved use of wind power to meet water access and electricity needs. The first project which focused on designing, manufacturing and installing of four wind turbines to pump water, was successful in achieving lower costs of construction.

The four small scale versions were pumping from 700-2400 liters of water per hour for agricultural use. The second project involved designing and installing turbines for electricity generation.

Several more turbines were later constructed which could operate at greater capacities, one type pumps 3000 liters of water per hour which is mostly used for drinking and another type pumps 9800 liters of water per hour for agricultural use.

## 1.5. WIND POWERED WATER PUMPING IN KENYA

Wind mills in Kenya were introduced by the colonial masters and have been used for unattended water supply for over 70 years. Their use however has not been so wide after the introduction of cheaper diesel powered pumps.

Their use has since then been small scale individual homestead windmills in the rural areas where diesel is not readily available and there is no connection to the country's electricity grid, in fact it is estimated that only about 15% of Kenyan homes are connected to electricity. Hence the need of cheap reliable energy, like wind energy.

Seven manufacturers currently provide windmills for sale in Kenya. Most of their products are drag mills for pumping applications. They range from the imported Southern Cross, to the locally manufactured kijito, to the locally fabricated PU500 (Ref. 7).

## 1.6 WIND ENERGY RESOURCE POTENTIAL AND DISTRIBUTION IN KENYA

Wind energy is more cost effective than Photovoltaic (PV) for both grid connected and isolated systems (through wind-diesel hybrid systems). Wind power installations cost 3.5 times less per Watt than PV installations and operate for 12-18 hours at good sites as opposed to 5-6hrs for PV systems.

The Equatorial areas are assumed to have poor to medium wind resource. This could be a general pattern for Kenya. However some topography specifics like channeling and hill effects due to the presence of the Rift Valley and various mountain and highland areas, have endowed Kenya with some excellent wind regime areas.

The North West of the country (Marsabit and Turkana districts) and the edges of the Rift Valley are the two large windiest areas (average wind speeds above 9m/s at 50 m high). The coast is also a place of interest though the wind resource is expected to be lower (about 5-7 m/s at 50 m high). Many other local mountain spots offer good wind conditions. Due to monsoon influence, some seasonal variations on wind resource are expected (low winds between May and August in Southern Kenya).

It is expected that about 25% of the country is compatible with current wind technology. The main issue is the limited knowledge on the Kenya wind resource. Kenya's wind resource is determined from wind speed data from meteorological stations. The Department has 35 stations spread all over the country. Information gathered is not adequate to give detailed resolutions due to sparse station network. There is significant potential to use wind energy for grid connected wind farms, isolated grids and off-grid community electricity and water pumping.

Use of wind turbines or wind pumps in Kenya is marginal. The current installed capacity of wind turbines is 750kW; 150kW of which are small isolated wind turbines and 600kW of medium grid connected wind turbines; 2 at Ngong Hills and 1 in Marsabit. There are plans underway to develop a 10-15MW wind farm in Kinangop. An average of 80-100 small wind turbines (400W) have been installed to date, often as part of a PV Wind hybrid system with battery storage.

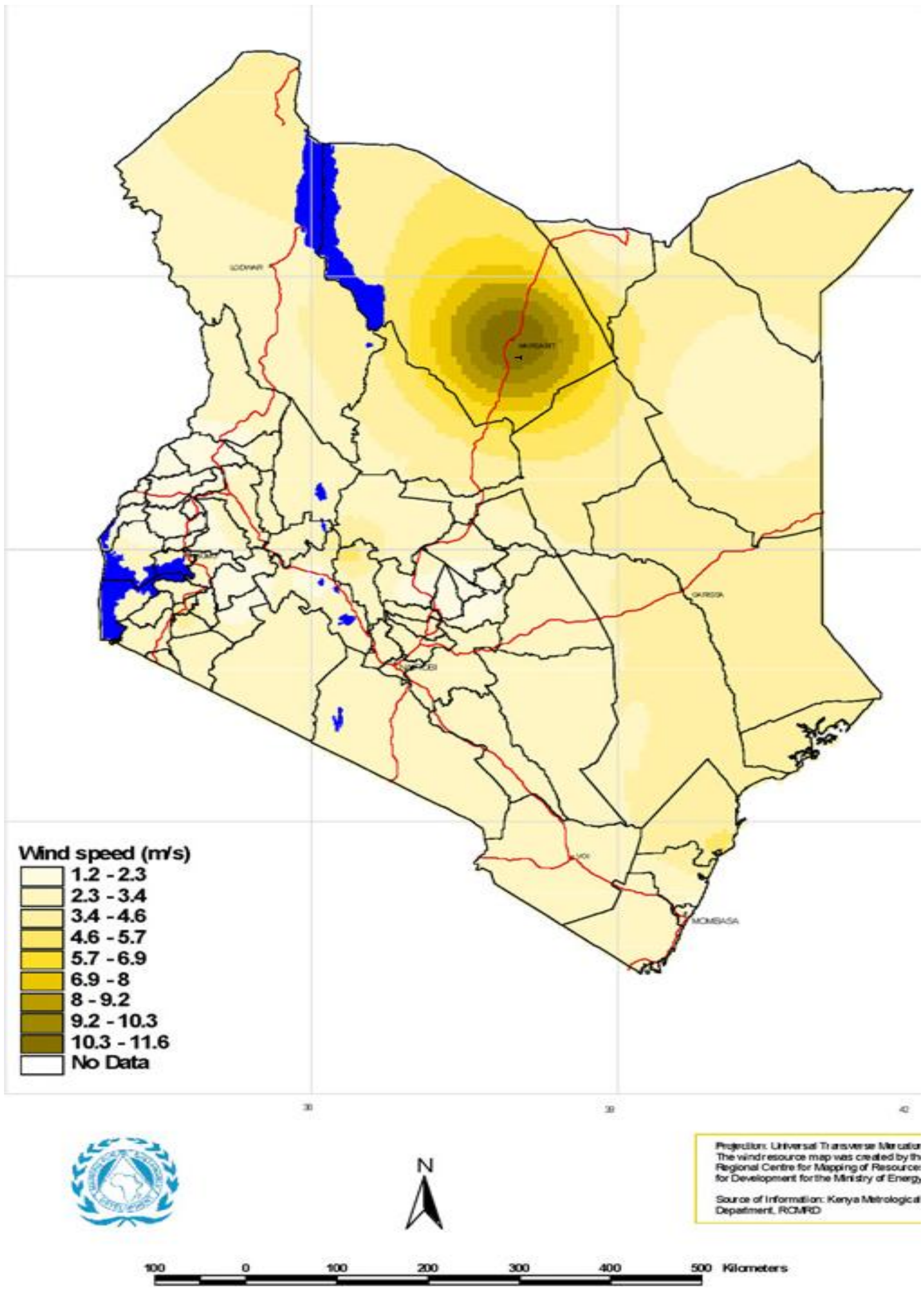



**Fig 1.1: Spatial Pattern of Mean Wind Speeds in Kenya (Ref. 2)**

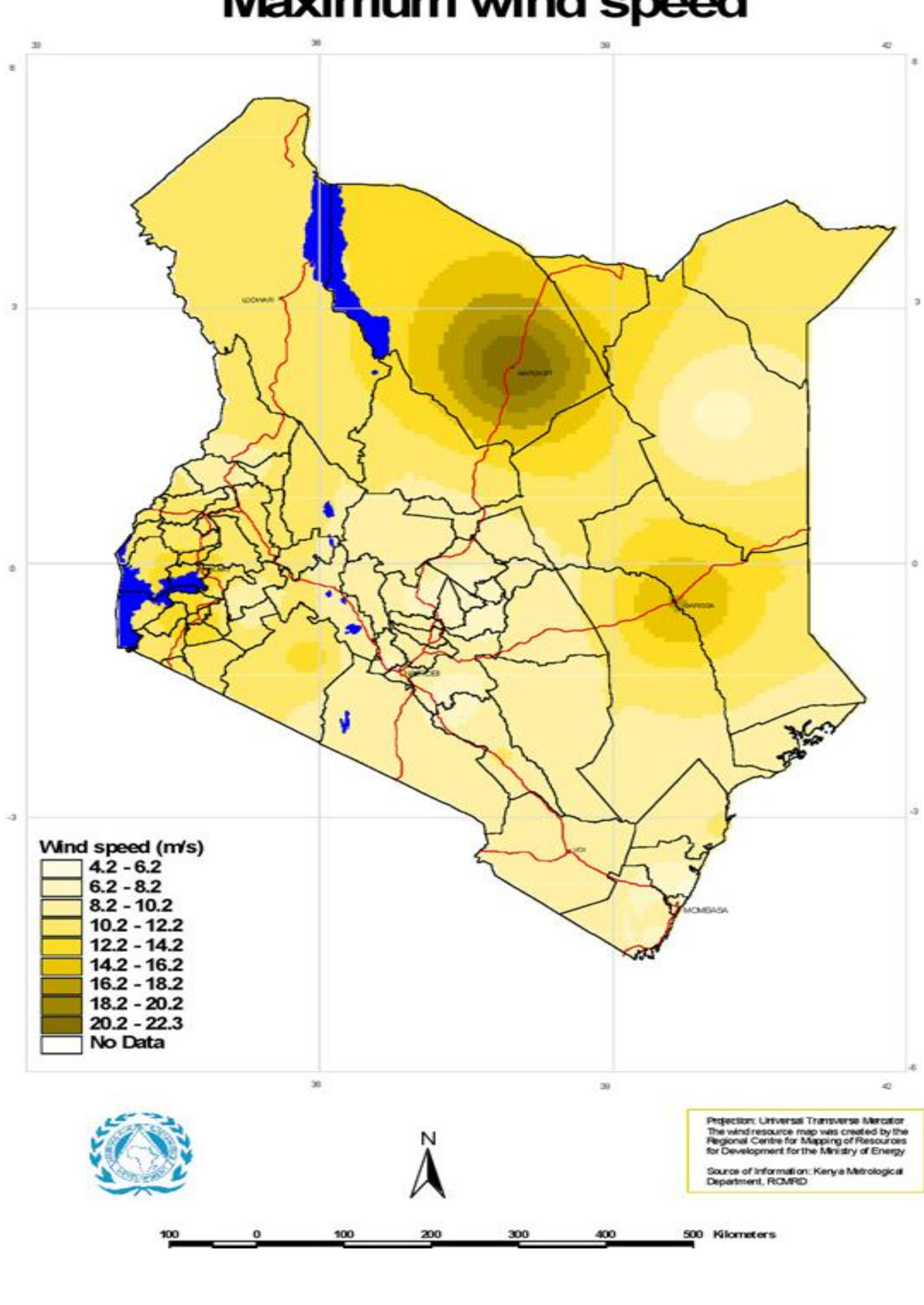



**Fig 1.2: Spatial Pattern of Maximum Wind Speeds in Kenya (Ref. 2)**

Wind pumps are more common than wind turbines, two local companies manufacture and install wind pumps. To date installations are in the range of 300-350 (Ref. 7).

Characteristics of a good wind power site are:

1. High annual wind speed.
2. An open plain or an open shore line.
3. A mountain gap.
4. The top of a smooth well rounded hill with gentle slopes lying on a flat plain or located on an island in a lake or sea.
5. There should be no full obstructions within a radius of 3 km.

The main characteristics of wind are:

- Wind speed increases roughly as $\frac{1}{7}$th the power of height. Typical tower heights are about 20-30 m.
- Energy-pattern factor – it is the ratio of the actual energy in varying wind to energy calculated from the cube of mean wind speed. This factor is always greater than unity which means that energy estimates based on mean (hourly) speed are pessimistic (Ref. 3).

## 1.7 ADVANTAGES AND DISADVANTAGES OF WIND ENERGY

The following are the advantages and disadvantages of wind energy:

### 1.7.1 Advantages

1. It is a renewable energy source.
2. Wind power systems being non-polluting have no adverse effect on the environment.
3. Fuel provision and transport are not required in wind energy conversion systems.
4. Economically competitive.
5. Ideal choice for rural and remote areas and areas which lack other energy sources.

### 1.7.2 Disadvantages

1. Owing to its irregularity, the wind energy needs storage.
2. Availability of energy is fluctuating in nature.
3. The overall weight of a wind power system is relatively high.
4. Wind energy conversion systems are noisy in operation.

5. Large areas are required for installation/operation of wind energy systems.
6. Present systems are neither maintenance free, nor practically reliable.
7. Low energy density.
8. Favourable winds are available only in a few geographical locations, away from cities, forests.
9. Wind turbine design, manufacture and installation have proved to be most complex due to several variables and extreme stresses.
10. Requires energy storage batteries and/or stand by diesel generators for supply of continuous power to load.
11. Wind farms require flat, vacant land free from forests.
12. Only in kW and a few MW range; it does not meet the energy needs of large cities and industry (Ref. 3).

## 1.8 CHALLENGES AFFECTING EXPLOITATION OF WIND ENERGY RESOURCES IN KENYA

- Site selection- Wind potential assessments are site specific and time consuming. This means that wind energy developments require a large initial investment for careful wind prospecting. Good equipment and quality work is needed, which is expensive.

- Updated wind resource map for Kenya - The ministry of Energy has made some progress in this area. Suppliers of wind turbines often have to rely on meteorological data and customers' observations to determine whether a site is viable. Such information is misleading and often leads to installation of poorly performing or non-performing systems. The SWERA (Solar and Wind Energy Resource Assessment) Program is also in the process of developing wind energy resource information for Kenya.

- Distance from transmission lines - Areas in the North that have the highest potential for wind energy generation are too far from the nearest transmission lines making grid connection uneconomical.

# CHAPTER 2:
# WIND POWER AS AN ALTERNATIVE

## 2.1 INTRODUCTION

There are many places in the world where wind energy is a good alternative for pumping water. Specifically these include windy areas with limited access to other forms of power. In order to determine whether wind power is appropriate for a particular situation an assessment of its possibilities and the alternatives should be undertaken. The necessary steps include the following:

a) Identify the users of the water.
b) Assess the water requirement.
c) Find the pumping height and total/overall power requirements.
d) Evaluate the wind resources.
e) Estimate the size of the wind machine(s) needed.
f) Compare the wind machine output with the water requirement on a seasonal basis.
g) Select a type of wind machine and pump from the available options.
h) Identify possible suppliers of machines, spare parts, repair, etc.
i) Identify alternative sources for water i.e. alternative power sources for water pumping.
j) Assess costs of various systems and perform economic analysis to find least cost alternative i.e. evaluating economics
k) If wind energy is chosen, arrange for obtaining and installing the machines and for providing for their maintenance.

## 2.2 DECISION MAKING PROCESS

### 2.2.1 Identifying the User

This step should not be ignored. By paying attention to who will use the wind machine and its water it will be possible to develop a project that can have continuing success. Questions to consider are whether they are villagers, farmers, or ranchers; what their educational level is; whether they have had experience with similar types of technology in the past; whether they have access to or experience with metal working shops. Who will be paying for the projects; who will own the equipment; who will be responsible for keeping it running; and who will be benefitting most? Another important question is how many pumps are planned. A large project to supply many pumps may well be different than one looking to supply a single site.

### 2.2.2 Assessing the Water Requirements

There are four main types of uses for water pumps in areas where wind energy is likely to be used. These are:

a) Domestic use
b) Livestock watering
c) Irrigation
d) Drainage

Domestic use will depend a great deal on the amenities available. A typical villager may use from 15 - 30 liters per day. When indoor plumbing is used, water consumption may increase substantially. For example, a flush toilet consumes about 10 liters with each use and a shower may take up to 40 liters or even more. When estimating water requirements, one must also consider population growth. For example, if the growth rate is 3%, water use would increase by nearly 60 percent at the end of 15 years, a reasonable lifetime for a water pump. Estimation of irrigation requirements is more complex and depends on a variety of meteorological factors as well as the types of crops involved. The amount of irrigation water needed is approximately equal to the difference between that needed by the plants and that provided by rainfall.

Various techniques may be used to estimate evaporation rates, due for example to wind and sun. These may then be related to plant requirements at different stages during their growing cycle.

Drainage requirements are very site dependent. Typical daily values might range from 10,000 to 50,000 liters per hectare. In order to make the estimate for the water demand, each user's consumption is identified, and summed up to find the total. It is desirable to do this on a monthly basis so that the demand can be related to the wind resource.

### 2.2.3 Finding Pumping Height and Total Power Requirement

If wells are already available their depth can be measured directly. If new wells are to be dug, depth must be estimated by reference to other wells and knowledge of ground water characteristics in the area. The total elevation, or head, that the pump must work against, however, is always greater than the static well depth.

Other contributors are the well draw down (the lowering of the water table in the vicinity of the well while pumping is underway), the height above ground to which the water will be pumped (such as to a storage tank), and frictional losses in the piping. In a properly designed system the well depth and height above ground of the outlet are the most important determinants of pumping head.

### 2.2.4 Evaluation of Wind Resource

It is well known that the power in the wind varies with the cube of the wind speed. Thus if the wind speed doubles, the available power increases by a factor of eight. Hence it is very important to have a good understanding of the wind speed patterns at a given site in order to evaluate the possible use of a wind pump there. It is sometimes recommended that a site should have an average wind speed at the height of a wind rotor of at least 2.5 m/s in order to have potential for water pumping. That is a good rule of thumb, but by no means the whole story. First of all, one seldom knows the wind speed at any height at a prospective windmill site, except by estimate and correlation. Second, mean wind speeds generally vary with the time of day and year and it makes an enormous difference if the winds occur when the water is needed. The best way to evaluate the wind at a prospective site is to monitor it for at least a year.

Data should be summarized at least monthly. This is often impossible but there should be some monitoring done if a large wind project is envisioned. The most practical approach may be to obtain wind data from the nearest weather station (for reference) and try to correlate it with that at the proposed wind pump site.

If at all possible the station should be visited to ascertain the placement of an anemometer and its calibration. Many times anemometers are placed too near the ground or are obscured by vegetation and so greatly underestimate the wind speed. The correlation with the proposed site is best done by placing an anemometer there for a relatively short time say at least a few weeks and comparing resulting data with that taken simultaneously at the reference site. A scaling factor for the long-term data can be deduced and used to predict wind speed at the desired location. Of course, possible locations for wind machines are limited by the placement of the wells, but a few basic observations should be kept in mind. The entire rotor should be well above the surrounding vegetation, which should be kept as low as possible for a distance of at least ten times the rotor diameter in all directions.

Wind speed increases with elevation above ground, usually by 15-20 percent with every doubling of height .Because of the cubic relationship between wind speed and power, the effect on the latter is even more dramatic.

### 2.2.5 Estimation of the Size of Wind Machines

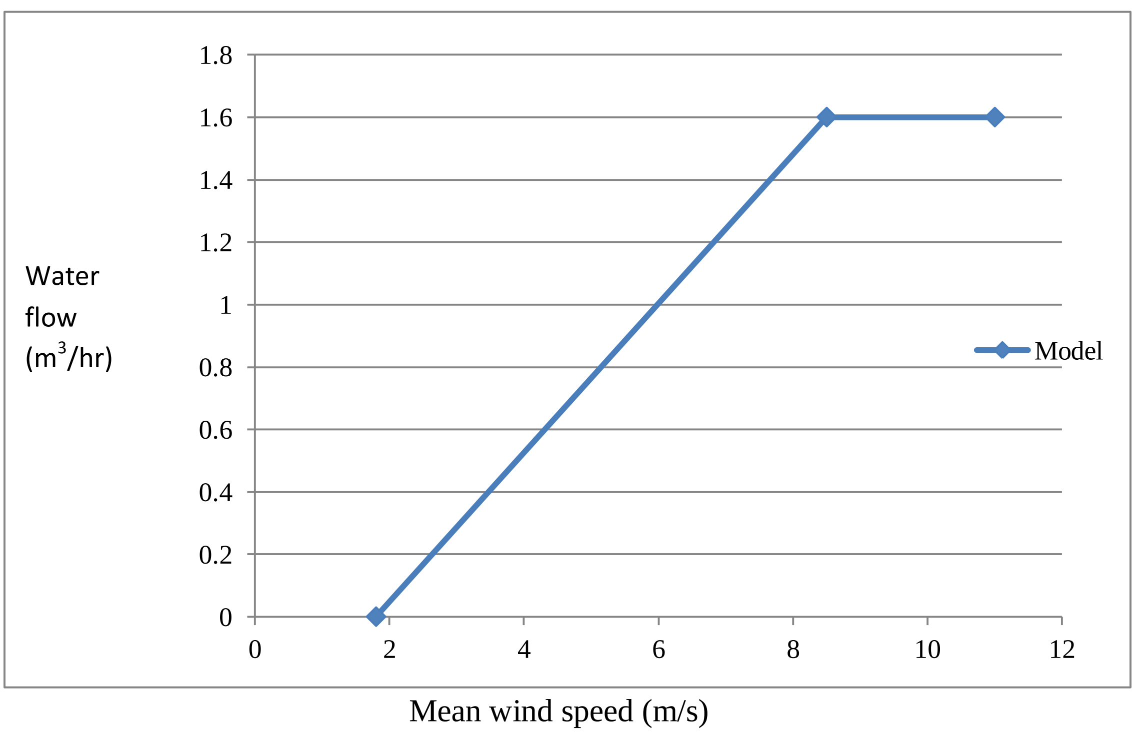
In order to estimate wind machine's size it is first necessary to have some idea how it will perform in real winds. As previously mentioned, the power in wind varies with the cube of the wind speed. It is also proportional to the density of the air. Atmospheric density is 1.293 $kg/m^3$ at sea level at standard conditions but is affected by temperature and pressure.

The power that a wind machine produces, in addition, depends on the swept area of its rotor and the aerodynamic characteristics of its blades. Under ideal conditions the rotational speed of the rotor varies in direct relation to the wind speed. In this case the efficiency of the rotor remains constant and power varies as the cube of the wind speed and rotational speed.

With wind pumps, however, the situation is more complicated. The majority use piston pumps, whose power requirements vary directly with the speed of the pump. At high wind speeds the rotor can produce more power than the pump can use. The rotor speeds up, causing its efficiency to drop, so it produces less power. The pump, coupled to the rotor, also moves more rapidly so it absorbs more power. At a certain point the power from the rotor equals the power used by the pump, and the rotational speed remains constant until the wind speed changes.

The net effect of all this is that the whole system behaves rather differently than an ideal wind turbine. Its actual performance is best described by a measured characteristic curve, shown below, which relates actual water flow at given pumping heads to the wind speed. This curve also reflects other important information such as the wind speeds at which the machine start and stops pumping, at low speeds and when it begins to turn away in high winds (furling).

**Table 2.1: Multiblade Windmill Performance, Observed and Model Results, One minute average readings (Ref. 8)**



Most commercial machines and those developed and tested more recently have such curves and these should be used if possible in predicting wind machine output. On the other hand, it should be noted that some manufacturers provide incomplete or overly optimistic estimates of what their machines can do. Sales literature should be examined carefully. In addition to the characteristic curve of the wind machine, one must also know the pattern of the wind in order accurately to estimate productivity. For example, suppose the frequency of the average wind speed was between 0-1 m/s, 1-2 m/s, 2-3 m/s, etc., in a given month. By referring to the characteristic curve, one could determine how much water was pumped in each of the groups of hours corresponding to those wind speed ranges. The sum of water from all groups would be the monthly total. Usually such detailed information on the wind is not known.

However, a variety of statistical techniques are available from which the frequencies can be predicted fairly accurately, using only the long-term mean wind speed and, when available, a measure of its variability. Many times there is little information known about a possible machine or it is just desired to know very approximately what size machine would be appropriate.

### 2.2.6 Compare Seasonal Water Production to Requirement

This procedure is usually done on a monthly basis. It consists of comparing the amount of water that could be pumped with that actually needed. In this way it can be told if the machine is large enough and conversely if some of the time there will be excess water. This information is needed to perform a realistic economic analysis. The results may suggest a change in the size of machines to be used. Comparison of water supply and requirement will also aid in determining the necessary storage size. In general storage should be equal to about one or two days of usage.

### 2.2.7 Selecting Type of Wind Machine and Pump

There is a variety of types of wind machines that could be considered. The most common use relatively slow speed rotors with many blades, coupled to a reciprocating piston pump. Rotor speed is described in terms of the tip speed ratio, which is the ratio between the actual speed of the blade tips and the free wind speed. Traditional wind pumps operate with highest efficiency when the tip speed ratio is about 1.0. Some of the more recently developed machines, with less blade area relative to their swept area, perform best at higher tip speed ratios (such as 2.0).

A primary consideration in selecting a machine is its intended application. Generally speaking, wind pumps for domestic use or livestock supply are designed for unattended operation. They should be quite reliable and may have a relatively high cost. Machines for irrigation are used seasonally and may be designed to be manually operated. Hence they can be more simply constructed and less expensive.

For most wind pump applications, there are four possible types or sources of equipment. These are:

a) Commercially available machines of the sort developed for the American West in the late 1800s.
b) Refurbished machines of the first types that have been abandoned.
c) Intermediate technology machines, developed over the last 20 years for production use in developing countries.
d) Low technology machines, built of local materials.

The traditional, American "fan mill," is a well developed technology with very high reliability. It incorporates a step down transmission, so that pumping rate is a quarter to a third of the rotational speed of the rotor. This design is particularly suitable for relatively deep wells (greater than 30m).

The main problem with these machines is their high weight and cost relative to their pumping capacity. Production of these machines in developing countries is often difficult because of the need for casting gears. Refurbishing abandoned traditional pumps may have more potential than might at first appear likely. In many windy parts of the world a substantial number of these machines were installed early in this century, but were later abandoned when other forms of power became available.

Often these machines can be made operational for much less cost than purchasing a new one. In many cases parts from newer machines are interchangeable with the older ones. By coupling refurbishing with a training program, a maintenance and repair infrastructure can be created at the same time that machines are being restored. Development of this infrastructure will facilitate the successful introduction of newer machines in the future.

For heads of less than 30m, the intermediate technology machines may be most appropriate. Some of the groups working on such designs are listed at the end of this entry. These machines typically use a higher speed rotor and have no gear box. On the other hand they may need an air chamber to compensate for adverse acceleration effects due to the rapidly moving piston.

The machines are made of steel, and require no casting and minimal welding. Their design is such that they can be readily made in machine shops in developing countries. Many of this wind pumps have undergone substantial analysis and field testing and can be considered reliable. Low technology machines are intended to be built with locally available materials and simple tools. Their fabrication and maintenance, on the other hand, are very labor intensive. In a number of cases projects using these designs have been less successful than had been hoped. If such a design is desired, it should first be verified that machines of that type have actually been built and operated successfully.

### 2.2.8 Identifying Suppliers of Machinery

Once a type of machine has been selected, suppliers of the equipment or the designs should be contacted for information about availability of equipment and spare parts in the region in question, references, cost, etc. If the machine is to be built locally, sources of material, such as sheet steel, angle iron, bearings, etc. will have to be identified. Possible machine shops should be visited and their work on similar kinds of fabrication should be examined.

### 2.2.9 Identifying Alternative Power Sources for Water Pumping

There are usually a number of alternatives in any given situation. What might be a good option depends on the specific conditions. Some of the possibilities include pumps using human power (hand pumps), animal power (Persian wheels, chain pumps), internal combustion engines (gasoline, diesel, or biogas), external combustion engines (steam, Stirling cycle), hydropower (hydraulic rams, norias), and solar power (thermodynamic cycles, photovoltaic's).

### 2.2.10 Cost comparison between a wind pump and a diesel pump

In rural Africa, the reason why small diesel engines so often fail is not because of their design is bad, but rather the level of maintenance required for the diesel machines is seldom readily available. The track record of diesel engines in terms of reliability and running costs is below standard. Wind pumps are competitive with diesel pumps for small and medium scale water supply applications, if the wind speed of the least windy month is 3.5m/s.

In remote areas where diesel fuel transport costs are high, wind pumps can be economical at even lower wind speeds, as long as the water level is high. Wind pumps are also economical in many remote cattle posts where small, dispersed water supplies are needed for livestock. Below is a table of cost comparison between a wind pump and a diesel pump:

**Table 2.2: Comparison between a Wind Pump and a Diesel Pump (Cost in US$) (Ref. 9)**

| Item | Diesel pump | Wind pump |
|---|---|---|
| Capital cost | 6000 | 10000 |
| Annual operating and maintenance cost | 250 | 100 |
| Fuel cost | 292 | 0 |
| Discount rate | 10% | 10% |
| Unit cost (US$/cubic meter) | 0.18 | 0.19 |

Assumptions: Lowest monthly wind speed is 3.5 m/s and wind pump output is 20 cubic meters per day at 60 m head. Diesel efficiency is 25% and fuel cost at US$ 0.60 per liter.

### 2.2.11 Evaluation of Economics of the System

For all the realistic options the likely costs should be assessed and a life cycle economic analysis performed. The costs include the first cost (purchase or manufacturing price), shipping, installation, operation (including fuel where applicable), maintenance, spare parts, etc. For each system being evaluated the total useful delivered water must also be determined.

The life cycle analysis takes account of costs and benefits that accrue over the life of the project and puts them on a comparable basis. The result is frequently expressed in an average cost per cubic meter of water. It should be noted that the most economic option is strongly affected by the size of the project. In general, wind energy is seldom competitive when mean winds are less than 2.5 m/s, but it is the least cost alternative for a wide range of conditions when the mean wind speed is greater than 4.0 m/s.

### 2.1.12 Installing the Turbine Machines

Once wind energy has been selected, arrangements should be made for the purchase or construction of the equipment. The site must be prepared and the materials all brought there. A crew for assembly and erection must be secured, and instructed. Someone must be in charge of overseeing the installation to ensure that it is done properly and to check the machine out when it is up. Regular maintenance must be arranged.

# CHAPTER 3:
# TYPES OF WIND MACHINES

## 3.1 INTRODUCTION

A windmill is a machine which converts the energy of wind into rotational energy by means of vanes called sails or blades. Originally windmills were developed for milling grain for food production. In the course of history the windmill was adapted to many other industrial uses.[3] An important non-milling use is to pump groundwater up with wind pumps, commonly known as wind wheels. Windmills used for generating electricity are commonly known as wind turbines (Ref. 10).

The various types of windmills are:

1. **Multiple blade type** – it is the most widely used windmill. It has 15 to 20 blades made from metals sheets. The sail type has three blades made by stitching out triangular pieces of canvas cloth. Both these types run at low speeds of 60 to 80 r.p.m.
2. **Savonius type** – this type of windmill has hollow circular cylinder sliced in half and the halves mounted on vertical shaft with a gap in between. Torque is produced by the pressure difference between the two sides of the half facing the wind. This is quite efficient but needs a large surface area. Characteristics of the savonius rotor are: self-starting, low speed and low efficiency.
3. **Darrieus type** – this windmill needs much less surface area. It is shaped like an egg beater and has two or three blades shaped like aerofoils. Characteristics of the Darrieus rotor are: Not self starting, high speed, high efficiency and potentially low capital cost.

Both the Savonius and Darrieus types are mounted on a vertical axis and hence they can run independently of the direction of wind. The horizontal axis mills have to face the direction of the wind in order to generate power (Ref. 3).

A wind turbine is a machine which converts wind power into rotary mechanical power. A wind turbine has aerofoil blades mounted on the rotor. The wind drives the rotor and produces rotary mechanical energy. Wind turbines can be separated into two types based by the axis in which the turbine rotates. Turbines that rotate around a horizontal axis are more common. Vertical-axis turbines are less frequently used.

Wind speeds for turbines:

1. Cut-in-speed: It is the wind speed at which wind-turbine starts delivering shaft power. For a typical horizontal shaft propeller turbine it may be around 7m/s.
2. Mean wind speed,

$$U_{wm}=\frac{Uw1+Uw2+\cdots+Uwn}{n} \tag{1}$$

3. Rated wind speed: It is the velocity at which the wind-turbine generator delivers rated power.
4. Cut-out wind velocity (furling wind velocity): It is the speed at which power conversion is cut out (Ref. 3).

## 3.2 HORIZONTAL AXIS WIND TURBINES

Horizontal-axis wind turbines (HAWT) have the main rotor shaft and electrical generator at the top of a tower, and must be pointed into the wind. Small turbines are pointed by a simple wind vane while large turbines generally use a wind sensor coupled with a servo motor.

Most have a gearbox, which turns the slow rotation of the blades into a quicker rotation that is more suitable to drive an electrical generator. Since a tower produces turbulence behind it, the turbine is usually pointed upwind of the tower.

Turbine blades are made stiff to prevent the blades from being pushed into the tower by high winds. Additionally, the blades are placed a considerable distance in front of the tower and are sometimes tilted up a small amount. Downwind machines have been built, despite the problem of turbulence, because they don't need an additional mechanism for keeping them in line with the wind, and because in high winds the blades can be allowed to bend which reduces their swept area and thus their wind resistance. Since cyclic turbulence may lead to fatigue failures most HAWTs are upwind machines12th-century windmills.

These squat structures, typically, at least, four bladed, usually with wooden shutters or fabric sails, were developed in Europe. These windmills were pointed into the wind manually or via a tail-fan and were typically used to grind grain. In the Netherlands they were also used to pump water from low-lying land, and were instrumental in keeping its polders dry.

In Schiedam, the Netherlands, a traditional style windmill (the *Noletmolen*) was built in 2005 to generate electricity. The mill is one of the tallest Tower mills in the world, being some 42.5139 ft tall.

### 3.2.1 HAWT advantages

**a)** Variable blade pitch, which gives the turbine blades the optimum angle of attack, allowing the angle of attack to be remotely adjusted gives greater control, so the turbine collects the maximum amount of wind energy for the time of day and season.

**b)** The tall tower base allows access to stronger wind in sites with wind shear. In some wind shear sites, every ten meters up, the wind speed can increase by 20% and the power output by 34%.

**c)** High efficiency, since the blades always moves perpendicularly to the wind, receiving power through the whole rotation. In contrast, all vertical axis wind turbines, and most proposed airborne wind turbine designs, involve various types of reciprocating actions, requiring airfoil surfaces to backtrack against the wind for part of the cycle. Backtracking against the wind leads to inherently lower efficiency.

### 3.2.2 HAWT disadvantages

a) The tall towers and blades up to 90 meters long are difficult to transport. Transportation can now cost up to 20% of equipment costs. Tall HAWTs are difficult to install, needing very tall and expensive cranes and skilled operators.

b) Massive tower construction is required to support the heavy blades, gearbox, and generator.

c) Reflections from tall HAWTs may affect side lobes of radar installations creating signal clutter, although filtering can suppress it.

d) Their height makes them obtrusively visible across large areas, disrupting the appearance of the landscape and sometimes creating local opposition.

e) Downwind variants suffer from fatigue and structural failure caused by turbulence when a blade passes through the tower's wind shadow (for this reason, the majority of HAWTs use an upwind design, with the rotor facing the wind in front of the tower).

f) HAWTs require an additional yaw control mechanism to turn the blades toward the wind.

### 3.2.3 Cyclic Stresses and Vibration

Cyclic stresses fatigue the blade, axle and bearing; material failures were a major cause of to rock through a few degrees, so that the main turbine failure for many years. Because wind velocity often increases at higher altitudes, the backward force and torque on a horizontal-axis wind turbine (HAWT) blade peaks as it turns through the highest point in its circle.

The tower hinders the airflow at the lowest point in the circle, which produces a local dip in force and torque. These effects produce a cyclic twist on the main bearings of a HAWT. The combined twist is worst in machines with an even number of blades, where one is straight up when another is straight down. To improve reliability, teetering hubs have been used which allow the main shaft bearings do not have to resist the torque peaks.

The rotating blades of a wind turbine act like a gyroscope. As it pivots along its vertical axis to face the wind, gyroscopic precession tries to twist the turbine disc along its horizontal axis. For each blade on a wind generator's turbine, recessive force is at a minimum when the blade is horizontal and at a maximum when the blade is vertical. This cyclic twisting can quickly fatigue and crack the blade roots, hub and axle of the turbines.

## 3.3 VERTICAL AXIS WIND TURBINES

Vertical –axis wind turbines (or VAWTs) have the main rotor shaft arranged vertically. Key advantages of this arrangement are that the turbine does not need to be pointed into the wind to be effective. This is an advantage on sites where the wind direction is highly variable. VAWTs can utilize winds from varying directions.

With a vertical axis, the generator and gearbox can be placed near the ground, so the tower doesn't need to support it, and it is more accessible for maintenance. Drawbacks are that some designs produce pulsating torque. Drag may be created when the blade rotates into the wind.

It is difficult to mount vertical-axis turbines on towers, meaning they are often installed nearer to the base on which they rest, such as the ground or a building rooftop. The wind speed is slower at a lower altitude, so less wind energy is available for a given size turbine. Air flow near the ground and other objects can create turbulent flow, which can introduce issues of vibration, including noise and bearing wear which may increase the maintenance or shorten the service life.

However, when a turbine is mounted on a rooftop, the building generally redirects wind over the roof and this can double the wind speed at the turbine. If the height of the rooftop mounted turbine tower is approximately 50% of the building height, this is near the optimum for maximum wind energy and minimum wind turbulence.

### 3.3.1 Advantages of VAWTs

a) A massive tower structure is less frequently used, as VAWTs are more frequently mounted with the lower bearing mounted near the ground.
b) Designs without yaw mechanisms are possible with fixed pitch rotor designs.
c) A VAWT can be located nearer the ground, making it easier to maintain the moving parts.

d) VAWTs have lower wind startup speeds than HAWTs. Typically, they start creating electricity at 6-10 km/h.
e) VAWTs may be built at locations where taller structures are prohibited.
f) VAWTs situated close to the ground can take advantage of locations where hilltops, ridgelines, and passes funnel the wind and increase wind velocity.
g) VAWTs may have a lower noise signature.

### 3.3.2 Disadvantages of VAWTs

a) Most VAWTs produce energy at only 50% of the efficiency of HAWTs in large part because of the additional drag that they have as their blades rotate in the wind.
b) A VAWT that uses guy wires to hold it in place puts stress on the bottom bearing as all the weight of the rotor is on the bearing. Guy wires attached to the top bearing increase downward thrust in wind gusts. Solving this problem requires a superstructure to hold a top bearing in place to eliminate the downward thrusts of gust events in guy wired models.
c) While VAWTs' parts are located on the ground, they are also located under the weight of the structure above it, which can make changing out parts nearly impossible without dismantling the structure if not designed properly.
d) Having rotors located close to the ground where wind speeds are lower due to wind shear, VAWTs may not produce as much energy at a given site as a HAWT with the same footprint or height.
e) Because VAWTs are not commonly deployed due mainly to the serious disadvantages mentioned above, they appear novel to those not familiar with the wind industry. This has often made them the subject of wild claims and investment scams over the last 50 years.

# CHAPTER 4:

# THE POWER IN THE WIND

## 4.1 INTRODUCTION

There are global wind patterns related to large scale solar heating of different regions of the earth's surface and seasonal variations in solar incidence. There are also localized wind patterns due to the effects of temperature differences between land and seas, or mountains and valleys. Wind speed data can be obtained from wind maps or from the meteorology office, even though general availability and reliability of wind speed data is extremely poor in many regions of the world.

However, significant areas of the world have mean wind speeds of above 3m/s which make the use of wind pumps an economically attractive option. It is important to obtain accurate wind speed data for the site in mind before any decision can be made as to its suitability. The power in the wind is proportional to:

a) The area of windmill being swept by the wind
b) The cube of wind speed
c) The air density – which varies with altitude (Ref. 6)

The wind power can be computed by using the concept of kinetics. The windmill works on the principle of converting kinetic energy of the wind to mechanical energy.

"Power density" in moving air is given by;

$$P_w = KU_w^3 \text{ W/m}^2 \quad (2)$$

Where $U_w$ = wind speed in km/hr

$K = 1.3687 \times 10^{-2}$

Theoretically a fraction $\frac{16}{27}$=0.5926 of the power in the wind is recoverable. This is called Gilbert's limit or Betz coefficient. Aerodynamically efficiency for converting wind energy to mechanical energy can be reasonably assumed to be 70 percent. So the mechanical energy available at the rotating shaft is limited to 40 percent or at the most 45 percent of wind energy.

Available wind power ($P_a$) may be given as:

$$P_a = \frac{1}{2} m U^2{}_w = \frac{1}{2}\rho.A.U_w U_w{}^2 = \frac{1}{2}\rho.\frac{\pi}{4}D^2.U_w{}^3$$

$$P_a = \frac{1}{8}\pi\rho D^2 U_w{}^3 \text{ watts} \tag{3}$$

Where ρ=density of air (1,225 kg/$m^3$ at sea level)

D=Diameter (in meters), in horizontal axis aero turbines

This above equation indicates that maximum power available from the wind varies according to square of the diameter of the intercept area (or square of the root diameter) normally taken to be swept area of the aero turbine. Thus, wind machines intended for generating substantial amounts of power should have large rotors and be located in areas of high wind speeds (Ref. 3).

**Total power** of a wind stream is equal to the rate of the incoming kinetic energy of that stream $K.E_i$, or

$$P_{tot} = \dot{m}KE_i = \dot{m}\frac{V_i{}^2}{2g_c} \tag{4}$$

Where $P_{tot}$ = total power, W

$\dot{m}$ = mass-flow rate, kg/s

$V_i$ = incoming velocity, m/s

$g_c$ = conversion factor, 1.0 kg/ ($N.s^2$)

The mass flow rate is given by the continuity equation,

$$\dot{m} = \rho A V_i \tag{5}$$

Where ρ = incoming wind density

A = cross-sectional area of stream, $m^2$

Thus,

$$P_{tot} = \frac{1}{2g_c}\rho A V^3{}_w \tag{6}$$

Therefore, the total power of a wind stream is directly proportional to its density, area, and the cube of its velocity (Ref. 1).

## 4.2 POWER IN THE AREA SWEPT BY THE WIND TURBINE ROTOR

The formula used for calculating the power in the wind is shown below:

$$\mathbf{P_W = \tfrac{1}{2}\,\rho\, A\, V^3} \qquad \textbf{(7)}$$

Where, $\mathbf{P_W}$ is power in watts available in the wind, W

$\boldsymbol{\rho}$ is the air density in kilograms per cubic meter, $kg/m^3$ (about 1.225 $kg/m^3$ at sea level less higher up)

**A** is the swept rotor area in square metes, $m^2$

**V** is the wind speed in meters per second, m/s

The fact that the power is proportional to the cube of the wind speed is very significant. This can be demonstrated by pointing out that if the wind speed doubles then the power in the wind increases by a factor of eight! It is therefore worthwhile finding a site which has a relatively high mean wind speed (Ref. 6).

The windmill extracts energy from moving air by slowing down the wind, and transferring this harvested energy into a spinning shaft, which usually turns an alternator or generator to produce electricity. The power available in the wind that can be harvested depends on two factors i.e. wind speed and the area swept by the propeller blades. There is very little power available in low winds. When wind speeds doubles, the power available increases eight times. The only way to increase the available power in low winds is by sweeping a larger area with the blades. The power available increases by a factor of 4 when the diameter of the blades is doubled. However, there is no way to harvest all of this available energy and turn it into electricity. As per Betz's law, 59.26% is the absolute maximum limit that can be extracted from the available power (Ref. 5).

## 4.3 WIND TURBINE POWER

Although the power equation above gives the power in the wind, the actual power that can be extracted from the wind is significantly less than this figure suggests. The actual power will depend on several factors, such as the type of machine and rotor used, the sophistication of blade design, friction losses, the losses in the pump or other equipment connected to the wind machine, and there are also physical limits to the amount of power which can be extracted realistically from the wind.

It can be shown theoretically that any windmill can only possibly extract a maximum of 59.3% of the power from the wind also known as the Betz limit. In reality, for a wind pump, this figure is usually around 30% to 40% and for a large electricity producing turbine around 45% maximum. So, modifying the formula for 'Power in the wind' we can say that the power that is produced by the wind machine can be given by:

$$\mathbf{P_M = ½C_p \rho A V^3} \quad (8)$$

Where, $\mathbf{P_M}$ is power (in watts) available from the machine

$\mathbf{C_p}$ is the coefficient of performance of the wind machine

It is known that a wind machine will only operate at maximum efficiency for a fraction of the time it is running, due to variations in wind speed. A rough estimate of the output from a wind pump can be obtained using the following equation;

$$\mathbf{P_A = 0.1\ A\ V^3} \quad (9)$$

Where, $P_A$ is the average power output in watts over the year

V is the mean annual wind speed in m/s.

A is the area swept by the rotor (π × Radius squared)

The power required to pump water is proportional to its density (water), acceleration due to gravity, the total pumping head and the volume flow rate of water; expressed in the following formula,

$$\textbf{Power = Density × Gravity × Head ×Flow rate} \quad (10)$$

The power is inversely proportional to the pump efficiency.

## 4.4 MAXIMUM POWER

As discussed above, the total power cannot all be converted to mechanical power (Ref. 1). Consider a horizontal-axis, propeller-type windmill, henceforth to be called a wind turbine, which is the most common type used today. Assuming that the wheel of such a turbine has thickness a-b, that the incoming wind pressure and velocity, far upstream of the turbine, are $P_i$ and $V_i$, and that the exit wind pressure and velocity, far downstream of the turbine, are $P_e$ and $V_e$, respectively. $V_e$ is less than $V_i$ because kinetic energy is extracted by the turbine.

Considering the incoming air between *i* and a as a thermodynamic system, and assuming that the air density remains constant (a good assumption since the pressure and temperature changes are very small compared to ambient), that the change in potential energy is zero, and no heat or work are added or removed between *i* and a, the general energy equation reduces to the kinetic and flow energy terms only. Thus,

$$P_i + \frac{{V_i}^2}{2g_c} = P_a + \frac{{V_a}^2}{2g_c} \tag{11}$$

Or

$$P_i + \rho\frac{{V_i}^2}{2g_c} = P_a + \rho\frac{{V_a}^2}{2g_c} \tag{12}$$

Where, *v* and ρ are the specific volume and its reciprocal, the density, respectively, both considered constant. The above equation is the familiar Bernoulli equation.

Similarly, for the exit region b-e,

$$P_e + \frac{{V_e}^2}{2g_c} = P_b + \frac{{V_b}^2}{2g_c} \tag{13}$$

The wind velocity across the turbine decreases from a to b since kinetic energy is converted to mechanical work there. The incoming velocity $V_i$ does not decrease abruptly but gradually as it approaches the turbine to $V_a$ and as it leaves it to $V_e$. Thus $V_i > V_a$ and $V_b > V_e$, and therefore from the above equations, $P_a > P_i$ and $P_b < P_e$; that is, the wind pressure rises as it approaches, then as it leaves the wheel. Combining these equations gives,

$$P_a - P_b = \left(P_i + \rho\frac{{V_i}^2 - {V_a}^2}{2g_c}\right) - \left(P_e + \rho\frac{{V_e}^2 - {V_b}^2}{2g_c}\right) \tag{14}$$

It is reasonable to assume that, far from the turbine at e, the wind pressure returns to ambient, or $P_e = P_i$ and that the velocity within the turbine, $V_t$, does not change because the blade width a-b is thin compared with the total distance considered, so that

$$V_t \approx V_a \approx V_b \tag{15}$$

Combining the above two equations gives,

$$P_a - P_b = \rho\frac{{V_i}^2 - {V_e}^2}{2g_c} \tag{16}$$

The axial force $F_x$ in the direction of the wind stream, on a turbine wheel with projected area, perpendicular to the stream A, is given by

$$F_x = (P_a - P_b)\, A = \rho A \left(\frac{V_i^2 - V_e^2}{2g_c}\right) \tag{17}$$

This force is also equal to the change in momentum of the wind $\Delta\,(\dot{m}V)/g_c$ where $\dot{m}$ is the mass-flow rate given by

$$\dot{m} = \rho A V_t \tag{18}$$

Thus,

$$F_x = \frac{1}{g_c}\rho A V_t\,(V_i - V_e) \tag{19}$$

Equating equations (17) and (19) gives,

$$V_t = \frac{1}{2}(V_i + V_e) \tag{20}$$

We now consider the total thermodynamic system bounded by *i* and e. The changes in potential energy are, as above, zero, but so are the changes in internal energy ($T_i = T_e$) and flow energy

($P_i v = P_e v$), and no heat is added or rejected. The general energy equation now reduces to the steady-flow work W and kinetic energy terms,

$$W = KE_i - KE_e = \frac{V_i^2 - V_e^2}{2g_c} \tag{21}$$

The power P is the rate of work. Using equation (18),

$$P = \dot{m}\,\frac{V_i^2 - V_e^2}{2g_c} = \frac{1}{2g_c}\,\rho A V_t\,(V_i^2 - V_e^2) \tag{22}$$

Combining with equation (20),

$$P = \frac{1}{4g_c}\,\rho A\,(V_i + V_e)\,(V_i^2 - V_e^2) \tag{23}$$

Equation (22) reverts to equation (20) for $P_{tot}$ when $V_t = V_i$ and $V_e = 0$; that is, the wind comes to a complete rest after leaving the turbine. This, obviously, is an impossible situation because the wind cannot accumulate at turbine exit. It can be seen from equation (23), where $V_e$ is positive in one term and negative in the other, that too low or too high a value for $V_e$ results in reduced power.

There thus is an *optimum exit velocity* $V_{e,\text{ opt}}$ that results in maximum power $P_{\max}$, which is obtained by differentiating $P$ in equation (23) with respect to $V_e$ for a given $V_i$ and equating the derivative to zero, i.e., $dP/dV_e = 0$, which gives;

$$3V_e^2 + 2V_iV_e - V_i^2 = 0$$

This is solved for a positive $V_e$ to give $V_{e,\text{ opt}}$

$$V_{e,\text{ opt}} = \frac{1}{3}V_i \qquad (24)$$

Combining with equation (23) gives $P_{\max}$,

$$P_{\max} = \frac{8}{27}\rho A V_i^{\,3} \qquad (25)$$

The ideal or maximum, theoretical efficiency $\eta_{\max}$ (also called the power coefficient) of a wind turbine is the ratio of the maximum power obtained from the wind to the total power of the wind,

$$\eta_{\max} = \frac{P_{max}}{P_{tot}} = \frac{8}{27g_c}\cancel{\rho A V_i^{\,3}} \text{ x } \frac{2g_c}{\cancel{\rho A V_i^{\,3}}} = \frac{16}{27} = 0.5926 \qquad (26)$$

Therefore, a wind turbine is capable of converting no more than 60 percent of the total power of a wind to useful power (Ref. 1).

## 4.5 ACTUAL POWER

Like steam and gas-turbine blades, wind turbine blades experience changes in velocity dependent upon the blade inlet angle and the blade velocity. Because the blades are long, the blade velocity varies with the radius to a greater degree than steam or gas-turbine blades and the blades are therefore twisted. The maximum efficiency (or power coefficient) given by equation (26) assumes ideal conditions along the entire blade. A rigorous treatment of the power extracted from the wind by a propeller-type wind turbine shows that the power coefficient is strongly dependent on blade-to-wind speed ratio, that it reaches its maximum value of about 0.6 only when the maximum blade speed, i.e., the blade speed at the tip, is some 6 or 7 times the wind speed, and that it drops rapidly at blade tip-to-wind speed ratios below about 2.0 (Ref. 1).

Because a wind turbine cannot be completely closed, and because of spillage and other effects, practical turbines achieve some 50 to 70 percent of the ideal efficiency. The real efficiency $\eta$ is the product of this and $\eta_{\max}$ and is the ratio of actual to total power,

$$P = \eta P_{tot} = \eta \frac{1}{2g_c} \rho A V_i^{\,3} \tag{27}$$

Where η varies between 30 and 40 percent for real turbines (Ref. 1).

## 4.6 FORCES ON THE BLADES

There are two types of forces operating on the blades of a propeller-type wind turbine. They are the *circumferential forces* in the direction of wheel rotation that provide the torque and the *axial forces* in the direction of the wind stream that provide an axial thrust that must be counteracted by proper mechanical design (Ref. 1).

The circumferential force, or torque, T is obtained from

$$\mathrm{T} = \frac{P}{\omega} = \frac{P}{\pi D N} \tag{28}$$

Where, T = torque,

ω = angular velocity of turbine wheel, m/s

D = angular diameter of turbine wheel = $\sqrt{4A/\pi}$ m

N = wheel revolutions per unit time, $s^{-1}$

For a turbine operating at power $P$ from equation (27), the torque is given by

$$T = \eta \frac{1}{8g_c} \frac{\rho D V_i^3}{N} \tag{29}$$

For a turbine operating at maximum efficiency $\eta_{max} = \frac{16}{27}$, the torque is given by $T_{max}$

$$T_{max} = \frac{2}{27} \frac{P D V_i^3}{N} \tag{30}$$

The axial force, or axial thrust, given by equation (17), here is,

$$F_x = \frac{1}{2g_c} \rho A \,(V_i^2 - V_e^2) = \frac{\pi}{8g_c} \rho D^2 \,(V_i^2 - V_e^2) \tag{31}$$

The axial force on a turbine wheel operating at maximum efficiency where $V_e = \frac{1}{3} V_i$ is given by

$$F_{x,\,max} = \frac{4}{9g_c}\,\rho A V_i^2 = \frac{\pi}{9g_c}\,\rho D^2 V_i^2 \tag{32}$$

The axial forces are proportional to the square of the diameter of the turbine wheel, which makes them difficult to cope with in extremely large-diameter machines. There is thus an upper limit of diameter that must be determined by design and economical considerations (Ref. 1).

## 4.7 PRINCIPLES OF WIND ENERGY CONVERSION

There are two primary physical principles by which energy can be extracted from the wind; these are through the creation of either lift or drag force or through a combination of the two. The difference between drag and lift is illustrated by the difference between using a spinnaker sail, which fills like a parachute and pulls a sailing boat with the wind, and a Bermuda rig, the familiar triangular sail which deflects with wind and allows a sailing boat to travel across the wind or slightly into the wind.

Drag forces provide the most obvious means of propulsion, these being the forces felt by an object exposed to the wind. Lift forces are the most efficient means of propulsion but being more subtle than drag forces are not so well understood. The basic features that characterize lift and drag are:

a) Drag is in the direction of air flow.
b) Lift is perpendicular to the direction of air flow.
c) Generation of lift always causes a certain amount of drag to be developed.
d) With a good aerofoil, the lift produced can be more than thirty times greater than the drag.
e) Lift devices are generally more efficient than drag devices.

There are several technical parameters that are used to characterize windmill rotors. The **tip speed** ratio is defined as the ratio of the speed of the extremities of a windmill rotor to the speed of the free wind.

Drag devices always have tip-speed ratios less than one and hence turn slowly, whereas lift devices can have high tip-speed ratios of up to 13:1 and hence turn quickly relative to the wind.

The proportion of the power in the wind that the rotor can extract is termed the coefficient of performance, $C_p$ (also known as the power coefficient or efficiency) and its variation as a function of tip-speed ratio is commonly used to characterize different types of rotor. There is an upper limit of $C_p$ = 59.3%, although in practice real wind rotors have maximum $C_p$ values in the range of 25%-45%.

**Solidity** is usually defined as the percentage of the area of the rotor, which contains material rather than air. High-solidity machines carry a lot of material and have coarse blade angles. They generate much higher starting torque which is the twisting or rotary force produced by the rotor, than low-solidity machines but are inherently less efficient than low-solidity machines. The wind pump is generally of this type.

Low-solidity machines tend to be used for electricity generation. High solidity machines will have a low tip-speed ratio and vice versa.

The choice of rotor is dictated largely by the characteristic of the load and hence of the end use. Some common rotor types and their characteristics are shown in the Table below.

**Table 4.1: Rotor types and characteristics (Ref. 18)**

**Comparison of rotor types**

| Type | Speed | Torque | $C_p$ | Solidity (%) | Use |
|---|---|---|---|---|---|
| **Horizontal axis** | | | | | |
| Multi blade | Low | High | 0.25 - 0.4 | 50 – 80 | Mechanical power |
| Three-bladed aerofoil | High | Low | up to 0.45 | Less than 5 | Electricity production |
| **Vertical axis** | | | | | |
| Panemone | Low | Medium | less than 0.1 | 50 | Mechanical power |
| Darrieus | Moderate | Very low | 0.25 - 0.35 | 10 - 20 | Electricity production |

The high solidity means high starting and running torque and low running speed which is desirable for use with the piston pump.

It is important to match the water pumping demand with the available wind and hence decide upon a suitable rotor size.

To calculate the demand we need to know the following data:

a) The head to which the water is to be pumped - in meters

b) Volume of water to be pumped per day - in meters cubed

For water at sea level the approximate energy requirement can be calculated using the following equation:

$$\mathbf{E = 0.002725 \times volume \times head}$$

The energy is given in kilowatt-hours.

Typically pumping heads can vary between a few meters and 100m or even, occasionally more, whilst the volume of water required can vary from a few cubic meters a day for domestic use to a few hundred cubic meters for irrigation (Ref. 6).

# CHAPTER 5:
# THE ALTERNATOR

## 5.1 PRINCIPLE OF THE ALTERNATOR

A.C. generators or alternators operate on the same fundamental principles of electromagnetic induction as D.C. generators. They also consist of an armature winding and a magnetic field. But there is one important difference between the two. Whereas in d.c. generators, the armature rotates and the field system is stationary, the arrangement in alternators is just the reverse. In their case, standard construction consists of armature windings mounted on a stationary element called *stator* and field windings on a rotating element called *rotor*.

The stator consists of a cast-iron frame which supports the armature core having slots on its inner periphery for housing the armature conductors. The rotor is like a flywheel having alternate *N* and *S* poles fixed to its outer rim. The magnetic poles are excited (or magnetized) from direct current supplied by a d.c. source at 125 or 250 volts. In most cases, necessary exciting or magnetizing current is obtained from a small d.c. shunt generator which is belted or mounted on the shaft of the alternator itself. Because the field magnets are rotating, this current is supplied through two slip-rings. As the exciting voltage is relatively small, the slip-rings and brush gear are of light construction.

When the rotor rotates, the stator conductors (being stationary) are cut by the magnetic flux, hence they have induced e.m.f. produced in them. Because the magnetic poles are alternately *N* and *S,* they induce an e.m.f. and hence current in armature conductors, which first flows in one direction and then in the other. Hence, an alternating e.m.f. is produced in the stator conductors (*i*) whose frequency depends on the number of N and S poles moving past a conductor on one second and (*ii*) whose direction is given by Fleming's Right-hand rule (Ref. 4).

## 5.2 ROTOR

There are two types of rotors used in alternators:

1. Salient-pole type
2. Smooth cylindrical type

### 5.2.1 Salient (or projecting) Pole Type

It is used in low and medium-speed (engine-driven) alternators. It has a large number of projecting (salient) poles having their cores bolted or dovetailed onto a heavy magnetic wheel of cast-iron or steel of good magnetic quality. Such generators are characterized by their large diameters and short axial lengths. The poles and pole-shoes (which cover 2/3 of pole pitch) are laminated to minimize heating due to eddy currents. In large machines, field windings consist of rectangular copper strip wound on edge.

### 5.2.2 Smooth Cylindrical Type

It is used for steam turbine-driven alternators i.e. turbo-alternators which run at very high speeds. The rotor consists of a smooth solid forged steel cylinder having a number of slots milled out at intervals along the outer periphery (and parallel to the shaft) for accommodating field coils. Such rotors are designed mostly for 2-pole (or 4-pole) turbo-generators running at 3600 r.p.m. (or 1800 r.p.m.). Two (or four) regions corresponding to the central polar areas are left unslotted. The central polar areas are surrounded by the field windings placed in slots. The field coils are so arranged around these polar areas that flux density is maximum on the polar central line and gradually falls away on either side. It should be noted that in this case, poles are non-salient i.e. they do not project out from the surface of the rotor. To avoid excessive peripheral velocity, such rotors have very small diameters (about 1 meter or so). Hence, turbo-generators are characterized by small diameters and very long axial or rotor length. The cylindrical construction of the rotor gives better balance and quieter operation and also less windage losses.

## 5.3 STATIONARY ARMATURE

The advantages of having a stationary armature (and a rotating field system) are:

1. The output current can be led directly from fixed terminals on the stator (or armature windings) to the load circuit without having to pass it through brush contacts.
2. It is easier to insulate stationary armature winding for high a.c. voltages which may have as high a value as 30kV or more.
3. The sliding contacts i.e. slip-rings are transferred to the low-voltage, low-power d.c. field circuit which can therefore, be easily insulated.
4. The armature windings can be more easily braced to prevent any deformation being produced by the mechanical stresses set up as a result of short-circuit current and the high centrifugal forces brought into play.

## 5.4 DETAILS OF CONSTRUCTION

### 5.4.1 Stator Frame

In d.c. machines, the outer frame (or yoke) serves to carry the magnetic flux but in alternators, it is not meant for that purpose. Here, it is used for holding the armature stampings and windings in position. Low-speed large-diameter alternators have frames, which because of ease of manufacture, are cast in sections. Ventilation is maintained with the help of holes cast in the frame itself. The provision of radial ventilating spaces in the stampings assists in cooling the machine. Instead of using castings, frames are generally fabricated from mild steel plates welded together in such a way as to form a frame having a box type section (Ref. 4).

### 5.4.2 Stator Core

The armature is supported by the stator frame and is built up of laminations of special magnetic iron or steel alloy. The core is laminated to minimize loss due to eddy currents. The laminations are stamped out in complete rings (for smaller machine) or in segments (for larger machines). The laminations are insulated from each other and have spaces between them for allowing the cooling air to pass through. The slots for housing the armature conductors lie along the inner periphery of the core and are stamped out at the same time when laminations are formed.

The wide open type slot has the advantage of permitting easy installation of form-wound coils and their easy removal in case of repair. But it has the disadvantage of distributing the air-gap flux into bunches or tufts that produce ripples in the wave of the generated e.m.f. The semi-closed type slots are better in this respect, but do not allow the use of form wound coils. The wholly-closed type slots or tunnels do not disturb the air-gap flux but (*i*) they tend to increase the inductance of the windings (*ii*) the armature conductors have to be threaded through thereby increasing initial labour and cost of winding and (*iii)* they present a complicated problem of end connections. Hence, they are rarely used.

### 5.4.3 Windings

#### 5.4.3.1 Damper Windings

Most of the alternators have their pole-shoes slotted for receiving copper bars of a grid or damper winding (also known as squirrel-cage winding). The copper bars are short-circuited at both ends by heavy copper rings. These dampers are useful in preventing the hunting (momentary speed fluctuations) in generators and are needed in synchronous motors to provide the starting torque. Turbo-generators usually do not have these damper windings because the solid field poles themselves act as efficient dampers.

### 5.4.3.2 Armature Windings

The armature windings in alternators are different from those used in d.c. machines. The d.c. machines have closed circuit windings but alternator windings are open in the sense that there is no closed path for the armature currents in the winding itself. One end of the winding is joined to the neutral point and the other is brought out (for a star-connected armature).

The two types of armature windings most commonly used for 3-phase alternators are:

a) Single-layer winding - it is variously referred to as concentric or chain winding. Sometimes, it is of simple bar type or wave winding.
b) Double-layer winding – this winding is either of wave-wound or lap-wound type (this being common especially for high-speed turbo-generators). It is the simplest and most commonly used not only in synchronous machines but in induction motors as well.

Short-pitched coils (winding) are deliberately used because of the following advantages:

a) They save copper of end connections.
b) They improve the wave-form of the generated e.m.f. i.e. the generated e.m.f. can be made to approximate to a sine wave more easily and the distorting harmonics can be reduced or totally eliminated.
c) Due to elimination of high frequency harmonics, eddy current and hysteresis losses are reduced thereby increasing the efficiency.

But the disadvantage of using short-pitched coils is that the total voltage around the coils is somewhat reduced. Because the voltages induced in the two sides of the short-pitched coil are slightly out of phase, their resultant vectorial sum is less than their arithmetical sum.

The pitch factor or coil-span factor $k_p$ or $k_c$ is defined as,

$$k_p = \frac{\text{vector sum of the induced e.m.fs per coil}}{\text{arithmetic sum of the induced e.m.fs per coil}} \tag{33}$$

$k_p$ is always less than unity.

## 5.5 SPEED AND FREQUENCY

In an alternator, there exists a definite relationship between the rotational speed ($N$) of the rotor, the frequency (f) of the generated e.m.f. and the number of poles $P$. The conductor being situated at the place of maximum flux density will have maximum e.m.f. induced in it.

When the conductor is in interpolar gap, it has minimum e.m.f. induced in it because flux density is minimum there. When the conductor is at the centre of a pole, it has maximum e.m.f. induced in it because flux density is maximum. One cycle of e.m.f. is induced in a conductor when one pair of poles passes over it. In other words, the e.m.f. in an armature conductor goes through one cycle in angular distance equal to twice the pole pitch.

Since one cycle of e.m.f. is produced when a pair of poles passes over a conductor, the number of poles of e.m.f produced in one revolution of the rotor is equal to the number of poles,

Let, $P$ = total number of magnetic poles

$N$ = rotative speed of the rotor in r.p.m.

$f$ = frequency of generated e.m.f. in Hz

Therefore, Number of cycles/revolution = $\frac{P}{2}$

Number of revolutions/second = $\frac{N}{60}$

$$\text{Frequency} = \frac{P}{2} \text{ x } \frac{N}{60} = \frac{PN}{120} \text{ Hz} \tag{34}$$

$N$ is known as the synchronous speed, because it is the speed at which the alternator must run in order to generate an e.m.f. of the required frequency. In fact, for a given frequency and given number of poles, the speed is fixed (Ref. 4).

## 5.6 INDUCED E.M.F.

Let, $Z$ = number of conductors or coil sides in series/phase

$Z = 2T$ – where $T$ is the number of coils or turns per phase (one turn/coil has two sides)

$P$ = number of poles

$f$ = frequency of induced e.m.f. in Hz

$\Phi$ = flux/pole in Weber's

$k_d$ = distribution factor = $\frac{\sin m\beta/2}{m\sin\beta/2}$

$k_c$ *or* $k_p$ = pitch or coil span factor = $\cos\frac{\propto}{2}$

$k_f$ = form factor = 1.11 ( if e.m.f. is assumed sinusoidal)

$N$ = rotative speed of the rotor in r.p.m.

In one revolution of the rotor (i.e. in 60/$N$ second) each stator conductor is cut by a flux of $\Phi P$ webers. Therefore,

$d\Phi = \Phi P$ and $dt = 60/N$ second

Average e.m.f. induced per conductor = $\frac{d\Phi}{dt} = \frac{\Phi P}{60/N} = \frac{\Phi NP}{60}$

We know that

$f = \frac{PN}{120}$ or $N = \frac{120f}{P}$

Substituting this value of $N$ above, we get

Average e.m.f. per conductor = $\frac{\Phi P}{60}$ x $\frac{120f}{P}$ = $2f\,\Phi$ volt

If there are Z conductors in series/phase, then

Average e.m.f./phase = $2f\Phi Z$ volt = $4f\Phi T$ volt

R.M.S value of e.m.f./phase = 1.11 x $4f\Phi T$ = $4.44\, f\, \Phi T$ volt

This would have been the actual value of the voltage induced if all the coils in a phase were (*i)* full-pitched and (*ii*) concentrated or bunched in one slot (instead of being distributed in several plots under poles). But this not being so, the actually available voltage is reduced in the ratio of these two factors ($k_c$ *and* $k_d$) (Ref. 4).

Actually available voltage/phase = $4.44\, k_c\, k_d\, f\, \Phi T = 4k_f\, k_c\, k_d\, f\, \Phi T$ volt

# CHAPTER 6:
# PUMPING WATER BY USE OF WIND TURBINES

A borehole may not always be positioned at a location where the wind is strong enough and hence the use of a turbine to produce electricity to run the pump may become important. In order to determine if one should use a wind pump or turbine, one should first, figure out the direction from which the prevailing winds in that area usually come.

This can be determined by observation during wind storms, and by looking at the trees near the site. Trees that are all leaning the same direction and that have branches mostly on one side of the trunk are a good indication of prevailing wind speed and direction.

Local airports and weather stations can sometimes provide this information. If the site experiences a mean wind speeds of less than 3 m/s then having a turbine instead would be recommended since the turbine doesn't have to be placed at that particular site.

This system has several advantages namely:

a) The wind turbine can be placed some distance from the borehole where the wind speeds are good, and the electricity it generates be used to drive the pump at the borehole.
b) Unlike mechanical windmills, these systems require no scheduled maintenance.
c) These systems are capable of pumping higher water volumes for say, a community water supply or small plot irrigation.

Wind-electric pumping systems are much less costly to install than solar pumping systems which are much less costly to operate than diesel pump systems.

This system usually consists of a wind turbine, a permanent magnet synchronous generator, an induction motor and a centrifugal water pump.

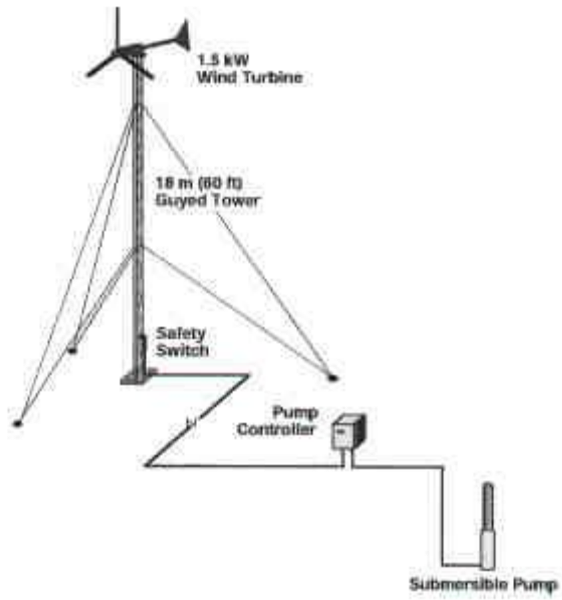



**Fig 6.1: A wind turbine connected to a submersible pump (Ref. 18)**

## 6.1 THE WIND TURBINE ROTOR

The three bladed rotor is the most important and most visible part of the wind turbine. It is through the rotor that the energy of the wind is transformed into mechanical energy that turns the main shaft of the wind turbine.

The front and rear sides of a wind turbine have a shape roughly similar to that of a long rectangle, with the edges bounded by the leading edge, the trailing edge, the blade tip and the blade root. The blade is bolted to the hub.

The first step in the installation of a wind turbine is to figure out what size of the turbine will be needed, whether it is for domestic or commercial water pumping needs. The main measure of the windmill size is the swept area.

The available power from the wind increases dramatically with the swept area, but so do the stresses on the blades, tower, bearings, and tail. More stress means stronger engineering materials are required, and a much larger, more complicated and expensive project.

The air flow around a wind turbine blade is completely dominated by the head wind from the rotational movement of the blade through the air. The blade aerodynamic profile produces lift because of its streamlined shape. The rear side is more curved than the front side.

The lift effect on the blade aerodynamic profile causes the forces of air to point in the right direction.

The blade width, thickness and twist are a compromise between the need for streamlining and strength.

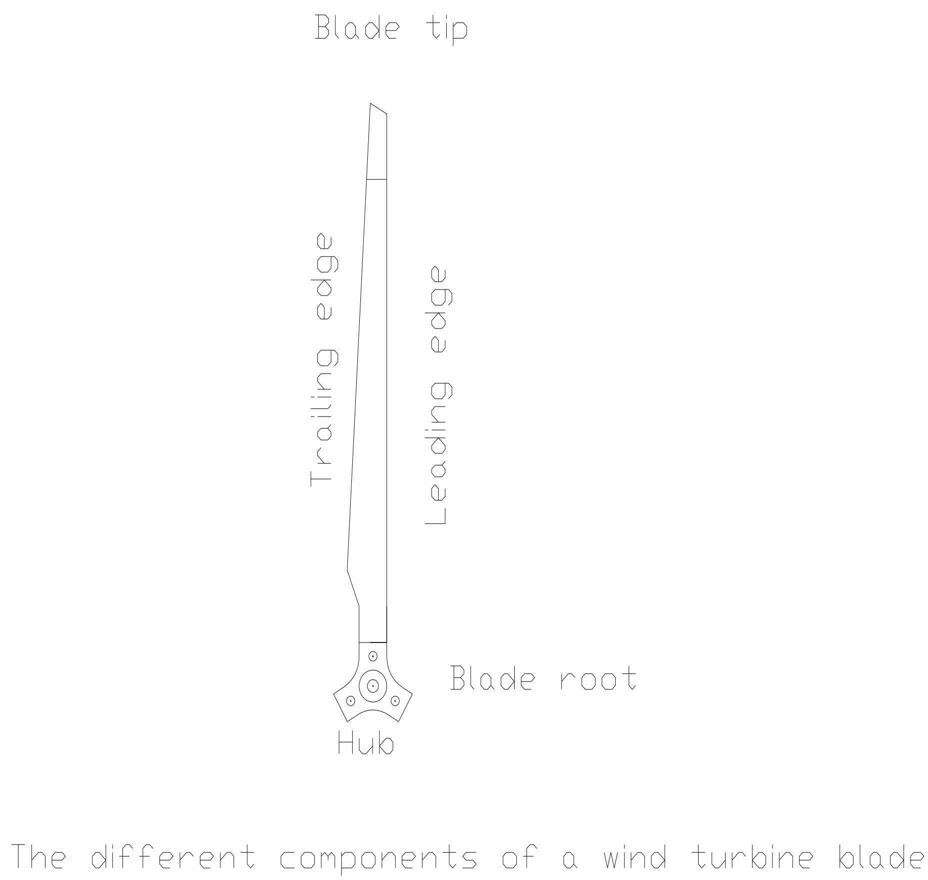



**Fig 6.2: The Different Components of a Wind Turbine Blade (Ref. 13)**

## 6.2 BLADE THEORY

A windmill gets its power from the wind. The blades slow it down, and the alternator collects the power. Both must be correctly matched to work together efficiently. The blades mechanically produce power to drive the alternator. The alternator converts this into electrical power. The power in the wind blowing through the rotor is given by this formula:

$$\frac{1}{2} \text{ x air-density x swept-area x (wind speed)}^3 \quad (35)$$

Since the blades can only convert at best half about 25-35% of the winds total power into mechanical power, so a simple thumb rule is;

$$\text{Blade power} = 0.15 \text{ x Diameter}^2 \text{ x Windspeed}^3 \quad (36)$$

**Blade Material –** Soft seasoned wood, which is strong and light, is the most appropriately suited material for blades. Cheap fiber reinforced plastic (FRP) is an ideal substitute for wood especially to cater for longevity and durability.

**Fig 6.3: A sample diagram showing a three bladed aerofoil (Horizontal axis wind turbine) (Ref. 5)**

**Diameter –** If the blades are too short, the alternator will not spin at desired speed to produce sufficient power. Likewise, blades that are too big may burn the alternator, or virtually runaway in a gale wind condition.

**Tip Speed Ratio (TSR) –** The rotor blades need to be designed keeping in mind the speed relative to the wind. This relationship is termed as **TSR**. This is a number, which defines how much faster than the wind speed the tips of propeller blades are designed to travel i.e. the speed the blade tips travel divided by the wind speed at that time. In some cases some tips of blades move faster than the wind by a ratio of as much as 10 times which leads to a speed of more than 200 mph, thereby resulting in noisy operation and rapid erosion of blade edges. A figure of 7 is considered as a reasonable value of TSR (Ref. 5).

$$\text{RPM} = \frac{\text{wind speed x 60 x TSR}}{\text{circumference}} \tag{37}$$

Where RPM = revolutions per minute

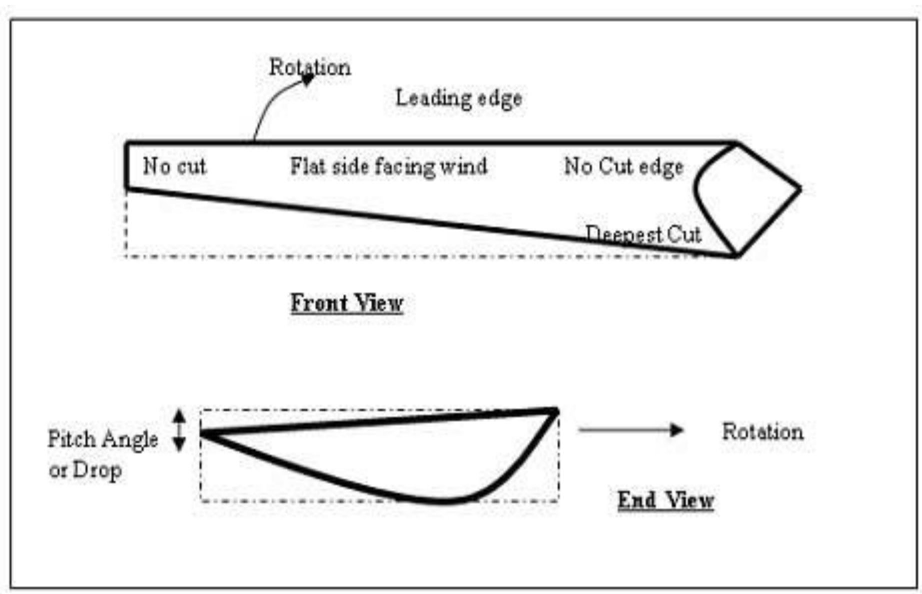



**Fig 6.4: Turbine Blade View (Ref. 5)**

**Blade Carving –** It is a simple carving process i.e. marking the cut-depth at the trailing edge at both the root and the tip and then using the basic carpentry tools available in the local carpentry shops.

**Balancing –** The blades have to be very well balanced to present any vibrations. But generally perfection can be achieved by using a normal weighing scale to ensure that each blade weighs exactly the same, and that each has the same centre of balance. Excess material from the heavy areas can be removed. The weight distribution can be adjusted by attaching some lead strips to the blade root (Ref. 5).

## 6.3 THE TRANSMISSION SYSTEM

The transmission is made up of components that connect the wind turbine rotor to the generator. These include:

a) The Hub
b) The main shaft
c) The Main bearings
d) The Clamping Unit
e) The Gearbox and
f) The Coupling

### 6.3.1 The Hub

The blades of the turbine are usually bolted to the hub. Older models had a flange joint where the glass fiber is molded out in a ring with steel bushes for bolts. Newer wind turbines have threaded bushes glued into the blade root itself. In both cases, bolts from the blade pass through the flange on the cast hub. The flange bolt-holes are elongated, enabling the blade tip angle to be adjusted.

The hub is cast on a special type of strong iron alloy; Cast Iron. This is because, the hub having a complicated shape, is difficult to make in any other way. A welded construction would also not be so appropriate since the hub must be highly resistant to metal fatigue, which may not be achieved by welding.

Cast Iron has a high carbon content which allows it to melt easily and thus easily flow into the casting form. The high carbon content makes it very brittle, therefore silicon has to be added to it during casting and heat treatment done after casting so as to achieve higher strength.

### 6.3.2 The Main Shaft

The main shaft of the wind pump is usually forged from hardened and tempered steel. Hardening and tempering is a result of forging the axle after it has been heated until its white hot at about 1000 degrees centigrade. By hammering or rolling the blank is formed with an integral flange, to which the hub is latter bolted.

The shaft is reheated a final time to a glowing red, following the forging process, and the plunged into a basin of oil or water. This treatment gives a very hard, but at the same time rather brittle surface. Therefore the axle is once again reheated to about 500 degrees centigrade, tempering the metal and thereby enabling the metal to regain its former strength.

### 6.3.3 The Main Bearings

All modern wind turbines have spherical roller bearings as main bearings. These spherical bearings have two sets of rollers, allowing for both absorption of radial loads from the weight of the rotor and the large axial force along the shaft resulting from the wind pressure on the rotor.

The main bearings are mounted in the bearing housings bolted to the main frame. They are always lubricated by greasing.

Sealing of the bearing housing is insured by the use of a labyrinth packing. No rubber sealing is used; the labyrinth with its long and narrow passage way prevents grease from escaping. Water and dirt are prevented from entering from the outside by the long passageways filled with grease, which is constantly and slowly trying to escape from the bearing.

The labyrinth maybe more expensive than rubber to use for sealing but its advantage is that the seal is not subject to wear, and under normal conditions it is a safe method to keep out pollutants that would otherwise in a short time could ruin roller bearings.

### 6.3.4 The Clamping Unit

By means of a clamping unit, the main shaft of the wind turbine is coupled to the gearbox. The gear has a hollow shaft that fits over the rear end of the main shaft. Torque between the two components is transferred by friction between the two.

A clamping unit, normally composed of inner ring and two outer rings with conical facings, is placed on the outside of the gear's hollow shaft. When the main shaft is placed inside the hollow shaft during the assembly of the wind turbine, the conical facings of the clamping unit are loosely positioned on the hollow shaft.

Following the control of the correct alignment of the gear and the main shaft, the rings are tightened by means of a large number of bolts. The outer rings are thereby pressed together, while the inner ring, positioned on the hollow shaft is pressed inwards under the tightening of the bolts.

The inner ring now presses hard against the hollow shaft that the inner part of the hollow shaft is in turn pressed hard against the main shaft. It is because of this pressure that the torque is transferred fro the main shaft to the wind turbine gear hollow shaft. It is like the hollow shaft is shrunk-fitted on the main shaft as a result of the pressure from the clamping unit.

Transferred torque is dependent upon friction between the main shaft and the hollow shaft. It is therefore vital that the components are carefully cleaned and completely dry before assembly, otherwise they would slip during strong wind conditions.

### 6.3.5 The Gearbox

This is usually placed between the main shaft and the generator and its main task is to increase the slow rotational speed of the rotor blades to the high generator rotation speeds which could be up to 1000 to 1500 revolutions per minute.

The gear consists of two sets of toothed gear wheels, the slow speed and the high speed stage. In the low speed stage, the larger gear wheel is mounted directly on the gears hollow shaft, while the smaller gear is machined directly on the intermediate shaft.

The difference in the size of the wheels is 1:5. When the two ratios are combined, the output shaft will turn 25 times for every rotation of the hollow shaft and the main shaft of the wind turbine combined. Normally the ratio in every set of gear is restricted to about less than 1:6.

Wind turbines which are meant to produce 450 kilowatts and above use epicyclic gears to achieve high generator speeds.

The teeth of the gears are usually case hardened so as to give them surface strength, while the inner material still has ductile properties.

### 6.3.6 The Coupling

The coupling is placed between the gearbox and the generator. It is always a flexible unit made from built in pieces of rubber, normally allowing variations of a few millimeters only. This flexibility allows for some slight differences in alignment between the gearbox and the generator since both the gearbox and the generator have tendencies of slight movement in relation to each other.

## 6.4 THE GENERATOR

This is the unit that transforms mechanical energy into electrical energy. This electrical energy can either be in form of direct current or alternating current depending on the settings of the generator.

Wind turbine generators are a bit unusual, compared to other generating units ordinarily found attached to the electrical grid. One reason is that the generator has to work with a power source which supplies very fluctuating mechanical power.
Generators need cooling while they work. On most turbines this is accomplished by encapsulating the generator in a duct, using a large fan for air cooling, but a few manufacturers use water cooled generators. Water cooled generators may be built more compactly, which also gives some electrical efficiency advantages, but they require a radiator in the nacelle to get rid of the heat from the liquid cooling system.

## 6.5 CONTROL AND SAFETY SYSTEMS

Control and safety systems comprise many different components. Common for all these is that combined together they are part of a more comprehensive system, ensuring that the wind turbine is operated satisfactorily and preventing possible dangerous situations from arising.

Normally the period between normal qualified maintenance for a wind turbine is 6 months, and so between these 6 months the control system of the wind turbine must function trouble free whether the wind turbine is in operation or not. A wind turbine should be able to look after itself and in addition have the ability to register faults and retrieve this stored information concerning any special occurrence, should things possibly not go exactly quite as planned.

A wind turbine if not controlled will spontaneously over speed during high wind periods. Without prior control it can then be almost impossible to bring to a stop. During high winds, a turbine can produce a much higher yield than its rated power. The wind turbine blade rotational speed is therefore restricted, and the wind turbine maintained at the rated power, by the grid connected to the generator.

Should the grid connection be lost, by reason of a power failure or if the generator for some other reason is disconnected, while the wind turbine is in operation, the wind turbine would immediately start to rapidly accelerate. The faster the speed the more power it is able to produce. The wind turbine is therefore said to be in 'run away' condition.

There are two methods to prevent a run away, namely:

a) The blade can be prevented from being able to achieve increased power production under this condition of rapidly accelerating blade rotational speed.
b) By other means prevent the rotational speed from rising to an unacceptable dangerous level.

These two can be done by use of principles of aerodynamic braking and use of the mechanical blade.

### 6.5.1 The Controller

The controller is involved in almost all decision making processes in the safety systems in a wind turbine. At the same time it must oversee the normal operation of the wind turbine and carry out measurements for statistical use. The controller is based on the use of a micro computer, specially designed for industrial use and therefore not compatible with a normal pc. It has a capacity roughly equivalent to that of a 80286 system processor. The control program is stored in a microchip called EPROM. The processor does the actual calculations and likewise is a microchip.

The controller measures the following parameters as analogue signals:

a) Voltage
b) Current
c) Frequency of one phase
d) Temperature inside the nacelle
e) Gear oil temperature
f) Gear bearing temperature
g) Wind speed
h) The direction of yawing
i) Low speed shaft rotational speed
j) High speed shaft rotational speed

Other parameters like electrical power are not measured since they can be calculated from the above parameters.

The Controller also measures the following parameters as digital signals:

a) Wind direction
b) Overheating of the generator
c) Hydraulic pressure level
d) Correct valve friction
e) Vibration level
f) Twisting of the power cable
g) Emergency brake circuit
h) Brake caliper adjustment
i) Centrifugal release activation.

The computer is equipped with certain control functions that supervise the computer not to make obvious calculation errors. In addition the wind software itself has extras to control functions like stopping the wind turbine should the wind speeds exceed the safe speeds.

The other safety principle of the controller lies in the duplication of systems, like the mechanical centrifugal release systems. These supervise the blade rotational speed and activate the braking systems, even if the speed measurement system of the controller should fail. The controller decides which operations are to be carried out while the hydraulic system operates the braking systems.

# CHAPTER 7:
# SOLAR ENERGY

## 7.1 SOLAR ENERGY RESOURCE IN KENYA

Most parts of Kenya enjoy a tropical climate but the temperature remains comfortably warm averaging about 22 ◦C throughout the year. It is relatively hot and humid at the coast, temperate inland and very dry in the north and northeast parts of the country. Some parts of the country experience an equatorial kind of climate especially the central highlands. There is plenty of sunshine all the year round; however, it is usually cool at night and early in the morning. The hottest period is from February to March and coldest from July to August. The average annual temperature for the coastal town of Mombasa (altitude 17 m) is 30 ◦C maximum and 22.4 ◦C minimum, the capital city, Nairobi (altitude 1661 m) 25.5 ◦C maximum and 13.6 ◦C minimum, Eldoret (altitude 2133) 23.6 ◦C maximum and 10.6 ◦C minimum, Lodwar (altitude 506 m) and the drier north plain lands 35.5 ◦C maximum and 24.3 ◦C minimum.

Kenya being astride the equator and extending four degrees on either side, receives a considerable amount of solar radiation, between 4 and 6 kwh/$m^2$/day. The country's annual average is about 5kwh/$m^2$/day, equivalent to 250 million tones of oil equivalent per day (ref: kiplagatetal2011). The **Table 1** below gives the annual average Direct Normal Irradiation and the analyzed spatial areas, whereas the **figure 1** below shows the annual sum of hourly Direct Normal Irradiation (DNI), averaged for the year 2000–2002.

**Table 7.1: Analysis of direct normal irradiation (DNI) available in Kenya (Ref. 15)**

| DNI (kW/m2/day) | Area (km2) |
|---|---|
| 3.50–3.75 | 41721 |
| 3.75–4.00 | 61515 |
| 4.00–4.25 | 140326 |
| 4.25–4.50 | 177347 |
| 4.50–4.75 | 137572 |
| 4.75–5.00 | 96199 |
| 5.00–5.25 | 62364 |
| 5.25–5.50 | 48826 |
| 5.50–5.75 | 33848 |
| 5.75–6.00 | 20211 |
| 6.00–6.25 | 24675 |
| 6.25–6.50 | 33690 |
| 6.50–6.75 | 22468 |
| 6.75–7.00 | 16240 |
| 7.00–7.25 | 6736 |

Kenya has high insolation rates with an average of 5 peak sunshine hours (The equivalent number of hours per day when solar irradiance averages 1000 W/m2). The total amount of energy ranges from 700 kWh in mountainous regions to 2650 kWh in arid and semi-arid regions per year, with most parts of the country lying in the 1750–1900 kWh range. However, only an insignificant amount out of this vast resource is hitherto harnessed. Diverse application of solar energy include solar thermal for heating and drying and solar photovoltaic (PV) for lighting, water pumping, crop drying, refrigeration and telecommunications.

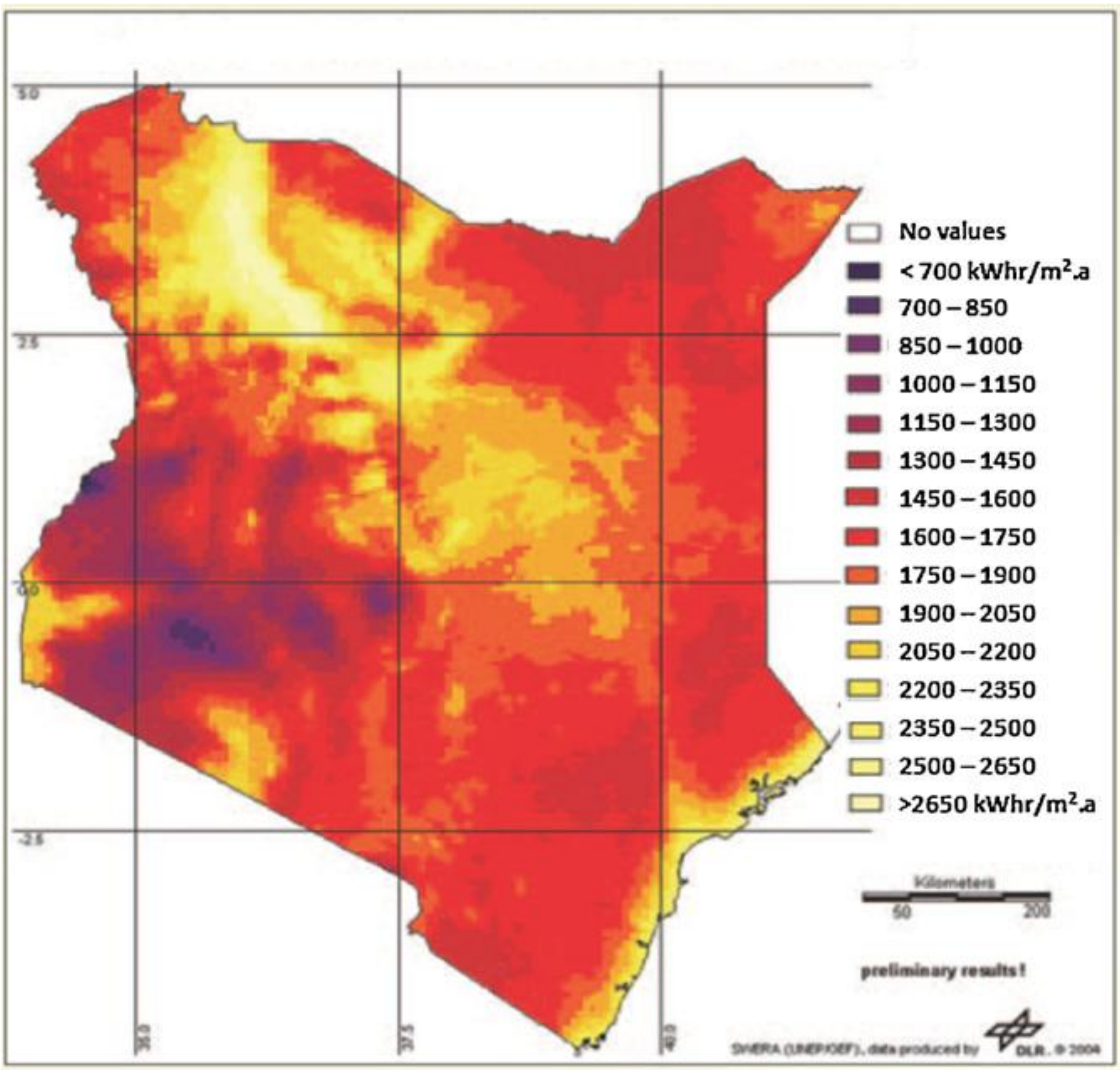



**Fig 7.1: Analysis of direct normal irradiation (DNI) available in Kenya 2000-2002(Ref 15)**

## 7.2 STATUS OF SOLAR ENERGY IN KENYA

A vibrant solar energy market has developed in Kenya over the years for providing electricity to homes and institutions remote from the national grid and for medium temperature water heaters for domestic and commercial usage. Solar electric systems are being imported and sold to end users in Kenya through a competitive and growing free market network that includes more than 10 import and manufacturing companies, as well as hundreds of vendors, installers, and after sale service providers. In 2003, the cumulative sales were estimated to be in excess of 220,000 units (more than 4 MW). On the other hand, about 7000 solar thermal (About 140,000 m2) are in use for drying of agricultural produce and water heating.

The government is currently implementing a solar PV electrification of schools and other institutions in selected districts, which are remote from the national grid as part of a national strategy to enhance the contribution of renewable sources of energy to the overall energy supply mix. By the end of 2009, about 150 public institutions were expected to have installed a total capacity of 360 kW of PV electricity, and the total capacity of all solar PV installations in rural areas of Kenya would be in the order of 6 MW. Despite this success, the percentage contribution of solar energy to the total energy mix is insignificant (less than 1%). Studies sponsored by Ministry of Energy have shown that Kenya holds tremendous potential in solar energy but only a small potion has been tapped.

## 7.3 SOLAR WATER PUMPING IN KENYA

Kenya lies right at the equator and this makes it a good candidate for solar energy applications. Kenya is currently estimated to have 20,000 to 40,000 solar systems installed in private homes and small businesses around the country and still growing at a considerable rate. However, even with these statistics solar usage as a source of energy is still at less than 1% in the country and even a lesser percentage of this is utilized in water pumping. It is sparingly practiced around the country where there are enough funds and capital to put up such projects. This is because of the high initial capital cost of the components of the solar water pumping system-most water pumping systems are powered by windmills which provide a cheaper capital to initialize.

## 7.4 SOLAR WATER PUMPS

A solar water pump is simply any water pump that uses solar energy for its power source. Solar water pumps are specially designed to utilize DC electric power from photovoltaic panels. They must work during low light conditions at reduced power, without stalling or overheating. Solar water pumps have one significant advantage over other types of pumps; they do not require the presence of an electric line in order to operate. This makes them extremely useful in rural locations such as ranches and farms, or in the developing world where electricity is often not available. In many parts of the world the cost of running traditional water piping or an electric line for a pump is cost prohibitive. A solar water pump is a perfect solution to this problem. Because of this they have been used extensively in places in Kenya both for pulling water from wells, providing water for livestock and domestic use.

They have become extremely popular for rural and agricultural well pumping and are starting to replace many pumps that were originally operated by wind mills. Many rural homes in Kenya rely on community well water and solar pumps can be a convenient approach for keeping their water tanks full.

Solar pumps are friendlier to the environment and cheaper to operate than conventional AC pumps. By harnessing the energy of the sun they eliminate the need to use traditional fuel sources such as oil or coal to generate the electricity they need to operate. This saves money as well, particularly in developing countries where electricity is both scarce and expensive. Also, because they eliminate the need for digging ditches for electric lines or putting up power line poles, they are less disruptive to the natural environment.

## 7.5 SOLAR PANELS FOR PUMPS

Solar pumps get their power from solar panels. The type of solar panels you would use is no different than the kind that might be put on a roof in a residential solar electric system. Solar panels come in many different sizes. Generally the larger they are the more watts of electricity they can generate. The smallest element of a PV panel is the solar cell. Each solar cell has two or more specially prepared layers of semiconductor material that produce direct current (DC)electricity when exposed to light. This DC current is collected by the wiring in the panel. It is then supplied either to a DC pump, which in turn pumps water whenever the sun shines, or stored in batteries for later use by the pump. Manufacturers normally rate voltage (volts) and current (amps) output from PV panels under peak power conditions.

Peak power (watts= volts x amps) is the maximum power available from the PV panel at 1000 $W/m^2$ solar irradiance (amount of sunshine) and a specified temperature, usually 25C (77 F). Typical output from a 60-watt PV panel is shown in Table 7.2. The amount of DC current produced by a PV panel is much more sensitive to light intensity striking the panel than is voltage generated. Roughly speaking, if you halve the light intensity, you halve the DC current output, but the voltage output is reduced only slightly.

**Table 7.2: Typical output from a 60-watt, 12-volt photovoltaic panel (Ref. 20)**

| | |
|---|---|
| Maximum Power | 60 Watts |
| Maximum Power Voltage | 16.9 Volts |
| Maximum Power Current | 3.55 Amps |

Individual PV panels can be wired in series or parallel to obtain the required voltage or current needed to run the pump. The voltage output from panels wired in series is the sum of all the voltages from the panels. For example, the maximum voltage output from two of the 12-volt PV panels shown in Table 1 wired in series is 33.8 volts. Thus, a 24-volt DC pump requires a minimum of two, 12-volt panels wired in series. The current (amps) output from these same panels wired in series is equal to the current (amps) output from an individual panel, 3.55 amps. The voltage and current output from panels wired in parallel is the exact opposite of series-wired panels. For panels wired in parallel, the current (amps) output is the sum of all the currents (amps) from the panels and the voltage is equal to the voltage output from an individual panel.

The number of watts you will need to generate, and therefore the number of solar panels you will need for your pump, depends upon the size of the pump and what you are going to use it for. For example, when using solar panels with submersible well pumps the number of panels you will need depends greatly upon the depth of the well -- the deeper the well, the more power needed, and therefore the more solar panels needed.

You can turn almost any pump into a solar powered water pump but pumps that are designed specifically to run on solar power are very energy efficient. That translates into, cost efficient, even though initially, they'll cost more. Conventional 110 volt AC model pumps are inefficient and require so much energy to start and run that they are mostly impractical to use with solar panels. Most DC pumps are fairly small and only require a single solar panel. The solar pump kit manufacturer will have properly matched the solar panels output to the power requirements of the pump. The main thing is to be sure that you don't exceed the maximum voltage the pump can handle.

Many low volume solar pumping systems use positive displacement (volumetric) pumps that seal water in cavities inside the pump and force it upward. Their design enables them to maintain their lift capacity all through the solar day at the slow, varying speeds that result from varying light conditions. Positive displacement pumps include piston and jack pumps, diaphragm, vane and screw pumps. Lift capacity is maintained even while pumping slowly. These mechanisms include diaphragm, vane and piston pumps. These differ from a conventional centrifugal pump that needs to spin fast to work efficiently. Centrifugal pumps are used where higher volumes are required.

Most solar pumping systems use water storage rather than batteries, for simplicity and economy. Depending on the application, a solar pumping system may use a water storage tank, which acts like a “Water Battery” during cloudy weather. A float switch can turn the pump off when the water tank fills, to prevent overflow. Compared with windmills, solar pumps are less expensive, and much easier to install and maintain. They provide a more consistent supply of water. They can be installed in valleys and wooded areas where wind exposure is poor. A PV array may be placed some distance away from the pump itself, even several hundred feet (100 m) away.

The smallest solar pumps require less than 150 watts, and can lift water from depths exceeding 200 Feet (65 m) at 1.5 gallons (5.7 liters) per minute. In a 10-hour sunny day a solar pump can lift 900 gallons (3400 liters). That's enough to supply several families, or 30 head of cattle. Slow solar pumping lets us utilize low-yield water sources. It also reduces the cost of long pipelines, since small-sized pipe may be used.

Without a battery, solar powered pumps will work as long as the sun strikes the solar panel. When the sun shines brightly and is directly overhead the pump will work to its optimum ability (given that the panel is sized correctly for the pump). If a cloud passes overhead and temporarily occludes the sun from the panel, the pump will either slow down or stop completely. Fortunately, for most solar powered water pump applications that's more than enough.

There's a significant cost to adding batteries to a system. Aside from being expensive (often costing more than the rest of the system) and requiring more maintenance than any other component of your solar pumping station, routing the energy through batteries decreases the operating voltage which ultimately reduces the pump's flow rate. Also, batteries like to be sheltered and function most favorably when maintained at certain temperature levels. And no matter how well you maintain most batteries they will have to be replaced every 5 years or so. When using a solar power pump for critical operations or where seasonal fluctuations of sunlight hours will affect active pumping time, a battery backup or other source of energy should be considered to ensure necessary operations.

## 7.6 SOLAR-POWERED WATER PUMPING SYSTEM CONFIGURATIONS

There are two basic types of solar-powered water pumping systems, battery-coupled and direct-coupled. A variety of factors must be considered in determining the optimum system for a particular application.

### 7.6.1 Battery-Coupled Solar Pumping Systems

Battery-coupled water pumping systems consist of photovoltaic (PV) panels, charge control regulator, batteries, pump controller, pressure switch and tank and DC water pump (Figure 2 ). The electric current produced by PV panels during daylight hours charges the batteries, and the batteries in turn supply power to the pump anytime water is needed. The use of batteries spreads the pumping over a longer period of time by providing a steady operating voltage to the DC motor of the pump. Thus, during the night and low light periods, the system can still deliver a constant source of water for livestock.

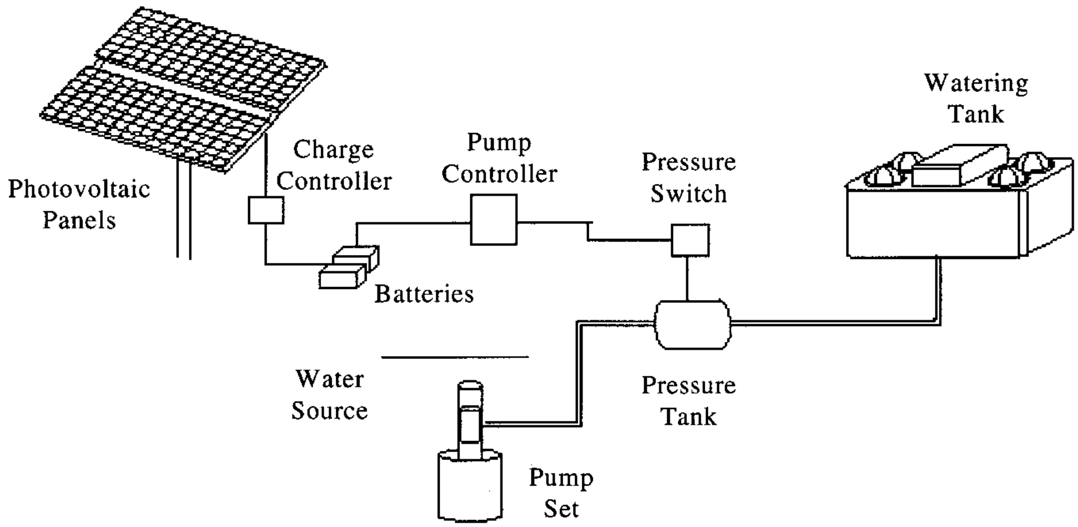



**Fig 7.2: Battery-coupled solar water pumping system (Ref. 16)**

As mentioned before, the use of batteries has its drawbacks. First, batteries can reduce the efficiency of the overall system because the operating voltage is dictated by the batteries and not the PV panels. Depending on their temperature and how well the batteries are charged, the voltage supplied by the batteries can be one to four volts lower than the voltage produced by the panels during maximum sunlight conditions. This reduced efficiency can be minimized with the use of an appropriate pump controller that boosts the battery voltage supplied to the pump.

## 7.6.2 System Components

### 7.6.2.1 Pump Controller

The primary function of a pump controller in a battery-coupled pumping system is to boost the voltage of the battery bank to match the desired input voltage of the pump. It enables solar pumps to operate more efficiently in low sunlight conditions and provides input points for float switch and water level sensors. Without a pump controller, the PV panels' operating voltage is dictated by the battery bank and is reduced from levels which are achieved by operating the pump directly off the solar panels. For example, under load, two PV panels wired in series produce between 30 to 34 volts, while two fully charged batteries wired in series produce just over 26 volts. A pump with an optimum operating voltage of 30 volts would pump more water tied directly to the PV panels than if connected to the batteries. In the case of this particular pump, a pump controller with a 24-volt input would step the voltage up to 30 volts, which would increase the amount of water pumped by the system.

#### 7.6.2.2 Charge Control Regulators

Solar panels that are wired directly to a set of batteries can produce voltage levels sufficient enough to overcharge the batteries. A charge control regulator should be installed between the PV panels and the batteries to prevent excessive charging. Charge controllers allow the full current produced by the PV panels to flow into the batteries until they are nearly fully charged. The charge controller then lowers the current, which trickle charges the battery until fully charged. The regulator installed should be rated at the appropriate system voltage (i.e., 12-volt, 24-volt, etc.) and the maximum number of amperes the solar panels can produce. The regulator should be installed near the batteries, in accordance with the manufacturer's instructions.

#### 7.6.2.3 Batteries

The most common batteries used in stand-alone PV systems are lead-acid batteries. They are rechargeable, easily maintained, relatively inexpensive, available in a variety of sizes and most will withstand daily discharges of up to 80 percent of their rated capacity. Another type of battery using nickel cadmium (NiCd) plates can be used in PV systems. Their initial cost is much higher than lead-acid batteries, but for some applications the life-cycle cost may be lower. Some advantages of NiCd batteries include their long-life expectancy, low maintenance requirements and their ability to withstand extreme conditions. Also, the NiCd battery is more tolerant to complete discharge. It is important to choose a quality battery rated at the required storage capacity.

Shallow-cycle (car batteries) should not be used for PV applications. These batteries are lighter, less expensive and are designed to produce a high-current cold-cranking amp for a short period. The battery is then quickly recharged. Generally, shallow-cycle batteries should not be discharged more than 25 percent of the rated battery capacity. Battery banks are often used in PV systems. These banks are set up by connecting individual batteries in series or parallel to get the desired operating voltage or current. The voltage achieved in a series connection is the sum of the voltages of all the batteries, while the current (amps) achieved in series-connected batteries is equal to that of the smallest battery. For example, two 12-volt batteries connected in series produce the equivalent voltage of a 24-volt battery with the same amount of current (amps) output as a single battery. When wiring batteries in parallel, the current (amps) is the sum of the currents from all the batteries and the voltage remains the same as that of a single battery.

Batteries must be protected from the elements. Batteries should be placed in a building where the temperature will remain optimum. Batteries should never be set directly on concrete surfaces, as self discharge will increase, especially if the concrete surface gets damp.

### 7.6.3 Direct-Coupled Solar Pumping System

In direct-coupled pumping systems, electricity from the PV modules is sent directly to the pump, which in turn pumps water through a pipe to where it is needed (Figure 3). This system is designed to pump water only during the day. The amount of water pumped is totally dependent on the amount of sunlight hitting the PV panels and the type of pump. Because the intensity of the sun and the angle at which it strikes the PV panel changes throughout the day, the amount of water pumped by this system also changes throughout the day. For instance, during optimum sunlight periods (late morning to early afternoon on bright sunny days) the pump operates at or near 100 percent efficiency with maximum water flow. However, during early morning and late afternoon, pump efficiency may drop by as much as 25 percent or more under these low-light conditions. During cloudy days, pump efficiency will drop off even more. To compensate for these variable flow rates, a good match between the pump and PV module(s) is necessary to achieve efficient operation of the system.

Direct-coupled pumping systems are sized to store extra water on sunny days so it is available on cloudy days and at night. Water can be stored in a larger-than-needed watering tank or in a separate storage tank and then gravity-fed to smaller watering tanks. Water-storage capacity is important in this pumping system. Two to five days' storage may be required, depending on climate and pattern of water usage.

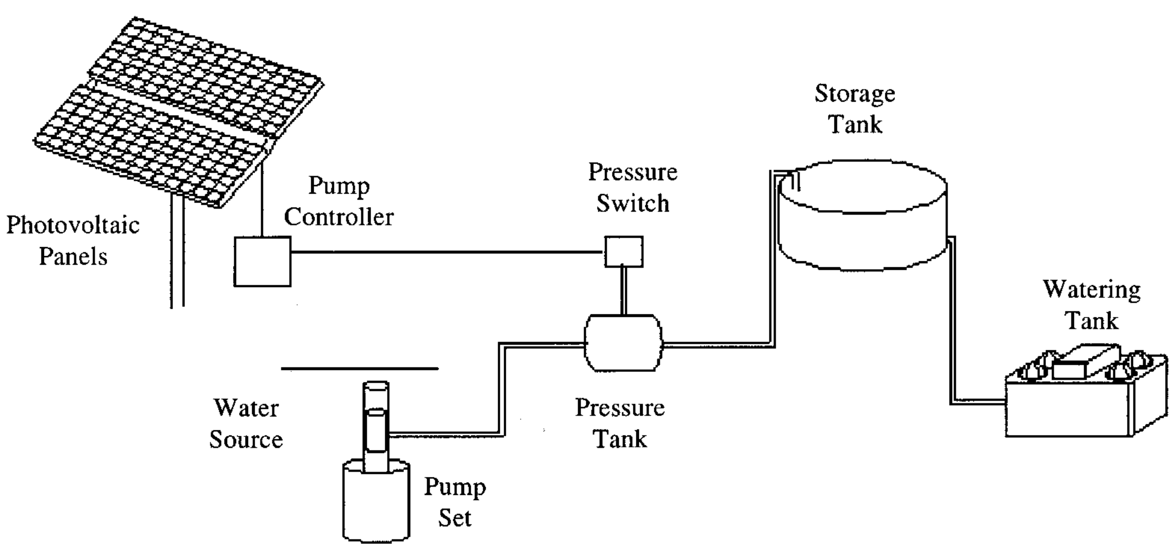



**Fig 7.3: Direct-coupled solar pumping system (Ref. 16)**

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Storing water in tanks has its drawbacks. Considerable evaporation losses can occur if the water is stored in open tanks, while closed tanks big enough to store several days water supply can be expensive.

### 7.6.4 System Components

#### 7.6.4.1 Power Controllers

The efficiency of a direct-coupled water pumping system is sensitive to the match between the pump and the PV system. PV panels produce a fairly constant voltage as the light intensity changes throughout the day; however, amperage changes dramatically with light intensity. During low-light levels, such as early morning and late evening, the PV array may be producing 30 volts at 1 amp. The pump motor needs current to start; however, it can run on a lower voltage. A pump controller's circuitry trades voltage for current, which allows the pump to start and run at reduced output in weak-sunlight periods. Matching pump motor performance to the available sunlight with a properly sized controller can increase the amount of water pumped in a day by 10 to 15 percent.

## 7.7 THE SOLAR PUMP

The other major component of these systems is the pump. Solar water pumps are specially designed to use solar power efficiently. Conventional pumps require steady AC current that utility lines or generators supply. Solar pumps use DC current from batteries and PV panels. Also, they are designed to work effectively during low-light conditions, at reduced voltage, without stalling or overheating. Most solar water pumps are designed to use solar power most efficiently and operate on 12 to 36 volts DC. Some solar pumps are fully submersible, while others are not.

### 7.7.1 Submersible Pumps

Some solar pumps are fully submersible, while others are not. Often with electronic load controllers, the pump will be submerged while the load controller is above ground. The use of submersible pumps eliminates potential priming problems. The advantages of this configuration are that it is easy to install, often with lay-flat flexible pipe work and the motor pump set is submerged away from potential damage.

**Submerged pump with surface mounted motor:** The main advantage here is the easy access to the motor for maintenance. The low efficiency from power losses in the shaft bearings and the high cost of installation has been disadvantages. In general this configuration is largely being replaced by the submersible motor and pump set.

### 7.7.2 Positive Displacement pumps

Many solar pumping systems use positive displacement pumps that seal water in cavities inside the pump and force it upward. Their design enables them to maintain their lift capacity all through the solar day at the slow, varying speeds that result from varying light conditions. These pumps include piston and jack pumps, diaphragm, vane and screw pumps. Positive displacement helical pumps have the best efficiency and the smallest PV panel for the same specs of water delivery volume pressure and head. They have low rotational speed. The pump is made up of a metal helical rotor which rotates in a rubber casing. They are suitable for bigger heads.

### 7.7.3 Centrifugal pumps

Centrifugal-type pumps that impart energy to the water using a rotating impeller are typically used for low-lift or high-volume systems. Centrifugal pumps start gradually and their flow output increases with the amount of current. For this reason, they can be tied directly to the PV array without including a battery or controls. However, because their output drops off at reduced speeds, a good match between the pump and PV array is necessary to achieve efficient operation.

## 7.8 PUMP PERFORMANCE

Pumps, because of their mechanical nature, have certain well-defined operating properties. These properties vary between types of pumps, manufacturers and models. The amount of water that a solar pumping system will deliver over a given period of time (usually measured in volume per minute/ volume per hour) depends upon the pressure against which the pump has to work. The system pressure is largely determined by the total vertical pumping distance (the vertical distance between the water source and the watering tank) referred to simply as elevation head. It is roughly equal to an increase of 1 PSI (Pound per Square Inch) for every 2.31 feet (0.704m) of elevation head. Simply put, as the vertical pumping distance increases, the amount of water pumped over a given period of time decreases. When system friction losses and discharge pressure requirements (if any) are added to elevation head, the total system head can be determined. Pump manufacturers publish information that describes how each pump will perform under varying operating conditions. The expected flow rates and minimum recommended solar panel sizes for a typical 24-volt, positive-displacement, diaphragm-type submersible pump are shown in **Table 7.3.** The choice of pump depends on water volume needed, efficiency, price and reliability.

**Table 7.3: Estimated flow rates in gallons per minute for a typical positive-displacement, 24-volt diaphragm type pump (Ref. 18)**

| Total Head (Feet) | Flow Rate (GPM) | Current (Amps) |
|---|---|---|
| 0 | 3.7 | 1.6 |
| 10 | 3.5 | 1.7 |
| 20 | 3.4 | 2.0 |
| 30 | 3.3 | 2.2 |
| 40 | 3.2 | 2.4 |
| 50 | 3.1 | 2.6 |

Solar pumps are available to pump from anywhere in the range of up to 200m head and with outputs of up to 250m³/day. Solar pumping technology continues to improve. In the early 1980s the typical solar energy to hydraulic (pumped water) energy efficiency was around 2% with the photovoltaic array being 6-8% efficient and the motor pump set typically 25% efficient. Today, an efficient solar pump might have an average daily solar energy to hydraulic efficiency of more than 9% but lower efficiencies of 2 -3% are still common. It is important to get the most efficient pump available as the difference in cost between the poor pump and a very efficient pump is much less that the additional cost required for a larger PV panel. Accurate sizing of the array is important in keeping costs down. A good sub-system (that is the motor, pump and any power conditioning) should have an electrical to hydraulic efficiency of around 70% using positive displacement pumps. With diaphragm pumps the efficiency will be around 45% and centrifugal pumps might have an efficiency of 20%.

## 7.9 SELECTING A SOLAR-POWERED WATER PUMPING SYSTEM

### 7.9.1 Assessing Water Requirements and Availability

The output of a solar pumping system is very dependent on good system design derived from accurate site and demand data. It is therefore essential that accurate assumptions are made regarding water demand/pattern of use and water availability including well yield and expected drawdown. Domestic water use per capita tends to vary greatly depending on availability. The long-term aim is to provide people with water in sufficient quantities to meet all requirements for drinking, washing and sanitation. Present short-term goals aim for a per capita provision of 40 litres per day, thus a village of 500 people has a requirement of 20 cubic metres per day. Most villages have a need for combined domestic and livestock watering. Irrigation requirements depend upon crop water requirements, effective groundwater contributions and efficiency of the distribution and field application system. Irrigation requirements can be determined by consultation with local experts as they are much more expensive and tasking.

Several water source parameters need to be taken into account and where possible measured. These are the depth of the water source below ground level, the height of the storage tank or water outlet point above ground level and seasonal variations in water level. The drawdown or drop in water level after pumping has commenced also needs to be considered for well and borehole supplies. This will depend on the ratio between pumping rate and the rate of refill of the water source. The pattern of water use should also be considered in relation to system design and storage requirements. Water supply systems should include sufficient covered water storage to provide for daily water requirements and short periods of cloudy weather. Generally, two to five days water demand is stored.

### 7.9.2 Cost of the system

Cost is a factor that must be considered when selecting a solar pumping system. Total cost depends on many factors, such as the type of system (direct-coupled or battery-coupled), daily water requirements, pressure the pump must work against to supply the required water flow, complexity of the water delivery system, etc. For example, low-volume solar pumping systems keep costs down, when compared to higher output solar pumping systems, by using a minimum number of solar panels and by using the entire daylight period to charge batteries or pump water.

### 7.9.3 Sizing the System

Many reputable solar equipment dealers provide technical assistance and expert advice on the performances from various systems. The dealers combine the information provided about the water requirements and livestock operation with the information on solar energy available in an area, and help select the solar pumping system that is best suitable for the available needs and budget. The type of information needed to have the system designed with consideration of the cost/budget includes:

- The maximum amount/volume of water needed daily for each month of the year.
- Description of water source.
- The total dynamic head of the system-Total vertical distance that water is to be pumped, as measured from the lowest level from the water source to the highest level of the watering tank, including the pipe outlet.
- Quality of water to be pumped. Is it clear, silty, high in mineral content or does it contain a lot of algae growth?
- Solar access: The amount of solar energy available in the location proposed (Is unobstructed sunlight available near the water source? If not, how far away?)

- Information on any water-pumping equipment, distribution system and storage capacity presently being used.
- A sketch of the desired lay out of the watering system-including the distances from the solar panels to the pump and from the pump to the watering tank(s).

The amount of solar energy available will give an indication of the number of solar modules needed to provide the power to pump the required quantity of water at the calculated head.

The **hydraulic energy** required (kWh/day)

$$= \text{volume required } (m^3/\text{day}) \text{ x head (m) x water density x gravity} / (3.6 \text{ x } 10^6) \qquad (38)$$

$$= 0.002725 \text{ x volume } (m^3/\text{day}) \text{ x head (m)} \qquad (39)$$

The **solar array power** required (kWp-kilowatt peak)

$$= \frac{\text{Hydraulic energy required (kWh/day)}}{\text{Av.daily solar irradiation } (\text{kWh}/\text{m}^2/\text{day x F x E})} \qquad (40)$$

Where, F = array mismatch factor = 0.85 on average
E = daily subsystem efficiency = 0.25 - 0.40 typically

### 7.9.4 Power required for water pumping

The amount of power that is required for a solar water pumping system depends on the quantity of water to be pumped, the rate at which it is to be pumped and the total head at which the system must operate.

Total head consists of two parts:

(i) The static head (the height through which the water must be lifted), and

(ii) The dynamic head (the pressure increase caused by friction through the pipe work and expressed as an equivalent height in metres).

The static head can be easily determined by measurement. The dynamic head depends on a flow rate (which must be based on the maximum pump performance in peak sunlight intensity), pipe sizes and pipe material. The smaller the pipes and the greater the flow rate, the higher the pressure required to force water through the pipe.

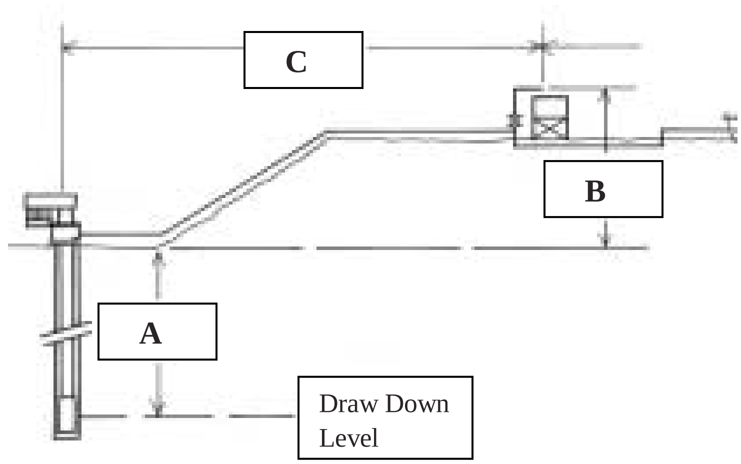


**Fig 7.4: Factors that influence the total head of the system (Ref. 21)**

Where: (A) — Bore Static Head/Pumping Water Level (Depth from surface to drawdown Level)
(B) — Static Delivery Head to point of free discharge.
(C) — Mainline Pipe Friction-Friction loss in discharge or mainline pipe.

Because the major cost in a solar water pumping system still remains in the solar modules, it is more cost efficient to consider a **large diameter pipeline** to significantly reduce the dynamic head and so lower the power requirements of the solar pumping system. In most applications, the flows associated with low-volume pumping systems use about 1-inch PVC pipe, recommended to keep friction losses negligible. Friction losses throughout the system can significantly increase the total head and thus reduce the amount of water that can be pumped. Sizing the solar array (power required) to suit your specific needs and location, should be done in consultation with a solar pumping supplier.

### 7.9.5 Water storage

Solar water pumping systems are generally not designed to operate as on–demand pressure systems. Water is pumped during daylight hours and stored for use as required. Storage can be either in a dam or a tank. It is usual to position the tank at a height which allows sufficient pressure to reticulate the water to where it is needed. Storage capacity should be great enough to provide four times the maximum demand (which may last for several days) or for days of heavy cloud cover, when pumping rates are lower.

The pump can be operated using either a standard pressure switch and recharged pressure tank commonly used with home well pumps or an electronic float switch.

The recharged pressure tank prevents the continuous on/off cycling of the pump when, for example, cattle drink from a nearly full watering tank. When the float valve closes in a recharged pressure tank system, the pump continues to run until the pressure tank is charged with water at the preset off-pressure. In this case, as the level in a near-full tank fluctuates when animals are drinking and the float valve opens and closes, water is supplied from the charged pressure tank and the pump does not cycle. When animals drink enough to lower the water level and the float valve remains open, the pressure tank water charge is exhausted and the pressure switch then turns on the pump. A check valve placed in line upstream from the pressure switch location prevents the water line from draining when the pump is not operating.

The electronic float switches can be used to turn the pump on and off when the livestock watering and/or storage tank is low or full. Control wires from the livestock watering tank and/or storage to the pump controller must be run to make the system operate

## 7.10 INSTALLING THE SYSTEM

### 7.10.1 Mounting PV Panels

The PV panels should be mounted facing a location where they receive maximum sunlight throughout the year. When choosing a site, it is essential to avoid trees or other obstructions that could cast shadows on the solar panels and reduce their output. Solar panels produce the most power when they are pointed directly at the sun. The tilt angle is the angle between the plane of the solar panel surface and the ground. For maximum energy collection, the panel surface should be perpendicular to the sun. In countries like Kenya with a lot of sunshine throughout the year, the desired tilt angle can be achieved by permanently mounting the panels on rooftops. Most manufacturers and distributors sell mounting hardware specifically designed for their panels.
This hardware is intended for multiple applications so parameters such as wind loading have been considered in the design. Using this mounting hardware is the simplest and often the most cost effective. Locating the PV modules close to the water source is important to keep voltage loss in the system wiring to a minimum. A fence around the PV modules is required to protect the PV panels from damage due to animals.

### 7.10.2 Wiring

Selecting the correct size and type of wire to connect the pump to the batteries or solar panels increases the performance and reliability of the system. If possible, keep the PV panel and pump sets within 100 feet of each other. At this distance, a # 12 gauge wire is sufficient to keep the voltage loss in most 24-volt systems to roughly 3%. Larger diameter wires will be required at distances greater than 100 feet to keep voltage loss in the system to a minimum. A voltage drop of only 5% translates to a 7.5% power loss at the pump. The use of underground wires (Direct Burial wires) simplifies installation, since the wire can be buried under the water pipe in the same trench without conduit.

All connections are made in water-tight junction boxes and all wires attached to support structures with wire ties. PVC conduits are used to protect the wires anytime they are above ground. Solar water pumping systems attract lightning because of the excellent ground they provide. If possible, do not locate the pump system, which includes the PV array, wiring and pump, on high ground. Ground the PV panel frame and all equipment boxes to metal well casings or to a driven ground rod. You might have to install lightning rods on higher terrain around the pump if lightning is a problem.

## 7.11 MAINTENANCE OF THE SOLAR SYSTEM

Most failures of solar pumping systems are caused by pump problems. Sand and silt pulled in by the pump are the primary cause of failure. Filtering out silt or sand at the pump intake with fine mesh screen will prolong the life of the pump. The amount of maintenance required by solar pumping systems depends on the type and complexity of the system. PV panels generally require very little maintenance; however, pumps, batteries and other components require periodic routine maintenance. Solar pumping systems failures can be avoided with the following preventative maintenance:

- Check the tightness of all electrical connections in the system. Battery connections should be cleaned and treated with a corrosion inhibitor available from any auto parts store.
- Follow the manufacturer’s recommended maintenance procedures for all batteries. Check the electrolyte level and do not overfill batteries.
- Check system wiring. Look for cracks in the insulation of exposed wires. Inspect wires entering and exiting junction boxes for cracks or breaks in the insulation. Replace as necessary.
- Check all junction boxes for water damage or corrosion. Check the tightness of the terminal screws and the general condition of the wiring. After inspection, make sure covers on junction boxes are closed and sealed.
- Inspect the array-mounting frame to be sure that all mounting hardware is tight. Loose bolts could result in a damaged panel. Remove any weeds, tree branches or any other objects that may be shading the PV panel.
- Check to see if the panel glass is clean. If it is dirty, simply clean it with a soft cloth, mild detergent and water. Rinse with clean water to prevent the detergent from forming a film on the panel.

## 7.12 HOW SOLAR SYSTEMS COMPARE TO OTHER SYSTEMS

The cost comparison between wind, solar, diesel engines and electricity, show that water pumping can be very cost competitive in certain circumstances. Every application is different and should be evaluated on its merit, giving consideration to the following:

- Initial cost of the system
- expected system life (15–20 years)
- running costs (e.g. fuel and oil for diesel engines)
- Maintenance costs
- Time and labor to supervise the system's operation
- Time value of money (discount rate of return).

Solar water pumping systems have many advantages over traditional windmill water pumps. They provide a more consistent supply of water and can be installed in wooded areas where wind exposure is poor. Solar pumps operate anywhere the sun shines while windmills work where there is a steady, constant wind supply. Both the initial and lifetime costs of solar powered systems are often far less than windmills due to lower shipping, installation, and maintenance costs. Finally windmills are stationary while solar systems can be more easily moved to meet seasonal or variable location needs. A PV array may be placed some distance away from the pump itself, even several hundred feet away.

Solar pumps are becoming a preferred choice in remote locations to replace the increasingly expensive diesel pumps. In such places, solar pumps are viable economically in comparison to extension of grid or running the pump on diesel.

## 7.13 ADVANTAGES OF SOLAR PUMPS

Along with the environmental advantages of solar power, solar pumps offer many other advantages as well.

I. **Low operating costs:** One of the important advantages is the negligible operating cost of the pump. Since there is no fuel required for the pump like electricity or diesel, the operating cost is minimal.

II. **Low maintenance:** A well designed solar system requires little maintenance beyond the previously mentioned checks.

III. **Harmonious with nature**: Another important advantage is that it gives maximum water output when it is most needed i.e. in hot and dry months. Slow solar pumping allows us to utilize low-yield water resources.

IV. **Flexibility:** The panels need not be right beside the well. They can be anywhere up to 20 meters/60 feet away from the well, or anywhere you need the water giving the users some freedom. These pumps can also be turned on and off as per the requirement, provided the period between two operations is more than 30 seconds.

## 7.14 LIMITATIONS OF SOLAR PUMPS

I. **Low yield**: Solar pumping is not suitable where the requirement is for a larger subject to be served e.g. large scale irrigation.

II. **Variable yield**: The water yield of the solar pump changes according to the sunlight. It is highest around noon and least in the early morning and late evening.

III. **Water quality**: As with ant other pump, solar pumps work best if the water is clean, devoid of sand or mud. However, if the water is not clean, it is advisable to clean the well before installation or use a good filter at the end of the immersed pipe.

# CHAPTER 8:

# WIND/SOLAR HYBRID SYSTEMS

## 8.1 INTRODUCTION

Depleting oil and gas reserves, combined with the growing concerns about global warming, have made it inevitable to seek alternative/renewable energy sources. The integration of renewable energies such as solar and wind energy is becoming increasingly attractive and is being used widely, for substitution of oil-produced energy, and eventually to minimize atmospheric degradation.

In the recent years, photo voltaic power generation has been receiving considerable attention as one of the more promising energy alternative. The reason for this rising interest lies in the direct conversion of sunlight into electricity. Photo voltaic energy conversion is one of the most attractive non conventional energy sources of proven reliability from the micro to mega watt level. Its advantages are:

1. Absence of moving part
2. Ability to function unattended for long periods
3. Modular nature in which desired current, voltage and power level can be obtained by mere integration
4. Long effective life and high reliability

The wide spread use of PV generation is however mainly hampered by economic factors. Efforts are being made worldwide to reduce the cost/watt through various technological innovations. Wind energy also is equally and effectively used in large scale wind farms to provide electricity to rural areas and other far reaching locations. Wind energy is being used extensively in areas like Denmark, Germany, Spain, India and in some areas of the United States of America. It is one of the largest forms of Green Energy used in the world today. Wind Energy is highly practical in places where the wind speed is 10 mph.

In the past 30 years, solar photovoltaic cells have increased in efficiency and the price levels have improved dramatically. Today the theoretical efficiency of a solar PV cell can be 25% - 30 % and a practical efficiency around 17%. Any improvement in efficiency of solar energy system will make a big difference in the use of solar panel. Developments are also taking place in finding new PV cells which can withstand high concentration of light and heat and produce more output per unit area. Small concentrating reflectors of a few centimeters across provide considerable concentration on cells made of special material and a number of such small concentrating units can be assembled to form a bigger panel. The panel as a whole is mounted suitably and tracking arrangements are made where necessary. The elevation angle of sun remains almost invariant in a month and various very little in a year. Therefore single axis position control scheme may be sufficient in most of the application where economy and ease of maintenance are important

Solar and wind energy are non-depletable, site-dependent, non-polluting, and potential sources of alternative energy options. Many countries are pursuing the option of wind energy conversion systems; in an effort to minimize their dependence on fossil-based non-renewable fuels. Also, presently thousands of photovoltaic (PV) deployments exist worldwide, providing power to small, remote, grid-independent or stand-alone applications.

For both systems, variations in meteorological conditions (solar irradiation and average annual wind conditions) are important. The performance of solar and wind energy systems are strongly dependent on the climatic conditions at the location. The power generated by a PV system is highly dependent on weather conditions. For example, during cloudy periods and at night, a PV system would not generate any power. In addition, it is difficult to store the power generated by a PV system for future use. To overcome this problem, a PV system can be integrated with other alternate power sources.

Combined wind and solar systems are becoming more popular for stand–alone power generation applications, due to advances in renewable energy technologies and subsequent rise in prices of petroleum products. The Economic aspects of these technologies show sufficient promise to include them in developing power generation capacity for developing countries. Research and development efforts in solar, wind, and other renewable energy technologies are required to continue improving their performance, establishing techniques for accurately predicting their output and reliably integrating them with other conventional generating sources.

Before building a system with several intermittent energy sources and variable consumption, guidance on the dimensioning of the individual components should be obtained by simulating the system operation under the local conditions, including as appropriate the weather, insulation, wind etc. In general a key objective of such systems is to use the maximum proportion of renewable energy, but other factors including the financial investment, social aspects, local infrastructure, durability etc. must also be considered.

The components and subsystems of a stand-alone system based on renewable sources are interconnected to optimize the whole system. The design of a hybrid system will depend on the requirements of the user (isolated or not isolated location, rural or urban, DC or AC supply), and on the power supply system (or water supply system in the case of water pumping applications).
Usually, most of hybrid systems are designed to supply electric power for lighting fixtures, radio/TV, domestic appliances, submersible water pumps etc. This is typical in isolated areas for rural households as well as of some public buildings such as schools, cultural establishments, etc

In Kenya, most of the solar/wind hybrid energy systems available are used for small scale power production. In the case of a larger demand or large scale application e.g. for inclusion into the main power grid a third energy source is used as a back up and in most cases it is a diesel generator.

## 8.2 BASIC COMPONENTS OF A SMALL HYBRID SYSTEM

A typical small hybrid power system can contain the following components:

**Solar PV Generator**: containing a number of series/parallel interconnected solar modules (depending on the necessary voltage), including connection and protection elements (bypass diodes and/or anti-return). This element delivers part of the electric energy supply through solar energy conversion.

**Wind generator**: providing part of the necessary electric energy by converting the mechanical energy from the wind.

**Storage unit (accumulator battery set):** Usually Pb, Ni-Cad or Ni-Fe batteries dedicated to applications in the area of renewable energy sources.

**Unit for power conditioning**: This can be a DC/DC converter (for DC loads) and/or inverters (for AC loads) depending on the pump to be used.

**Pump**: Selected type of pump, whether AC/DC, submersible, reciprocating or centrifugal depending on requirements.

## 8.3 DESCRIPTION OF PHOTOVOLTAIC SYSTEMS

PV modules are rated on the basis of the power delivered under Standard Testing Conditions (STC) of 1 kW/m² of sunlight and a PV cell temperature of 25 degrees Celsius (°C). Their output measured under STC is expressed in terms of "peak Watt" or Wp nominal capacity. Note that annual industry shipments of 165 MWp indicates that PV manufacturers made modules with the ability to generate 165 MWp of electric power (nameplate capacity) under STC of 1 kW/m² of sunlight, 25°C cell temperature, and an air mass of 1.5.

Because the first important applications of PV involved battery charging, most modules in the market are designed to deliver direct current (DC) at slightly over 12 Volts (V). A typical crystalline silicon module consists of a series circuit of 36 cells, encapsulated in a glass and plastic package for protection from the environment. This package is framed and provided with an electrical connection enclosure, or junction box. Typical conversion (solar energy to electrical energy) efficiencies for common crystalline silicon modules are in the 11 to 15% range.

Several electronic devices are used to control and modify the electrical power produced by the photovoltaic array.
These include:

- Battery charge controllers - regulate the charge and discharge cycles of the battery;
- Inverters - convert the direct current (DC) output of the array or the battery into alternating current (AC). AC is required by many appliances and motors; it is also the type of power used by utility grids and therefore on grid systems always require the use of an inverter;
- Rectifiers (battery chargers) - convert the AC current produced by a alternator into the DC current needed to charge the batteries.

Power conditioning units (inverters) play a key role in the energy efficiency and reliability of PV systems. The energy generated by a PV-module depends on the instant value of solar irradiation, module temperature and the operating point of the module. Therefore, the system requires a power conditioning component which can optimize the delivered power based on the operation conditions.

## 8.4 DESCRIPTION OF WIND TURBINES

Wind turbine technology has reached a mature status during the past 15 years as a result of international commercial competition, mass production and continuing technical success in research and development (R&D). The earlier concerns that wind turbines were expensive and unreliable have largely been allayed. Wind energy project costs have declined and wind turbine technical availability is now consistently above 90%. Wind energy project plant capacity factors have also improved from 15% to over 30% today, for sites with a good wind regime.

Modern wind energy systems operate automatically. The wind turbines depend on the same aerodynamic forces created by the wings of an airplane to cause rotation. An anemometer that continuously measures wind speed is part of most wind turbine control systems. When the wind speed is high enough to overcome friction in the wind turbine drive train, the controls allow the rotor to rotate, thus producing a very small amount of power. This cut-in wind speed is usually a gentle breeze of about 4 m/s. Power output increases rapidly as the wind speed rises. When output reaches the maximum power the machinery was designed for, the wind turbine controls govern the output to the rated power. The wind speed at which rated power is reached is called the rated wind speed of the turbine, and is usually a strong wind of about 15 m/s.
In some designs if the wind speed increases further, the control system shuts the wind turbine down to prevent damage to the machinery. This cut-out wind speed is usually around 25 m/s.

The major components of modern wind energy systems typically consist of the following:

- Rotor, usually 3 blades, which converts the energy in the wind into mechanical energy onto the rotor shaft;
- Gearbox to match the slowly turning rotor shaft to the electric generator;
- Tall tower which supports the rotor high above the ground to capture the higher wind speeds;
- Solid foundation to prevent the wind turbine from blowing over in high wind conditions.
- Control system to start and stop the wind turbine and to monitor proper operation of the machinery.

## 8.5 WIND POWER TECHNOLOGY

A simple relationship exists relating the power generated by a wind-turbine and the wind parameters:

$$P = 0.5\rho A C_p v^3 \eta_g \eta_b \tag{41}$$

Where, $\rho$ = air density (about 1.225 kg/m$^3$ at sea level, less at higher elevations).

$A$ = rotor swept area, exposed to the wind (m$^2$).

$C_p$ = Coefficient of performance (0.59 to 0.35 depending on turbine).

$v$ = wind speed in meters/sec

$\eta_g$ = generator efficiency

$\eta_b$ = gearbox/bearings efficiency

## 8.6 BENEFITS AND LIMITATIONS OF WIND/SOLAR HYBRID SYSTEMS

The Wind/Solar hybrid systems are encouraged because they increase the reliability and efficiency of a renewable energy system while reducing the cost. By using wind and solar you can reduce the size of the solar battery bank while reducing the cost of renewable energy power producers.

### 8.6.1 Benefits

i. 20-50% reduction in the initial capital cost of the system.
ii. Battery based renewable energy systems are 20% more efficient when using the power when it is being produced. By adding wind, which is operational almost 24 hrs a day, you increase the efficiency of your system.
iii. Another benefit of using the energy as it is being created is less cycling in the battery which means a longer battery life.
iv. Hybrid systems allow for larger variations in average wind speeds-Wind turbines become viable in areas with wind speeds as low as 2m/s.
v. Environmental protection, especially in terms of $CO_2$ emissions reduction.

### 8.6.2 Limitations

i. The initial cost of hybrid wind/solar machines is relatively high compared to other sources of energy machines e.g. diesel generators, even though they have low operating and maintenance costs.
ii. Excess energy storage could be a problem during calm and cloudy days when there are low winds and little sunlight.
iii. These hybrid systems are complex systems that require proper matching and sizing. Taking energy from two different systems and integrating them into one is a complex process.

# CHAPTER 9:
# RESULTS AND ANALYSIS

## 9.1 DATA RESULTS

Data was obtained detailing the wind speeds and wind speed directions of different areas. These areas were Marsabit, Garissa, Kericho, Dagoretti and Laikipia. The data showed wind speeds in knots and this was converted to the metric form of m/s. A conversion factor of 0.51 was used to convert knots into m/s i.e. 1 knot = 0.51 m/s

Charts showing the wind speed direction are provided to show the wind movement in these named areas.

**Table 9.1: Table showing wind speeds in different areas (Ref. 12)**

| Location | Wind speed in knots | Wind speed in m/s |
|---|---|---|
| Marsabit | 20.84 | 10.6284 |
| Garissa | 6.78 | 3.4578 |
| Kericho | 2.59 | 1.3209 |
| Dagoretti | 3.20 | 1.632 |
| Laikipia | 7.55 | 3.8505 |

With Marsabit having high wind speeds, it is therefore a preferable location for setting up the wind turbine since the power available from the turbine is directly proportional to the wind speed. In choosing Marsabit District as a most preferable area, we picked Bubisa location as a point for setting up the wind machine.

Bubisa location, with a latitude of 2.75 (2° 45' 0 N) and a longitude of 38.08 (38° 4' 60 E), is a hydrographic (waterhole(s)) located in the North Eastern part of Kenya. The location is situated 195 kilometers north (3°) of the approximate center of Kenya and 470 kilometers north (17°) of the capital Nairobi.

A 100 square km area around Bubisa has an approximate population of 15361 (0.000154 persons per square meter) and an average elevation of 854 meters above the sea.

**Table 9.2: Table of Boreholes Data in Bubisa, Marsabit (Ref. 11)**

| Borehole | TD | WSL | WRL | PWL | Depth of pump | Yield |
|---|---|---|---|---|---|---|
| Bubisa 1 (Centre) | 275m | 252m | 215.80m | 216.73m | 259m | 14.54$m^3$/hr |
| Bubisa 2 (Tinga ) | 285m | 270m | 233.70m | 234.24m | 268m | 12.02$m^3$/hr |
| Bubisa 3(Youth Camp) | 245m | 184,204 | 187.30m | 188.30m | 231m | 17.29$m^3$/hr |

**KEY**

TD – Total Depth

WSL – Water Struck Level

WRL – Water Rest Level

PWL – Pump Water Level

## 9.2 ANALYSIS

Selecting a preferable wind turbine for the hybrid system, we chose the WM-3000 wind turbine from SRM Power and supplied by Davis. This turbine was found to provide the necessary needed power to charge our power storage unit for running the pump. The turbine had the following specifications:

**Table 9.3: Table of Chosen Turbine Specifications (Ref. 13)**

| | |
|---|---|
| Model | WM-3000 |
| Rated power (W) | 3000 |
| Rotor Diameter (m) | 4 |
| Rated wind speed (m/s) | 10 |
| Start-up Wind Speed(m/s) | 3 |
| Working Wind Speed (m/s) | 3 -25 |
| Working Voltage (V) | 240V |
| Material and number of the blades | Fiber Reinforced Plastic *3 |
| Generator Style | Three phase, permanent magnet |
| Speed Regulation Method | Tail Furl / electronic controller |
| Tower Height (m) | 12 |

Power in the wind, from equation (7)

$$\mathbf{P_W = \frac{1}{2} \rho A V^3}$$

From the wind turbine specifications, in Table 9.3, the rotor diameter was found to be 4 metres.

Wind speed of Bubisa from Wind Rosets figure= 20.84 knots

1 knot = 0.51 m/s

Therefore, 20.84 x 0.51 = 10.6284 m/s

$$P_w = \frac{1}{2} \text{ x } 1.225 \text{ x } \frac{\pi x 4^2}{4} \text{ x } (10.6284)^3 \qquad (42)$$

$$= 9241.014 \text{ W}$$

$$= 9.241 \text{ kW}$$

This is the total power in the wind, $P_{tot}$. Therefore, $P_{tot} = P_w$

From equation (25),

$$\boldsymbol{P_{max} = \frac{8}{27} \rho A V_i^{\,3}} \qquad \text{with } \boldsymbol{\rho}=1.225 \text{ kg/m}^3$$

Where $P_{max}$ = maximum power obtained from the wind

$$P_{max} = \frac{8}{27} x \ 1.225 \ x \ \frac{\pi x 4^2}{4} \ x \ (10.6284)^3 \qquad (43)$$

$$= 5476.15 \text{ W}$$

$$= 5.476 \text{ kW}$$

From equation (26),

$$\eta_{max} = \frac{P_{max}}{P_{tot}}$$

$$\eta_{max} = \frac{5.476 \ kW}{9.241 \ kW} = 0.59257 \qquad (44)$$

This shows that the turbine is capable of converting 59.257% of the total power of the wind to useful power.

From equation (8),

$$\mathbf{P_M = ½C_p ρAV^3}$$

From **Table 9.3**, the power available in the machine was found to be 3000W which is the rated power of the turbine. Therefore,

$$3000 = \frac{1}{2} \text{ x } C_p \text{ x } 1.225 \text{ x } \frac{\pi x 4^2}{4} \text{ x } (10.6284)^3 \qquad (45)$$

Therefore, $C_p$ = 0.3246 ≈ 0.325, which is a reasonable value that falls within the range stipulated in **Table 4.1** for three bladed aerofoil horizontal axis turbines.

From equation (36),

**Blade Power =** $0.15 \text{ x (diameter)}^2 \text{ x (wind speed)}^3$ (46)

$= 0.15 \text{ x } (4)^2 \text{ x } (10.6284)^3$

= 2881.475 W

= 2.881 kW

From equation (37),

$$\textbf{RPM} = = \frac{\text{wind speed x 60 x TSR}}{\text{circumference}}$$

A figure of 7 is considered as a much preferable value of TSR (Ref. 5).

$$\text{Therefore, RPM} = \frac{10.6284 \text{ x } 60 \text{ x } 7}{\pi \text{ x } 4} = 355.228 \text{ r.p.m.} \qquad (47)$$

This value of RPM is the speed of the blades in revolutions per minute.

**Fig 9.2: Inventor Software simple Diagrammatic representation of a three bladed wind turbine with an alternator.**

In the design specifications for pumping systems, the requirements to be met are; a discharge flow rate for transfer of water from suction to discharge reservoir and a total pressure head to be overcome by the pumping system. The discharge flow rate required is stated in litres per second (l/s), or cubic metres per second ( $m^3$/s ). It is determined by a study of water demand. For domestic water demand, the population to be served and its per capita water consumption is estimated and from this data the aggregated water demand is computed.

Taking a community of a population of 600 people in Bubisa location and with each person consuming approximately 30 litres of water per day (WHO guidelines aim for a per capita provision of 30 to 50 litres per day for domestic use only), the total water used per day is (30 x 600) litres.

Total water used per day = 18,000 litres

But, 1 $m^3$ = 1000 litres, therefore

Total water used per day = 18$m^3$

It is required that a water reservoir for a water pumping system be designed for a storage of 50% of a day's consumption. Therefore taking an assumption that enough water is pumped to serve the sample community population for three days, the reservoir is obtained to store all this water.

Since the consumption is $18m^3$/day, the total consumption for three days will be $54m^3$ and thus the volume of the reservoir that is required.

Most motors used with pumps are most efficient when running from 65-100% of the rated power. However, the motors are considered overloaded or performing at low efficiencies when running for long periods of time. Taking an optimum pumping time of 6hrs per day, the total pumping hours for three days will be (6x3) hrs. Therefore, the pumping hours will be 18hrs.

Therefore, the required discharge rate (Q) = $\frac{54\mathrm{m}^3}{18\mathrm{hrs}} = 3\mathrm{m}^3/\mathrm{hr}$ (48)

Taking the water entry point to the reservoir as being raised to a distance of 6m from the ground level and calculation of the friction head loss, the total pressure head is found. The total pressure head is also referred to as the dynamic head. This is because it is the sum of the static head and the friction head. It is referred to as dynamic because it incorporates the head loss due to fluid friction in the pipeline which arises only during the dynamic conditions of the fluid flow.

Therefore, total pressure head to be overcome by pumping system is given by the expression:

$$H = h_{ts} + h_f$$

Where, $H$ = Total or dynamic pressure head to be overcome by pumping

$h_{ts}$= Total static head to be overcome by pumping

$h_f$ = Pressure head loss due to fluid friction in pipeline

From the Darcy equation,

$$h_f = \frac{f \times L \times V^2}{2g \times D} \quad (49)$$

Where, $f$ = friction factor

L= length of pipe

V=flow velocity

D=pipe diameter

g=gravitational acceleration

Friction factor *f* depends on the Reynolds number (Re) and pipe internal roughness ($^{K}/_{D}$)

$$Re=\frac{VD}{\nu}$$

Where, V=flow velocity

D=diameter of pipe

ν=Kinematic Viscosity=$1x10^{-6}$

A preliminary selection of the pipeline is therefore made using a recommended flow velocity for water pipelines. This flow velocity recommended for preliminary design of water pipelines is chosen such that pressure losses due to fluid friction in pipeline are kept within acceptable limits. This ensures that pumping equipment size and costs are also kept within certain limits.

The recommended range of flow velocities for water pipelines, to be applied during preliminary design, is between 1 and 3 m/s.

From the Davis and Shirtliff UPVC borehole pipe specifications applicable for the head to be pumped, our pipe diameter is chosen to be 38 mm UPVC (unplasticized polyvinyl chloride) pipe (Ref. 22). The only other material of pipe available in Kenya is the steel pipe, which are too costly.

Therefore, $Re=\frac{3\times 0.038}{1\times 10^{-6}} = 1.14x10^{5}$

$$^{K}/_{D} = {}^{0.015}/_{38} = 0.00039 \qquad (50)$$

From the Moody Chart, the value of *f* was read against the values of Re. and $^{K}/_{D}$ to be 0.0048.

Thus,

$$h_f = \frac{0.0048\times 256\times 3^2}{0.038\times 2\times 9.81} = 14.8334 \text{ MoW (metres of water)}$$

And the dynamic head becomes,

$$H = (230+6) + 14.8334 \text{ m} = 250.8334 \text{ m} \qquad (51)$$

From equation (10), the power required to pump water is

$$P_{required} = 1000 \text{ x } 9.81 \text{ x } 250.8334 \text{ x } \frac{3}{3600}$$

$$P_{required} = 2050.56 \text{ W} = 2.0506 \text{ kW} \qquad (52)$$

Taking the pump efficiency to be 80% (a safe value between 65 – 100% as mentioned above),

The power required by the pump becomes,

$$\mathbf{P_{pump}} = \frac{2.0506\ kW}{0.8} = 2.56325\ \text{kW} \tag{53}$$

When selecting the appropriate pump, we considered the following factors:

a) Depth to pumping water level.
b) Head loss and friction loss.
c) Well diameter and well yield.
d) Distance between pump and final outlet point.
e) Pump operating costs.
f) Flow rate and Head (discharge head)
g) Environment factors.
h) Life of pump/maintenance/cost.

After considering the factors in section above, it was found that the preferable pump was the DS3/60 pump model from Davis & Shirtliff group, a supplier in water related equipment.

This model has the following specifications:

- Pump model : DS3/60
- Pump type : Multistage centrifugal submersible pump
- 3 phase 4KW Direct coupled motor
- Maximum water depth of 300m
- Speed of 2900 rpm
- Full load current 10.2A
- Starting current 55

The power that must be injected into the pump shaft by the motor (**P$_s$**) is given by,

$$\mathbf{P_s} = \frac{\text{Prequired}}{\eta_p \times \eta_c} = \frac{2.0506}{0.8 \times 1} = 2.56325\ \text{kW} \tag{54}$$

Where, $\eta_p =$ overall pump efficiency, horizontal centrifugal (80%)

$\eta_c$ = efficiency of transmission coupling ($\eta_c$=1 for direct coupling)

Electric motor speeds can be chosen to make direct coupling to the pump shaft appropriately. Assuming the transmission efficiency is 1, the power output required from the motor then equals the power absorbed by the pump shaft.

The power input required by the electric driving motor can be determined from the input power required by the pump shaft as follows,

$$P_m = \frac{P_s \times s.f}{\eta_m}$$

Where, $P_m$ = power input required by motor

$P_s$ = power input required by pump shaft

s.f = safety factor (1.3)

$\eta_m$ = efficiency of motor (0.9)

$$P_m = \frac{2.56325 \times 1.3}{0.9} = 3.7025 \text{ kW} \qquad (55)$$

For Battery Sizing (Ref. 23), we consider the size of the battery required with a 3-day backup capacity. Our load is the pump rating (4 kW pumping 6hrs a day). To calculate the battery size required to provide for 3 days of back-up in the event there was no sun or wind, the battery bank would need to be rated as follows:

$$\text{Battery sizing} = \frac{\text{Total Load} \times \text{Days of storage}}{\text{System Voltage} \times \text{Efficiency after system losses}}$$

Total load = 4kW x 6hrs = 24kWh

System Voltage (48V) = sum of the rated open-circuit voltage of the series-connected PV modules.

Our battery sizing was

$$= \frac{24{,}000\text{W} \times 3 \text{ days}}{48\text{V} \times 0.8}$$

$$= 1875 \text{ Ah} \qquad (56)$$

Deciding to use 200Ah batteries, the numbers of batteries required will be:

$$\frac{1875 \text{ Ah}}{200\text{Ah}} = 9.375 \text{ batteries} \approx 10 \text{ batteries} \qquad (57)$$

This is approximately equal to 10 batteries which will form the battery bank for the hybrid system.

The total required power for pumping selected above for the system is 4kW and the wind turbine rating is 3kW therefore only 1Kw of solar photovoltaic modules is required. This will result in 10 solar PV modules each with a rating of 150W and the total amounting to 1.5kW (150W x 10). This is a safe design due to the fact that batteries reduce the efficiency of the system though they allow for longer periods of pumping. The solar section of the hybrid system will be the battery coupled solar pumping configuration as described in section 7.6.1 and a 48kv inverter is required to convert the dc voltage from the battery to the ac voltage required by the submersible pump.

## 9.3 COSTING

Since the wind/solar hybrid system is found to be a long-term efficient alternative in pumping water in comparison to other types of energy, it is important that the cost remains as low as possible. The initial cost of putting up a wind/solar hybrid system may not be low but the long term costs are far much lower as compared to other means of pumping water. The following is a table showing the pricing of the different components used in the design of the proposed system:

**Table 9 .4: Table of costs of proposed system components**

| ITEM | PRICE | QUANTITY | COST | SUPPLIER |
|---|---|---|---|---|
| Submersible Borehole Pump | 277,000 | 1 | 277,000 | Davis & Shirtliff |
| Opti SP 5000 48V DC Hybrid Inverter | 190,000 | 1 | 190,000 | Davis & Shirtliff |
| Sealed solar battery 200Ah 12V | 45,000 | 10 | 450,000 | Davis & Shirtliff |
| PVC Borehole Pipes Size 1.5” | 2,000 | 85 | 170,000 | Davis & Shirtliff |
| Concrete Tank ($54m^3$) | 550,000 | 1 | 550,000 | - |
| Wind Turbine 48V c/w controller | 124,000 | 1 | 124,000 | Davis & Shirtliff |
| Multicrystalline Solar Modules | 36,000 | 10 | 360,000 | Davis & Shirtliff |
| Labour costs | | | 50,000 | |
| | | **Total Cost** | 2,171,000 | |

# CHAPTER 10

## 10.1 DISCUSSION

Seasonal variation in wind and sun means there are periods where your stand-alone solar system or wind system will be limited in how much power it can produce to pump water i.e. during periods of low winds or calm, turbine produces limited power and on cloudy days the solar system is likewise limited.

Fortunately, we can utilize a hybrid system of wind and solar to capture the strength of each system, to create a balanced approach to producing energy of pumping. And on a bonus, for those days where we have both wind and sun, you increase your total efficiency since the system will be working under optimum conditions.

The proposed wind/solar hybrid system seeks to optimize and maximize the exploitation of wind energy and solar energy while experiencing the shortcomings that arise from the dynamic nature of wind and the uncertainty of the sun. The proposed design comes with a relatively high cost but with the output of the system, the benefits are immeasurable considering that enough water can be supplied to the proposed Bubisa community.

With the use of a 3phase centrifugal pump, water pumping at the high head(s) present in Bubisa can be made more efficient to provide the required water amount. A structure of three-day's worth of storage can be constructed to cater for the unfavorable periods with less than optimum weather.

The maintenance of this solar/wind hybrid system is not tasking since the machines can be inspected regularly every month, unlike the diesel machine which are known to break down frequently. The major components of the hybrid system being the wind turbine machine and the solar array as well as the batteries require little maintenance and have longer life.

## 10.2 RECOMMENDATIONS

A model of the proposed design should be constructed and tested in the field to ascertain the actual cost and performance of the system.

Such hybrid systems should be undertaken in Kenya due to various factors including:

- The favorable conditions available in the country to run such a project i.e. 12hours of sunshine throughout the year due to its geographical location along the equator and adequate wind speeds.
- The need for water distribution in most of rural Kenya and also to increase the water capacity available in the country thus tackling the problem of water shortages in the urban areas.

Alternative application of the wind/solar hybrid system would be to generate electricity to the adjacent region where the water pumping project has been put up depending on the scale of the undertaken project.

The are also challenges that will be met in setting up such a system due to its complexity in terms of matching the system components and sizing the system to suit the purpose, but this should not deter this kind of project being taken up therefore a detailed study of its feasibility should be done before a decision in undertaking it is done.

Pumping provides exposure to such risks as cavitation and pressures should therefore be kept at an optimum otherwise there would be an increase in maintenance costs of the pump.

In order to distribute water fairly to the rural community, it is recommended to first pump it to a storage facility and then distribute it by gravity. This way, enough pressures can be built up at the storage tank to facilitate water distribution by gravity. In addition, water will continuously flow in the tank, which helps to reduce growth of bacteria.

## 10.3 CONCLUSION

From the above results and analysis we have found out that a wind/solar hybrid system can be put up in most areas of Kenya with mean wind speeds of about 3 m/s since the average solar irradiation in the country is adequate due to its geographical position.

Through this system, we can supply water to the larger part of the 65% rural Kenya lacking access to piped water. Using the engineering design principles of setting up a water pumping system with all factors involved under consideration, we can use these natural energy resources to supply water as well as, depending on output and demand, supply electrical energy.

These hybrid systems are also eco friendly and seek to preserve the environment by reducing pollution levels by a considerable amount when compared to diesel, for example, as an alternative.

The solar / hybrid systems require a lot of starting capital but looking at the long term benefits, the systems are feasible. The maintenance procedures are also not complex though proper education is required in order not to mismanage or inappropriately use of the system e.g. overcharging of the battery and overloading of the system. The demand in Kenya for such systems is on the rise both for water pumping and electricity generation since both these amenities, water and electricity, are under a lot of pressure with an increasing consumption rate every year.

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