Study on the Development, Implementation and Validation of a Design model simulated for photovoltaic water pumping systems (PVPS)

A thesis submitted in partial fulfillment of the requirements for the degree of
Master of Science in Renewable Energy Technology

at the

Institute of Energy, University of Dhaka
January 2016

By

Momotaz Mahin Khan
Examination Roll number: 425
Registration number: HA- 327
Admission session: 2013-14

Supervisor's Declaration

The MS level research on "Study on the Development, Implementation and Validation of a Design model simulated for photovoltaic water pumping systems (PVPS)" has been carried out and the dissertation was prepared under my direct supervision. Herby I confirm that, to the best of my knowledge the thesis represents the original research work of the candidate; the contribution made to the research by me, by others of the University was consistent with normal supervisory practice, and external contributions to the research are acknowledged.

I believe the thesis to be in a suitable presentational form and is ready for examination.

Date: ____________________

Dr. Zahid Hasan Mahmood
Professor
Electrical and Electronic Engineering
University of Dhaka
Dhaka, Bangladesh

Candidate's Declaration

I confirm that this thesis represents my own work; the contribution of any supervisors and others to the research and to the thesis was consistent with normal supervisory practice. External contributions to the research are acknowledged.

Date: ____________________

Momotaz Mahin Khan
MS student
3rd Semester, Admission Session: 2013-2014
Institute of Energy, University of Dhaka
Dhaka, Bangladesh

Acknowledgement

The author wishes to express his deepest gratitude to his supervisor Dr. Zahid Hasan Mahmood for his guidance, advice, criticism, encouragements and insight throughout the research.

The author sincerely acknowledges Mr. Sheikh Zihadul Haque, Deputy Manager, B-Trac Engineering Ltd. Without his active participation, it was impossible to get the details and components required to designing a photovoltaic Pumping System (PVPS). Also the practical field data required to size a practical applicable and implement the PVPS.

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Abstract

In this thesis work a C++ (Programming language) Codelite, V9.0.1 Software was used to design a stand-alone Photo Voltaic Pumping System (PVPS). An algorithm was developed, which would design a stand-alone Photo Voltaic system for pumping underground water. The algorithm calculates the amount of energy required to draw the water for the specified height to give pump rating and the flow rate. The inputs required are amount of water required per day, number of autonomy days, the total dynamic height and the pump efficiency. To design the solar array the inverter voltage, single panel voltage and current (dependent on the individual panel power) is used to design the series and parallel array. The developed sizing method has been validated by applying it to one real scenario case where PVPS was already present. The obtained results was (1000 cubic meter water in 7.7 hours was pumped using 10 HP pump with 21 solar panel in series and 3 parallel arrays) have been compared with the characteristics of the real PVPS. The reliability of the design procedure has been verified, observing the similarity between the calculated out puts and the respective real values.

Abbreviations

- PV = Photovoltaic
- PVPS = Photovoltaic pumping systems
- TDH = Total dynamic head

Symbols

- E = Emittance [= 58.71 * 10^4 W m^{-2}].
- σ = Stephan-Boltzmann constant [= 5.67 * 10^{-8} W $m^{-2}K^{-4}$].
- T_s = Temperature of sun surface [K].
- E_s = Total radiation emitted by the sun [= 3.56 * 10^{24} W].
- R_s = Radius of sun [= 6.95 * 10^8 m].
- F_s = Solar constant [= 1370 W m^{-1}].
- d = Distance between earth and sun is about [= 1.49 * 10^{11} m].
- A = Albedo factor for the earth [= 0.28].
- R_{earth} = Radius of the earth [m].
- λ = Wavelength [m].
- t_s = Time of day.
- n = Number of days of the year.
- ΔE = Energy exchanged, *n* is an integer.
- ν = Wave frequency.
- h = Planck's constant [= 6.6261 * 10^{-34} J s].
- L = Length of pipe [m].
- g = Gravity acceleration [= 9.81 m s^{-2}].
- v = Average velocity of fluid [m s^{-1}].
- f = Friction factor.
- D = Diameter of the pipe [m].
- Q = Flow rate [m^3 s^{-1}].
- V_w = Daily volume required [m^3 day^{-1}].

- *pt* = Pumping time [hours].
- v= Water velocity [m s^{-1}].
- D= Diameter of the pipe [m].
- μ = Dynamic viscosity.
- h = Static suction head (+) or static suction lift (--) [m]
- $h =$ Suction line losses (friction, entrance and fittings) [m].
- h = Absolute pressure at the liquid's free surface [m].
- h = Vapor pressure of liquid at pumping temperature [m].
- ρ = Water density [= 1000 Kg m^{-3}].
- g = Acceleration due to gravity [9.81 m s^{-2}].
- η_r = Efficiency of the PV array at reference temperature [= 25°C].
- G_r = Solar radiation at reference temperature [= 1000 W m^{-2}].
- G_T = Global daily solar radiation on tilted PV array surface [kWhm^{-2}].
- η_{PV} = Efficiency of PV array under operating conditions [%].
- α = Cell efficiency temperature coefficient.
- T_r = Reference temperature [= 25°C]
- T_c = Daily average cell temperature [°C].
- T_a = Hourly ambient temperature [°C]
- *NOCT* = Module junction temperature under normal operating condition [°C].
- $G_{tot} =$ Irradiance in [W m^{-2}].
- *sh* = Daily number of sun shine hours.
- V_w= Daily required volume V_w [m^3/day]

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1. INTRODUCTION

Bangladesh is country where 16.3% GDP growth is achieved from the agricultural industry. Though the contribution to GDP reflects decrease but in reality, it actually is on the rise, with the growing technology. Rice is cultivated in approximately 75% of the land and water is an important factor that determines the cultivation/growth of rice. At times of draught, reduced rainfall can cause heavy damage to the agricultural crops. Proper irrigation system can be a solution to the problem.
As the first the irrigation activity requires to draw the water from the natural source. Depending by the cases it can be pumped from wells or from surface sources as a rivers or lakes. Subsequently the pumped water is supplied with different irrigation methods to the cultivated fields. Generally in remote agricultural areas all the pumping operations for the existent irrigation systems are usually driven manually or diesel powered. Indeed the national electric network is usually not enough wide to supply the needed electricity to the remote countryside. The lack of access to electricity for water pumping scopes is the main obstacle to irrigation deploying. PV stand alone systems are an available solution to produce directly in situ the electricity needed for the water pumping. So the operating principle behind any PVPS results quite simple: a solar generator provides electricity to drive a coupled motor--pump system, which in turn pumps water to an elevated tank that satisfy the water demand during night time periods and cloudy days [1]. *Figure 1* PV technologies also represents an expanding market as they present a good and viable solution for rural areas. However PV electricity is moderately cost effective when compared with the electricity provided by the national electric network, but it becomes cost--effective when the costs for extension of grid are considered and also when the payback is calculated. Moreover the stand--alone systems are cost effective when the load is not very large as for this kind of local water pumps [2]. This technology also doesn't increase the production of greenhouse gases by not using of fossil fuels. All the advantages of PVPS diffusion is in line with strategy of sustainable development.

The objective of the project is to develop and demonstrate a C++ software of an integrated the renewable PV water pumping technology for the agricultural purpose together with sustainable water resources management. It must improve the current difficult condition in rural areas.

The aim of this Master Thesis has been to develop a standard method to design PVPS. It consists in calculation model to size the PVPS (implemented by C++ Software) which has been integrated with the necessary design guidelines. PVP systems design is a complex activity because different regions have different environmental characteristics which require different technologic supplies. The PVPS can vary greatly in their technical characteristics depending on the conditions under which the pumping must take place. For example a considerable variability exists as regard the water need and source features:

- required water flow
- Water requirements schedule
- Water availability
- Depth from which it must to be pumped
- Replenishment rates of the source
- Variability of hydraulic head

In addition to size a good PVPS it is necessary to take in count the characteristics of solar irradiance. Such aspects are the working parameter which the designer must analyze to size a PVPS using the most suitable components as regard the PV array and the motor-pump subsystem. Therefore to choice the most suitable devices become very important to investigate their characteristics and feasibility. The weak point for their distribution is lack of tools serving to size these systems and predict their performances [3]. This master thesis has wanted to answer to this need.

The developed design method has been validated, applying it to one real cases of study. In this work for the one case has been assumed to design new PVPS, following the developed procedure. Then to verify the reliability of the method, the obtained outputs have been compared with the results presented in the two reference case. Finally using the implemented software has been investigated the effect of some input variables on the final PVPS characteristics. In particular motor-pump subsystem features and the variability of total head have been analyzed. In that way some additional recommendations for PVPS design have been obtained.

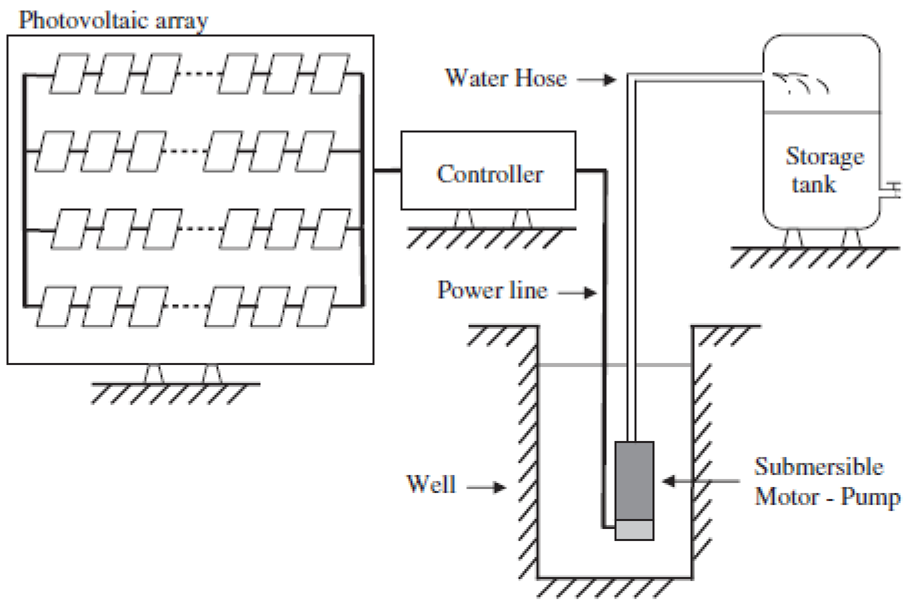


Figure 1: *Photovoltaic pumping system scheme* [4]

1.1 Objectives

The main objectives of this thesis are:

- To provide the guidelines useful to design PVPS system
- To implement a C++ Programme tool to size PVPS
- To study Environmental Impact Assessment (EIA) of using PVPS.

The model combines the advantages of simple input to obtain as output the power size of the array and the relative pump system. With this data and by other consideration about the work condition the designer can decide the most suitable components and layout of system.

1.2 Methodology

The great part of the background has been written using mainly as sources scientific articles, literature and internet. The developed PVPS design method consists of a mathematical part and a part concerning the technical guidelines. The mathematic method has been implemented using C++ software to create the software useful to size the PVPS. Such software has been integrated by the technical guidelines. The developing of PVPS design method has been inspired by procedures described for real cases of PVPS studies. For the validation procedure has been selected real components from manufacturer catalogues.

2. TECHNICAL CHARACTERISTICS OF PVPS

2.1 Advantages of PVPS

In remote areas where the extension of the national electric grid presents high cost, it is necessary to employ standalone technologies to produce the energy to pump water. Diesel water pumping remains an attractive solution due to the large power range of pumps. They can also provide different demands over the day, adapting to the variability of water need. This technology is already highly developed and common. However recent increase of fuel price and the needed of intense skilled maintenance for the diesel motor makes these systems a costly solution in the long run. Even if the water pumps are becoming more efficient, the water demand is always high, and the pumps still to have a high energy consumption [5]. Wind pumps offer long lasting solutions with a quite simple technology which can be easily understood and locally maintained. However, even wind pumps in last years have become expensive to install and to replace [6]. Other renewable technological options for renewable energy are hybrid system that combine solar--wind electricity generation, or can use dual fuel engines using biogas or producer gas [7]. However for the Chinese considered areas PV technology meets easily the needs of these remote communities. In particular for Qinghai area which is located in the high latitudes, the solar radiation resource is rich with the influence of dry climate. It also necessary to consider that PV technology comes down in price in the last 30 years. The PV systems are also very reliable if well designed and installed, also if a local assistance infrastructure is created for long term maintenance. Today the weak point is often represented from the battery. But such problem can be directly avoided using water tanks instead the battery bank [8]. PV pumping is a good cost effective solution for small distributed stand alone situations outside the electric grid. All these factors together are allowing the solar powered pumps to emerge in the market. Nowadays it exist a market for solar pumps which offers a range of different capabilities:

- Submersible pumps which can pump up to 200 m heads;
- Pumps that are able to deliver at 100 m a flow of 10 m^3/day or at 50 m a flow of 20 m^3/day;

According to [9] one of the advantages of solar powered pumps is its reliability. It usually requires little maintenance (3 to 5 years is the gap period between check-ups). The pumps for these systems need to be designed with the higher possible efficiency allowing the decrease of the size of the solar array and so lower upfront costs. Although there are no limits to how large solar pumps can be realized, they become more cost effective the smaller they are i.e. when diesel motors are less economical. The most effective way to minimize the cost of PVPS is to decrease the water demand through flow control. As example for the irrigation scopes the drip irrigation systems require a lower water consumption allowing to less pumped water.

In this thesis work it is simulated the usage of solar energy to supply a water pump which pumps water intended to an irrigation system.

2.2 General scheme for PVPS

Photovoltaic pumping system can be designed with different layouts. There are several motor and pump types that can be used. They present disadvantages and advantages at different operating condition, so it several factors must be considered in determining the optimum system for a particular application. Possible configurations of system are shown in *Figure 2*.

In general the simplest photovoltaic water pumping system is composed by a solar panel array directly connected to a DC motor that drives the water pump. This configuration uses DC motors and centrifugal pumps because they can be easily matched to the output of photovoltaic panel. Directly- coupled systems do not require inverter, battery and power conditioning circuitry. It leads to less costs, low maintenance and long life. However there are some cases when these systems can’t be used:

- Centrifugal pumps can’t be used with reasonable efficiency with large values of head.
- The pumping rate during the bright sunshine hours is greater than the water source renewal.

- It is necessary to use battery for energy storage (there are limits for the water storage).
- Location is characterized by excessive cloudy weather.

Whereas directly-coupled system can't be designed, the implementing of PV water pump proceeds by the evaluation of other components and configurations as it is described later.

The use of batteries can be avoided with the use a water storage tank. Batteries are commonly the weakness of the system, because they have short life expectancy and high cost of maintenance and replenishment. The solution of storage water than electricity reduces at the same time cost and complexity of the system [10]. In this MS thesis will be analyzed PVPS without batteries.

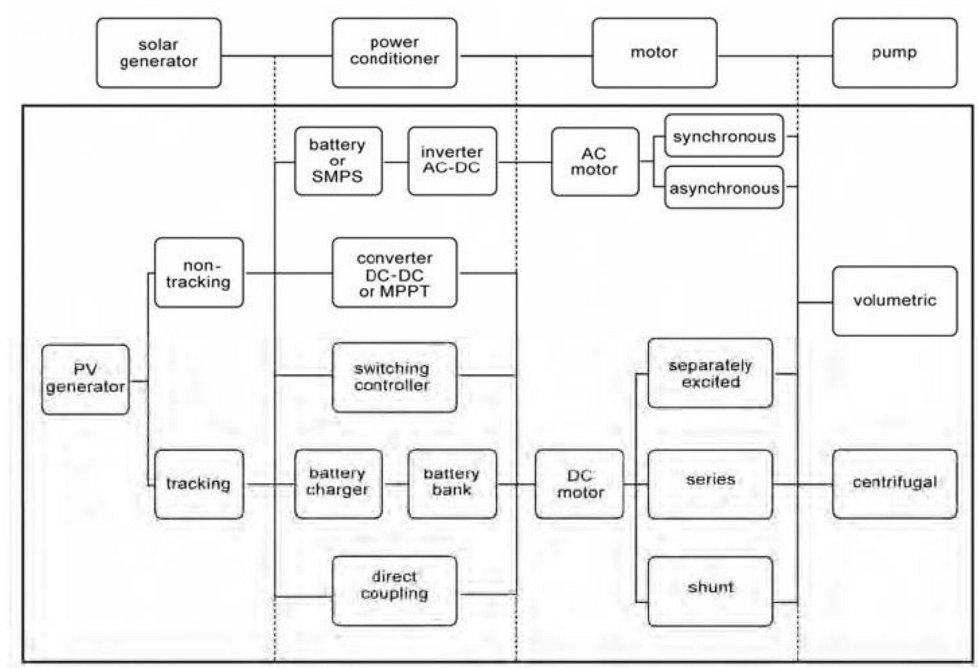


Figure 2: *Photovoltaic pumping system components and configurations [11]*

3. ENVIRONMENTAL VARIABLES

The environmental variables which affect the PVPS sizing process are ascribable to: the sun radiation, the water source characteristics and the daily water demand for irrigation.

3.1 Solar energy

The solar energy is radiant energy. With the scope to estimate the average energy amount that reaches the earth it is enough to consider the sun as a source of radiant energy similar to a blackbody at the temperature of 5800 K, as shown in *Figure 3*. The power emitted by the sun per solar area unit and time, is obtained from the Stephan--Boltzman law:

$$E = \sigma . T_s^{\ 4} \tag{3.1}$$

E = Emittance [= 58.71 * 10^4 W m^{-2}].

σ = Stephan--Boltzmann constant [= 5.67 * 10^{-8} W $m^{-2}K^{-4}$].

T_s= Temperature of sun surface [K].

Since the sun can be approximated to a sphere, it is possible to calculate the total radiation emitted as a product of the emittance by the surface of the sun:

$$E_s = E.4.\pi.R_s^{\ 2} \tag{3.2}$$

E_s= Total radiation emitted by the sun [= 3.56 * 10^{24} W].

R_s = Radius of sun [= 6.95 * 10^8 m].

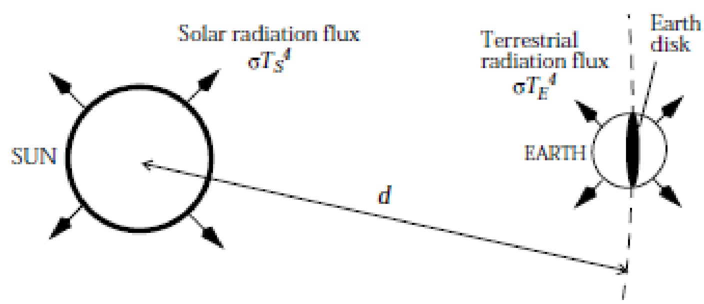


Figure 3: Flux of solar radiation [12]

Considering that the. The flux of solar radiation at that distance is uniformly distributed on a sphere centered in the sun and with a radius equal to the distance between the sun and the earth. The flux near the Earth's atmosphere is equal to:

$$F_s = E_s / 4.\pi.d^2 \tag{3.3}$$

Where,

F_s = Solar constant [= 1370 W m^{-1}].

d = Distance between earth and sun is about [= 1.49 * 10^{11} m].

The solar constant represents the thermal power that strikes a unit surface area placed perpendicular to the sun rays at the limits of the atmosphere. In reality it is not a constant because its value varies during the year of ± 3.3% due to the elliptical orbit of the earth [12]. Assuming to schematize the earth as a disk of radius equal to the Earth, some of the radiation intercepted is reflected back into space by clouds, snow, ice, etc... The factor *A* is called albedo, for the earth is 0,28. So the earth absorbs a radiation per unit equal to:

$$F_s = \pi \, . \, R^2_{earth} \, . \, (1 - A) \tag{3.3}$$

Where:

A = Albedo factor for the earth [= 0.28].

R_{earth} = Radius of the earth [m].

This means that the flux of solar radiation absorbed per unit area of the Earth's surface is equal to:

$$\frac{F_s \, . \, \pi \, . \, R^2_{earth} \, . \, (1 - A)}{4\pi \, . \, R^2_{earth}} = \frac{F_s (1 - A)}{4} \cong 169 \text{ W m}^{-2} \tag{3.4}$$

Therefore the power of solar energy which reaches a square meter of Earth's surface is very low. But there still be all the listed above advantages of photovoltaic energy compared with the other energy sources.To evaluate how much energy a photovoltaic can produce, it is necessary to evaluate which are the parameters that affect the solar radiation intercepted by the PV array. These parameters are of two types:

- Astronomical/geometric
- Weather

The former are due to rotation of the earth around its axis, the rotational motion and the motion of the earth around the sun. The astronomical parameters/geometry can be determined analytically. The meteorological parameters, unlike the former can't be calculated analytically because of their uncertainty. Therefore it is needed to base their studies on statistical analysis [13].

3.1.1 Astronomical and geometrical factors

Thermonuclear fusion reactions that occur inside the sun produce the solar energy. The hydrogen nucleus combines with the helium nucleus releasing energy. The energy produced in these reactions is transferred by radiation and convection to the outer part of the sun called photosphere. From here, the sun radiates radiant energy to the whole space form as electromagnetic radiation with the emission spectrum of *Figure 4.*

The emission spectrum represents the power spectral density Φ_λ [W m^{-2} μm^{-1}] as a function of the wavelength λ [m]. The emission spectrum of the sun is included for the 7% in the ultraviolet band, between 0.2 and 0.4 µm, for the 42% in the visible range between 0.4 and 0.8 µm and the rest in the infrared band between 0.8 and 3 microns. The photochemical reactions in the atmosphere are responsible of the absorption and the transformation of the energy radiation. The absorption of electromagnetic radiation from the sun is mainly due to:

- N_2 and O_2 absorption of X-‐rays and low-‐wavelength radiation.
- O_3 absorption of the ultraviolet radiation.
- $(H_2O)_{vap}$ absorption in the infrared.
- CO_2 absorption in the infrared.

The power density is the area under the curve of spectral density at the atmosphere surface, i.e. the solar constant:

$$\int_0^\infty F_S = \text{A.d}\,\lambda \qquad (3.5)$$

Where:

λ = Wavelength [m].

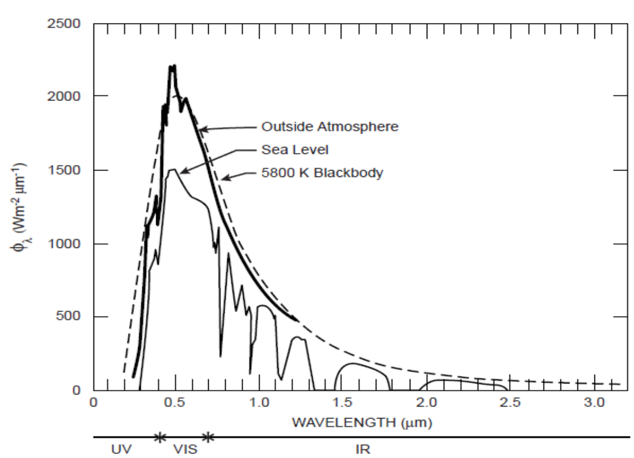


Figure 4: Emission spectrum of the sun [15]

The solar constant by definition refers to a surface disposed at right angles to the sun. The orthogonal condition does not usually occur on different points of the earth's surface. Indeed the sun's rays strike the ground with a certain angle respect to the plane surface, as it is shown in *Figure 5*. The angle varies during the day hours and also by days of year, due to:

- Changing of the seasons, the effect of rotation of the earth around the sun.
- Earth's axis tilted respect of the earth orbit plane.
- The night/day alternation and the effect of the earth's rotation around its axis.
- Relative position respect the equator.

Respectively, the effects produced by the rotational motion and the motion of revolution can be expressed mathematically by two angles as shown in *Figure6*. Hourly angle, it is the variation of the sun position above the horizon:

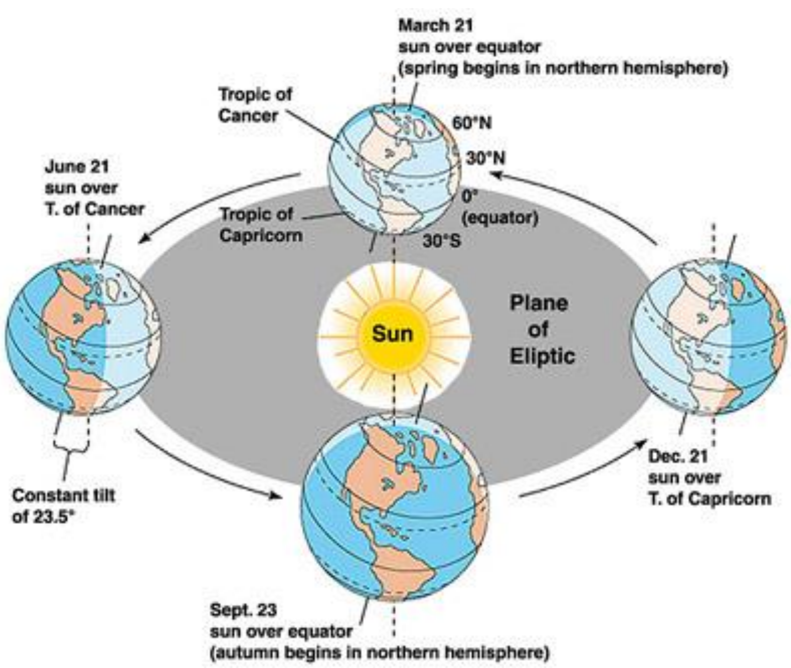


Figure 5: Motion of rotation and revolution of the earth [14]

$$\omega = 15\ (t_s - t) \qquad (3.6)$$

Where:
t_s = Time of day, ω takes values of the range from 0 to 12 solar hours and it varies of 15° per hour. It results in negative in the afternoon.

- Angle of declination, expressed by the formula of Cooper:

$$\delta = 23.5 \text{ Sin } \frac{[360 \,.\, (284+n)]}{365} \tag{3.7}$$

It represents the tilt angle of the equatorial plane with respect to the sun.

Where: $n =$ is the number of days of the year,

δ varies from -23.5 ° for the winter solstice to +23.5 ° at the summer solstice. It is null at the equinoxes.

The location position is expressed only in terms of latitude φ. Known the hourly angle, the declination angle and the location latitude, it is possible to calculate the solar power density for any location on Earth. By the following relation:

$$F = F_s(\cos\varphi.\cos\delta.\cos\omega + \sin\varphi.\sin\delta) \tag{3.8}$$

In addition, known the hourly angle, the angle of declination, the latitude of the site, the tilt and orientation of the collectors it is possible to calculate the sunlight incidence angle on the collector's surface for each hour of the day. In this way it is possible to determine the optimum tilt and orientation to maximize solar energy capture by the panels and so the cost-effectiveness of system. As regard the collectors orientation, considering only the astronomical factors, the optimum orientation is towards the south because in that direction there is the maximum exposure throughout the day. The deviation between the panels and the South is defined azimuth angle. The azimuth angle is 0 in the case of the collector facing South, +90 ° in the case where the orientation is to the West and -90 ° in the case of orientation towards the East.

3.1.2 Meteorological Factors

The atmosphere induces the phenomena of reflection on the solar radiation. Other not negligible effects are refraction and absorption. As first it is necessary to know the daily and the yearly average air temperature for the location and the cloudiness which influences the radiation. It would be desirable to know the speed and direction of wind. Indeed they can influence the temperature of the collectors, but simultaneously it is difficult to find that data. Moreover as regard the radiation, it is

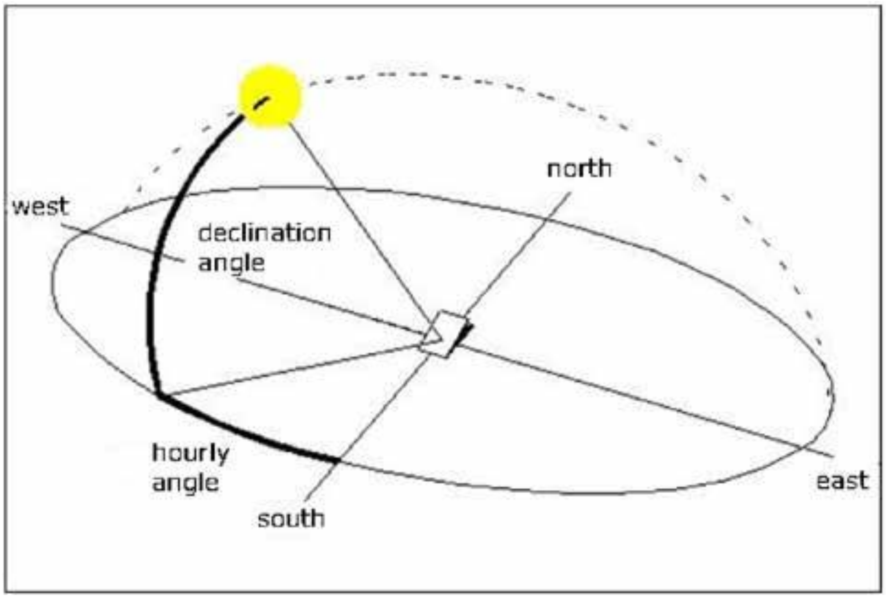


Figure 6: Hourly Angle and declination angle [14]

important to distinguish between the direct component, the diffuse one and the reflected light (albedo) which together make up the global radiation. The direct normal radiation is due to the rays which strike directly on the module surface and therefore it depends to: the orientation and inclination of the collectors and the position of sun respect the horizon. The diffuse component depends to the action of the atmosphere, clouds and aerosols. It causes a spread of radiation. The structure of radiation released changes depending by the weather conditions. Under conditions of completely overcast sky, the diffuse radiation is isotropic i.e. at each point an identical radiation is received from all directions. In favorable weather conditions the direct radiation contributes about the 90%. While during cloudy days the radiation which strikes the panels is almost exclusively diffused. The absorption of solar radiation also depends to the average density of the atmosphere and to the length of sunlight travel.

3.1.3 Solar potential

The solar potential can be described by the irradiance and the global solar radiation. The first one is the amount of solar power striking a given area. It is a measure of the intensity of sunshine and is given in units of watts (or kilowatts) per square meter (W m^{-2}), on a sunny day it is about 1000 W m^{-2}.

The second one is the amount of solar energy received on a given area measured in kilowatt--hours per square meter (KWh m^{-2}).This value is equivalent to peak sun hours, it is defined as the equivalent number of hours per day, with solar irradiance equaling 1000 W m^{-2} , that would give the same amount of energy. Therefore peak sun hours correspond directly to average daily radiation in KWh m^{-2} [15] as it is shown in *Figure 7.*

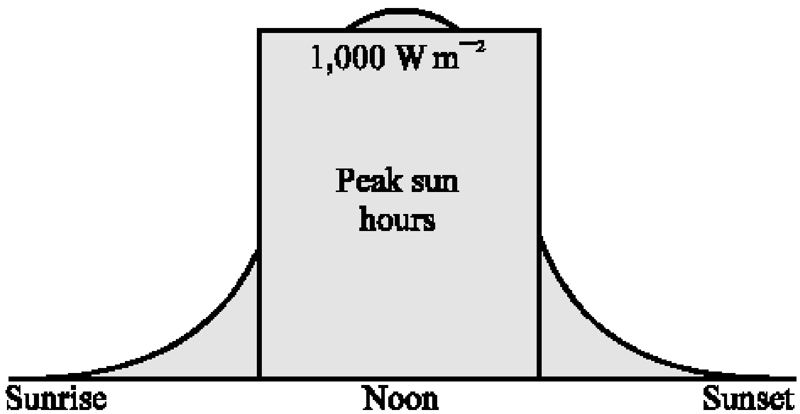


Figure 7: Definition of peak sun shine hours [16]

The global solar radiation (or peak sun hours) is normally chosen to size PVPS. It is usually selected the lowest monthly value of the irrigation period to ensure continuity of supply throughout that period which can be seasonally or yearly [16]. Solar radiation data are often presented as an average daily for each month, there are some online database or software which can help the search of that information.

3.2 Water source evaluation and supply

The water demand is the one main factors used to size the system. As first step it is necessary to analyze the water source characteristics. Depending by the different location, water can be available either from surface water (rivers, lakes etc.) or groundwater (wells). Some aspect should be taking in count as: availability, topography, hydrological ground features, annual rainfall and characteristics of the ground aquifer [2]. Also the quality of water is an important factor to be considered, for example a water source characterized by pollution as well as saltwater is unusable. Mainly deep wells have a better quality of water than shallow ones and surface sources.

As first step it is necessary to choose the exploitable water source of the area. Then the water demand for irrigation needs to be estimated. That procedure can turn out to be complex because it can depend by several factors, as:

- Size of the cultivated area
- Typology of the crop
- Soil characteristics
- Irrigation method
- Meteorological factors

However it is possible to use the *Table 1* to obtain a rough value of water demand. In that way just the size of the cultivated area and the typology of the crop are required.

In general it is needed to deliver the maximum water supply for a relatively short period (growing season). This peak of water demand is generally used to size the irrigation system [17].

Table 1: Estimating the water demand for an irrigation application [17]

Crops	Daily Water Requirement (m^3/ha)
Rice	100
Rural village farms	60
Cereals	45
Sugar cane	65
Cotton	55

4. SOLAR GENERATOR

4.1 Physics of photovoltaic conversion

The mechanism of photo-conversion can produce electricity directly from solar energy. A solar generator can directly convert the solar irradiance to electrical current. The conversion is performed by solar cells. A solar module (or panel) is a packaged, connected assembly of photovoltaic cells. This application uses the photovoltaic effect or more specifically the photoelectric effect. The semiconductor material atoms absorb the photons of solar light which is composed by solar ultraviolet, visible and infrared. That process promotes the electrons of this material from the valence band to the conductivity one. These electrons with the presence of an electromotive force move in an organized manner creating an electrical current [4].

To understand the process of converting sunlight into electricity is necessary to introduce some concepts in physics:

- photon energy
- energy band structure
- photoelectric effect
- generation of electron--hole pairs
- process of semiconductor doping
- p--n junction.

In 1900, Max Planck suggested that energy exchanges between the atoms of a body and the electromagnetic radiation do not occur continuously but by discrete packets called "quanta". This means that an electromagnetic wave exchanges with matter only these energy packets, proportional to the frequency of the wave:

$$\Delta E = n.h \cdot v \qquad (4.1)$$

Where:

ΔE= Energy exchanged, *n* is an integer
V= Wave frequency
h = Planck's constant [= 6.6261 * 10^{-34} J s]

In 1905 Albert Einstein starting from the Plank's idea, said that the radiation consists in itself of energy quanta called photons (the term photon was introduced later, in 1926 by Gilbert Lewis). The energy of photon at the frequency ν is:

$$E_{photon} = h \cdot \nu \tag{4.2}$$

Introduced the concept of photon, considering the material upon which the photon must interact it is possible to describe the concept of energy band,. The energy band is the set of energy levels possessed by the electrons within matter. This band is composed of:

- *Valence band*, it is the collection of electrons which have a low energy level. At this level belong the valence electrons responsible for chemical bonds.
- *Conduction band*: to the totality of electrons characterized by an energy level higher than valence band, sufficient to free an electron from binding with its individual atom and allow it to move freely within the atomic lattice of the material. Electrons within the conduction band are mobile charge carriers in solids, responsible for conduction of electric currents in metals and other good electrical conductors.
- *Band gap*: the totality of the energy levels is not allowed between the valence band and the conduction band. It is called energy-gap i.e. the amount of energy required to move an electron from the valence band to the conduction band.

In insulating materials the energy gap between the conduction band and the valence one is high and therefore only a few electrons have the ability to move to the conduction band. In case of conducting materials the two bands are overlapped and so the band gap is lacking. In this condition most of the electrons in the valence band have the energy needed to make the jump from the conduction band. This generates an electrical flow. Instead the semiconductor materials have a intermediate behavior between the two previously described. The energy gap is limited and therefore it requires sufficient photon energy to promote electrons from the valence band to the conduction. The energy of the photon must be:

$$E_{photon} = h \cdot v \geq E_g \tag{4.3}$$

Where E_g is the energy-gap and its value depends on the type of metal. This phenomenon is called the photoelectric effect and it doesn't occur just in metals but in all systems (atom, molecule or crystal) kicked by electromagnetic radiation. For such frequencies, when $E_{photon} > E_g$, there will be free electrons with a kinetic energy equal to:

$$E_k = E_{photon} - E_g \tag{4.4}$$

The kinetic energy of the electrons promoted from the valence band to the conduction band is a function of the incident radiation according to the relations:

$E_k = 0$ for $E_{photon} < E_g$ (issued no photoelectrons)

$E_k = 0$ for $E_{photon} = E_g$ (issued photoelectrons haven't kinetic energy left)

$E_k = E_{photon} - E_g$ for $E_{photon} > E_g$ (issued photoelectrons have a kinetic energy which grows Proportionally with the frequency)

The *Figure 8* shows the photoelectric effect for a slab of potassium [18].

Photons with sufficient energy are able to trigger the photoelectric process, while all the others only help to raise the temperature of the material that is due to molecular agitation. Nowadays the material mainly used for the production of solar cells is the crystalline silicon. Taking in count its atomic structure, each atom has 14 electrons, four of them the most external are the valence electrons. The latter are shared with four other silicon atoms to form covalent bonds which characterize the structure of the material. Silicon belongs to the 4th Group of elements in the periodic table. These bonds can be broken if an amount of energy is supplied to the material to promoting the valence electrons to a higher energy level (i.e. the conduction band, the energy-gap of silicon is approximately 1.1 eV). The flux of electrons from the valence band to the conduction one creates an hole. It is a gap which will be filled by an electron from an adjacent atom, creating electron-hole pairs. The generation of these pairs is random and disordered. To overcome this problem and create an orderly flux of charges (electricity) it is necessary to create an electric field inside the semiconductor. The creation of an electric field inside the silicon is obtained by two solutions:

1. The controlled introduction of impurities into the crystalline structure. It is called doping process.
2. The creation of a *p-n junction* joining two regions within the semiconductor, one doped p-type and one doped n-type.

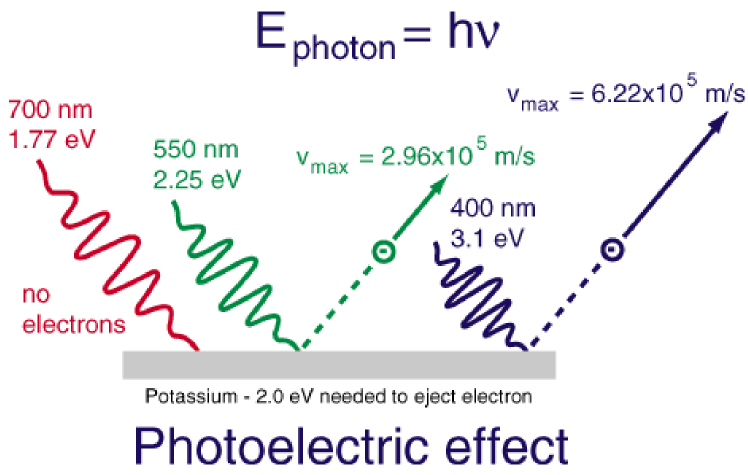


Figure 8 Schematic representation of the photoelectric effect for a slab of potassium [18]

The process of doping, shown in *Figure 9*, is the introduction of controlled substances into the silicon structure. They are impurities which can change the concentration of mobile charges. The silicon, which belongs to 4th Group, is doped with trivalent substances belonging to 3rd Group or by substances belonging to the 5th Group. The first ones are called acceptors while the second ones are donors' substances. Introducing the atoms of phosphorus (P) in the crystal structure of silicon, it is possible get a free electron for every atom of phosphorus entered. Phosphorus has 5 valence electrons by four of them it can form four covalent bonds with four silicon atoms, while the last one remain weakly bound to phosphorus atom. This last electron is able to move freely within the crystal lattice. Therefore it is available to conduct. For the silicon doping process with elements of 5th Group, the positive charges represented by the gaps are less than the negative charges. This amended semiconductor is called *n-type*. If boron (B) atoms are inserted into the crystal lattice of silicon, there will be a gap for each atom of boron released. Boron is an element of 3rd Group. Therefore it has three valence electrons which can form covalent bonds with three silicon atoms. This mechanism creates a gap which is able to move freely within the lattice. Hence it is also available to run. In the process of doping by trivalent substances, the positive charges (the gaps) are in excess

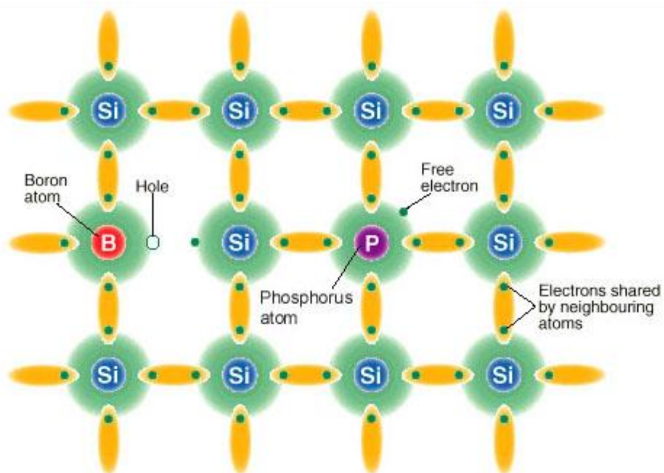


Figure 9: Semiconductor doping process [19]

Compared to the negative charges, electrons. So the doped semiconductor is called *p--type.* Semiconductor in both cases are electrically neutral, hence to generate an electric field and so an ordered electric current, it is necessary to put in contact the two layers of silicon p and n, resulting in a *p--n junction*. The connection of the two layers triggers a flux of electrons from the n--layer to the p--layer. When the point of electrostatic equilibrium is reached, there is an excess of positive charges in the n--layer due to the phosphorus atoms with one electron less and an excess charge positive in the p--layer due to electrons migrate from the n--layer. The n--type silicon is positively charged while the p--type is positively charged. The result is an electric field inside the device. The interaction between the photoelectric effect and the presence of an electric field creates the effect PV. Illuminating the p--n junction from the n--type silicon there is the electron--hole pair generation in both zones n and p. The electric field pushes in opposite directions the excess generated electrons by absorption of light and their respective holes. The electrons are pushed to the n--layer and the gaps to the p--layer. The free electrons, once crossed the field can't go back because the field would prevent that. Then connecting the p--n junction with a conductor, in the external circuit will result in a flow of electrons from the layer n that part of the junction to a greater potential to lower potential p--layer, as it is shown in *Figure 10*.

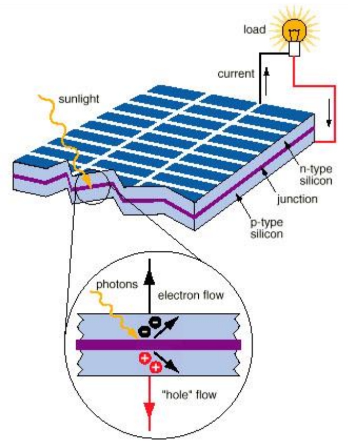


Figure 10: Photovoltaic effect [19]

4.2 Photovoltaic cell

Photovoltaic cell that is the fundamental device of each PV system, it is where the conversion of sunlight into electricity happen. The solar cell consists in a layer of a suitably doped semiconductor material with a thickness of between 0.2 and 0.35 mm. The cell is treated with an anti-reflective coating formed by the deposition of a thin layer of titanium oxide (TiO_2) which can reduce the reflected component. The flux of electricity generated within the cell can be channel through a collecting frontal metal grille and a back contact. The part of the energy radiated by the sun that can theoretically be converted into electricity in a photovoltaic cell is approximately 75%. That fraction is associated to radiation with a wavelength less than 1.1µm which is able to activate the photovoltaic effect. However in real cases the electrical efficiency of photovoltaic cells is less than 75% and it is between 12% and 17% depending on the type of technology used. This is due to:

- *Optical losses*: not all incident photons are able to arrive at the junction. Some are reflected by the glass in front of the host cell or by the grid.
- *Photons too much or too little energetic*: to break the bond between the electron and the nucleus requires certain energy, and not all the photons have enough energy. On the other hand, some much energetic photons generate electron-hole pairs, dissipating as heat the extra energy which is necessary to remove the electron from the nucleus.
- *Losses due to recombination* are observed when some pairs of positive and negative charges recombine before crossing the circuit.

- *Losses due to dissipation of heat or Joule effect*: a part of the energy is converted and lost as heat.

The solar cell can be schematized as a component of an electrical circuit. It comprise a diode which represents the p--n junction, then there is a current source represented by the current generated by light and finally there are two resistors, one in series and one in parallel which represent the losses due to joule effect and recombination. The equivalent circuit is shown in *Figure 11.*

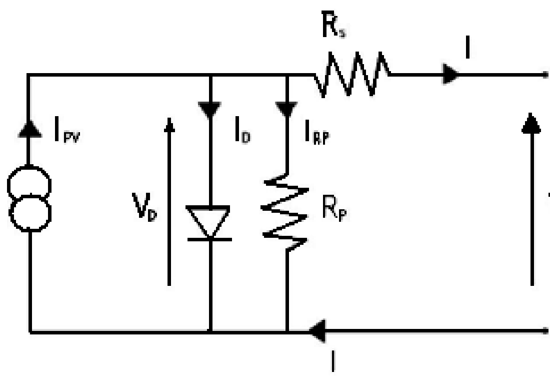


Figure 11: Electric circuit equivalent of a photovoltaic cell [20]

The characteristic curve of a photovoltaic cell, *Figure 12*, shows the trend of voltage--current for a given value of the incident radiation. The V_{oc} point is the cell's voltage for the open circuit while I_{sc} is the short circuit current. Considering that values of current and voltage, the electrical power supplied is represented by the area between the abscissa and the ordinate of the curve's point. In general, the product of the current--voltage is the power produced by a cell. At the project work point, the power P_m produce by the cell is maximum and it is calculable as the product between the voltage V_m and the generated current I_m. The cell doesn't produce power at open circuit condition (zero current and maximum voltage) or a for short circuit condition (maximum current and voltage zero) [20].

The performances of the photovoltaic cell are described by the fill factor *FF* (4.4). The cell efficiency η is calculated as the ratio between the maximum output power and the power of incident solar radiation:

$$FF = \frac{P_m}{V_{OC} \times I_{SC}} = \frac{\eta \times A_c \times G}{V_{OC} \times I_{SC}}. \qquad (4.$$

$$\eta_P = P_{m}/P_{inc} \qquad (4.5)$$

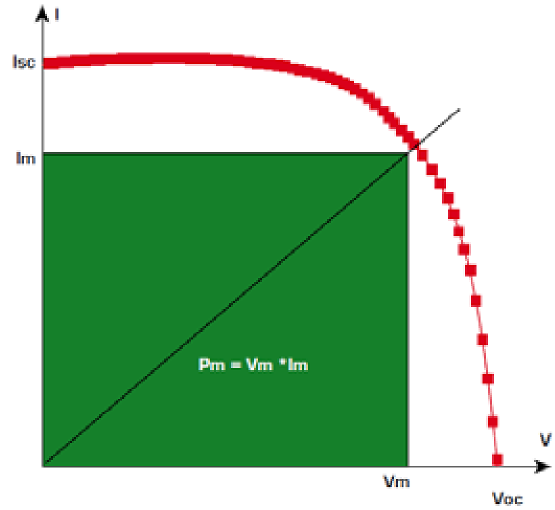


Figure 12: Characteristic curve of a photovoltaic cell [20]

The power of a solar cell varies with temperature and solar incident radiation. In particular, the temperature reduces the open circuit voltage, while the decrease of the incident radiation lowers the produced current as it is shown in *Figure 13* and *Figure 14* [20].

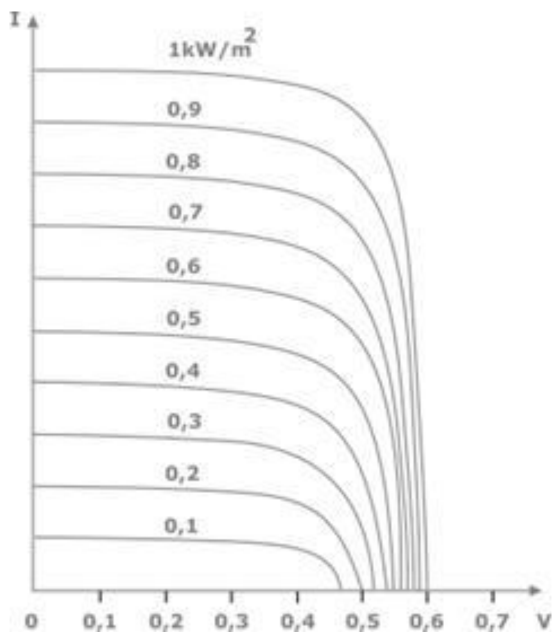


Figure 13: Characteristic curve to changes in the value of radiation [20]

To compare the characteristics of different solar cells, there are some international norms which set the standard test conditions (STC):

- Incident radiation: 1000 W/m^2

- Temperature of modules: 25 ° C
- Spectrum: atmospheric mass of
- 1.5 Wind speed: 0 m/s

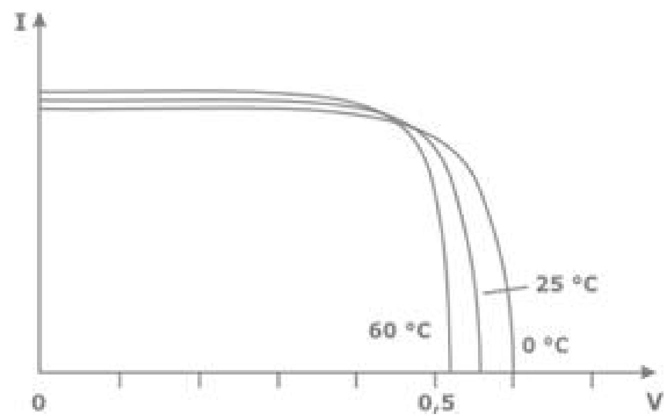


Figure 14: Characteristic curve to changes in the value of radiation [20]

The power that a cell is able to provide under standard conditions is that peak power *Wp*. The nominal operating temperature of the cell, *NOCT*, provides the thermal behavior of the modules and it is defined under the following operating conditions:

- Incident radiation: 800 W/m^2
- Temperature: 20 ° C
- Wind speed: 1 m / s

It is important to consider that when operating conditions deviate from standard values, the power output doesn't coincide with the peak and generally at temperatures above 25 °C the power output decreases depending by the *NOCT*. In general, the reduction of efficiency with increasing temperature is estimated at 0.4 to 0.6% per °C [19].

4.3 Available technical solutions

According with the available manufacturer processes, there are two mayor types of crystalline silicon solar cell now available on the market [20][21]:

- *Monocrystalline cells*: modules maiden with these cells have some advantages as: a very high efficiency between 12 and 16%, a high durability and maintenance characteristics over time. Some manufacturers provide the panel for more than 20 years with a loss of efficiency at the end of its lifetime of 10%. Nevertheless the most significant disadvantage of this technology remains the high cost due to the complex production process: Czochralski process. By this process it is possible to obtain a single crystal cylindrical ingot from a mono-crystalline silicon seed immersed in molten silicon. The cells are obtained by cutting the ingot into wafers of 0.20 to 0.25 mm thick. The upper surface of the wafer then undergoes a mechanical treatment designed to produce micro-grooves to reduce the losses by reflection. Monocrystalline cells are characterized by a homogeneous dark blue color *Figure 15*. The module surface area required is about $7m^2$/kW

- *Polycrystalline cells*: in this case the wafer has a thickness of 0.18 to 0.30 mm. They are produced by melting and then subsequent new crystallization of scrap silicon from electronics industry. The efficiency is lower than the monocrystalline silicon, it is around 12-14%. However, they have the advantage to be cheaper than monocrystalline cells and both the lifetime and the maintenance of performance over time are very high. The module surface area is about 8 m^2/kW. *Figure 16.*

Figure 15: Monocrystalline cell [22]

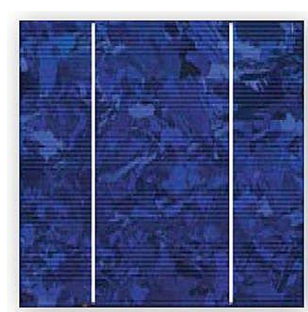


Figure 16: Polycrystalline cell [23]

In recent years the photovoltaic industry has had a remarkable development which has allowed investing in research and development of new technologies. The three main areas where research efforts are focusing are:

- *Thin film*: is the so-called "second generation" of solar cells. Nowadays the first applications are starting to spread on commercial scale.
- *DSC cells (Dye Sensitized Cell), organic and hybrid*: they represent the "third generation"

solar cells. This technology is still confined to research laboratories but it is the most innovative trend in the photovoltaic field.

- *Concentration systems*: they allow to exploit the effect of solar radiation concentration to reduce the use of silicon but maintaining the same installed power.

Actually, there are three families of modules known as thin--film technology for which expects strong growth in the coming years:

-

Modules in amorphous silicon (a--Si): It was the first thin--film technology used for PV, and they are the most common thin--film module in use. They are produced by a process of vaporization and subsequent deposition of a thin layer of silicon (1--2 µm) on a support surface, usually glass or flexible plastic materials. Amorphous cells are cheaper than crystalline silicon cells, but they have low efficiencies, typically 6--8%. Another limitation is the significant degradation of performance after the first few months of exposure to sunlight. An interesting application of thin--film modules is multi--junction (or tandem technology), where a layer of amorphous silicon is coupled with one or more layers of polycrystalline silicon. Each junction is treated differently in order to have different responses to the spectrum of light. The result is the increase of the operating band in the solar spectrum. For example, a photovoltaic module constructed with this type of technology, compared with a silicon crystal, although less efficiently, at the same power it can yearly produces a 20% of more energy because it has a better response to diffuse solar radiation. The surface required is about 16 m^2 kW^{-1}.

- *Cd--Te modules*: they are produced using cadmium tellurium as the semiconductor. It has a spectrum absorption band higher than the silicon semiconductor. The efficiency of this type of modules is greater than the silicon modules at high temperatures and with diffuse radiation. However the disadvantage consists on the hazard of cadmium, despite the presence of this element is very small. It amounts to 50 g/m^2.
- *Forms CIS / CIGS:* their working is based on the use of ternary compounds, or their alloys, formed by elements such as sulfur, aluminum, gallium, copper, selenium with a crystal lattice suited to facilitate the current.

Also the third generation photovoltaic cells can be classified into three type's families:

- *DSC cells (Dye Sensitized Cells)* they are electrochemical cells where the absorption of solar radiation occurs by a dye molecule attached to a nanostructured titanium oxide electrode. There is a great faith on this technology according with the further reduction of production costs.

- *Organic cells:* they include all those devices of which the photoactive part consists of a thin film, based on carbon compounds. It is placed between two conductive electrodes and supported by a substrate of glass or plastic. The most efficient organic cells (efficiency of 1-2%) bases their working principle on the photosynthesis process. They use a mixture of materials to maximize the absorption of the solar spectrum.
- *Hybrid cells*: they are obtained by deposition of organic and inorganic hybrid materials in liquid solution on a support material (even flexible). Actually, the efficiency of this type of cells is around 1%, but the main advantage lies in a very low production costs. Indeed typical production processes of the printing industry can be employed, avoiding in that way the high costs of material and the typical process of the semiconductor industry.

The concentrator PV systems use special optics to concentrate the solar radiation in order to irradiate silicon solar cells. Unlike conventional solar panels, this type is able to exploit only the direct solar radiation. Nowadays there are two main types:

- *Type systems "Focus Point":* each cell has a dedicated optical concentrator and the concentration is punctual.
- *Type systems "Dense Array"*: there is only one optical concentrator for multiple cells arranged along a line where the concentration takes place.

The efficiency varies from about 12% when monocrystalline cells are used with a concentration optical factor of 30x, to a maximum of about 40% in the case of multi-junction cells with a concentration optical factor of 200x.

4.4 Photovoltaic modules

A PV module consists of the parallel--series connection of individual cells in order to obtain the voltage and current desired. The manufacturing process of the modules is divided into three phases:

- Electrical connection
- Encapsulation
- Mounting frame and junction box

The electrical connection is done assembling the cells with similar electrical characteristics in order to reduce losses due to decoupling. Then the cells are encapsulated between a glass plate and a plastic seal, thus ensuring the resistance to ultraviolet rays and high temperature. The encapsulation ensures the long modules lifetime which currently stands at around 25--30 years. The mounting of the module frame provides extra strength and it allows anchoring the module on the support structures. The mechanical connection of several modules assembled in a single frame is called the photovoltaic panel. A string is a configuration where the panels are electrically connected in series. While the parallel connection of two or more strings form the photovoltaic field [19].

The main technology of modules used for PV water pumping: polycrystalline and thin film (amorphous--silicon and cadmium--telluride).

The reasons to choice polycrystalline modules for water pumping are:

- Actually 85% of PV modules produced in world are polycrystalline, so it is easy to find replacement modules or adding additional modules to array.
- Module efficiency is higher than thin film (12 to 14% versus 3 to 8%), so a small number of modules are required saving more space.
- Lifetime over 30 years has been warranties up to 20 years are obtainable (thin film modules have shorter lifetime).
- They can be disposed off in landfills while the thin film cadmium--telluride modules can’t because the cadmium is toxic.

- Only slightly declining power output with time (about 1% per year) while a-Si thin film modules experience decreases about 20% in power output, during first 6 months when it is exposed at sun. Even if the performance decreases similar to polycrystalline after initial 20% decrease.
- Less probability of break than the thin-film technology. Indeed the tempered glass results very resistant.

However even thin-film modules have some advantages of thin-film:

- They can generate higher voltages than polycrystalline modules. The high voltages are important in water pumping applications above 200W.
- Since most of the multi-megawatt PV installations in world are Cd-Te, the price per Watt for thin film is cheaper for large PV installations.
- Less percentage of power loss for increased panel temperature compared to polycrystalline.

4.5 Tracking

As regard the practical make up of solar panels, the modules can be installed in a tilted stationary position or on a mobile support which can vary their position following the movement of the sun. In that way sun rays can strike directly the panel surface all over the day. Thanks to the tracking system the modules can deliver about 40% more electricity in an average year than static modules in favorable climatic local condition [24]. There are two common tracking options *Figure 17* : one-axis tracking *a)* and two-axis tracking *b).*

However the traditional static configuration still attractive because requires minor complexity and less costs, and also the thin-film price continues to fall, making this latter solution more competitive than tracking system. A basic form of tracking can be achieved manually, adapting three or four times a day the position of the panel surface depending by the sun's trajectory, in that way it is possible to reach over the 90% of the electricity yielded by a fully automatic tracker can be obtained [18]. Tracking is recommended for latitudes less than 40°[21].

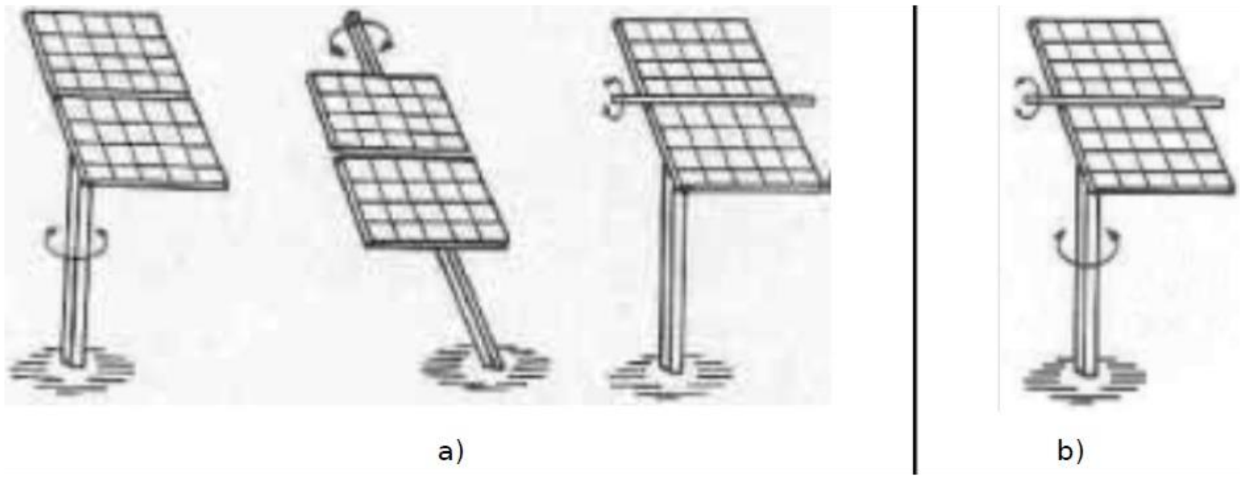


Figure 17: Common tracking options: one--axis tracking fig a) and two--axis tracking fig b) [25]

5. MOTOR-PUMP SUBSYSTEM

Motor--pump subsystems are generally composed by a drive motor and a pump. Before analyzing the most common motor pump--subsystem configurations, it is useful analyzing the two main components separated. In that way it is possible to understand in which working conditions different types of devices are most suitable.

5.1 Drive motors

The drive unit converts electrical energy into mechanical energy, and since rotational motion is preferable for use in operating pumps, electric motors are inherently well suited for the task [25]. Small motors (< 2 kW) of high efficiency that are well suited to photovoltaic water pumping are still relatively rare. Indeed there is a typical fall off in performance as motor size decreases *Figure 18*, which compounds the problem of reduced pump efficiency at smaller sizes. The *Figure 18* also clearly shows the superior efficiency of DC versus AC motors. Owing to the high cost of solar panels, it becomes justifiable in many applications to use more expensive DC motors to gain an efficiency advantage. However, there is the decreasing trend of PV modules prices which will tend to shift priorities away from motor efficiency in favor of lower cost, lower maintenance machines. Moreover, AC motors general tend to be cheaper, which often complicates the choice [11].

Motors are generally classified into two main families DC and AC.

5.1.1 DC motors

This kind of motor is driven by a direct current. A DC power supply has two wires one positive and the other negative. When they are connected to the DC motor, the shaft rotation is driven by magnetic flux through armature, following the principle of Lorenz. Indeed it states that any current--carrying conductor placed within an external magnetic field experiences a torque. Permanent magnet or the field winding produces this magnetic flux that causes the current--carrying armature conductors to create torque on the shaft which rotates the load (pump).

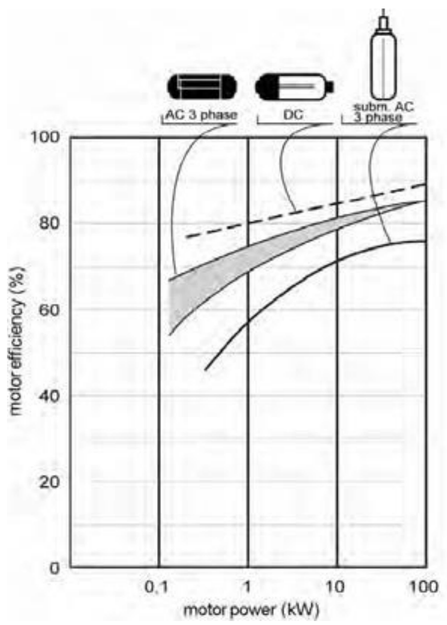


Figure 18: Performance of DC and AC motors as a function of size [11]

There are four basic types of DC motors:

- *Series--Wound DC motors* have severe limitation when they are driven directly by photovoltaic panels because a decrease of light intensity produces current drop in the armature winding which causes a motor performance down. Therefore they tend to pump more water than shunt DC motors on sunny days [26].
- *Permanent magnet DC motor* overcomes the limitation of above motor *Series--Wound DC motors*. Indeed they have permanent magnets instead the field windings; therefore the produced magnetic flux is constant and independent by the armature current and light intensity. So the performance results independent by external variables. Beside to improve the motor starting torque for low light levels, it also ensures excellent performance under reduced

loads. At half load such motors reduce their efficiency less than 10%. This makes this type of motor attractive for smaller PV applications [11].

- *Shunt-Wound DC motors* for these motors the field current is determined directly by the motor voltage according to:

$$I_f = V_m / R_f \tag{5.1}$$

Where I_f is the field current, V_m is the motor voltage and R_f is the field resistance. Similarly, for the armature:

$$V_m = I_a R_a + K\phi N \tag{5.2}$$

Where I_a is the armature current, R_a is the armature resistance and $K\phi N$ is the motor electromotive force (where K is the motor constant, ϕ is the permanent magnetic flux, and N is the motor speed). Initially N is zero, which means, in systems where motors are directly coupled to solar panels the startup is limited on high values of light flux to obtain the needed voltage to win the armature resistance. Therefore this type of motor results unsuitable for direct coupling to photovoltaic panels, they must be used only in conjunction with a booster [11].

- *Brushless DC motor* has the permanent magnets in the rotor and electronically commutates the stator to remove the need for brushes. They tend to be more expensive than other motors. But they still have very significant advantages compared to the above three motor types which have brushes [27]. Indeed brushes can be globally considered as a weak point for a motor, because these components are subjected to certain wear out so they require a replacement every 1–5 years with the relative increase for the costs of maintenance. Moreover brushes represent an operative limit for this motors which can't operate in submersible conditions [5].

5.1.2 AC Motors

This kind of motor is driven by an alternate current. There are several types of AC motors commercially available, and they have been used for many years in wide range of applications. That is due mainly to the low cost rather than the operation efficiency. In particular they don't result very suitable for application like stand-alone PV pump system where in general the powers required are low as about 1 KW. They have good efficiency for medium an elevate power demand [28][29].

The simplest and cheapest type of AC motors is the squirrel-cage induction (asynchronous) motor. Its low cost and the rough construction make it the most employed motor for PV applications. The other types of induction motor are the wound-rotor motor but they are generally used for industrial applications [17].

Induction motors with squirrel-cage rotors are available in either single phase or three phase. They require inverters at their inputs and also an additional power conditioning circuitry is generally required to provide the high starting currents [11]. An induction motor operates at nearly constant speed and the use of inverters to control induction motor speeds is highly efficient for a wide range of speeds and loads [17].

5.2 Pumps

A pump displaces a volume by physical or mechanical action. Depending by their operating mode pumps are classified in two main families: rotodynamic and positive displacement pump.

5.2.1 Rotodynamic pumps

According to [28], the rotodynamic pump works with the principle of converting kinetic energy of a flowing fluid into static pressure. These pumps use a rotating impeller (or rotor) to increase the fluid pressure. This movement accelerates the fluid so when it exits from the impeller, a part of the momentum is converted into static pressure. That kind of pumps is normally employed to pumping large water volumes at low medium heads. In particular they are very suitable if a direct tied to solar panels is required. The high efficiencies are obtained for small pumping heads, less than 25 m. It is important to considerer that such pumps are designed for a fixed head, so their efficiency noticeably decreases when the pumping head varies from the design value. To improve performances several impellers are stacked in a pump to create enough pressure to lift water to a higher head (multi stage arrangement). These devices have also a good feasibility due to compact size which makes that pumps well suited for small diameter bores or exist wells. Other vantages are: cost--effective (large-- scale production), easy starting and a broad range of head and delivery specific applications [1].

Commercially available rotodynamic pumps are [11][17]:

- *Axial flow pumps (propeller pumps):* They are good for high flow and low heads application. Generally these kinds of pumps are designed at 0.04--4 m^3 s^{-1} demand and 1.5--3.0 m head for vertically mounted applications, by additional impeller it can achieve to 10m. They need large pipe diameters; the concrete types are common used instead of steel pipes to contain costs. However significant civil works are needed to system installation
- *Radial flow pumps (often called centrifugal pumps):* They can be surface--mounted, floated or submersible depending on the requirement. Such pumps can lift medium to large volumes of water (to about 200 m^3/day) from shallow to deep wells (till 150--200 m) using a series of impellers especially on submersible configurations. Floating pumps are suspended just below the water surface thanks to a float. They use just an impeller and the lifting capacity of such pumps is limited to approximately 6 meters.
- *Vertical turbine pumps:* Generally consist of submerged stacked impellers powered by a long drive shaft from a surface--mounted motor. They have the advantage surface-- mounted motor which can be easily accessed for repair and maintenance. However, that motor layout is a limit as regard the pump efficiency which is reduced by twisting, vibration, and friction in the drive shaft. These pumps may also have bearing problems. Moreover installing them can be difficult and time consuming. They are used for deep well but actually they are supplanted by submersible centrifugal pump sets.

5.2.2 Positive displacement (volumetric pump)

Commercially available positive displacement pumps are categorized into two types: submersible (diaphragm) and non--submersible (jack, piston, and rotary vane). The most common is the jack pump. All positive displacement pumps have many mechanical parts such as pistons, cylinders and elastic diaphragms. All these components can easily wear out, so such pumps require regular maintenance to replace or repair worn parts. These pumps are self--priming and also their efficiencies tend to suffer less conditions of partial load than the centrifugal types. The water output of a positive displacement pump is almost independent of head but is directly proportional to speed of operation, with a fairly constant torque required. The torque developed by a motor depends directly on the current in armature so it requires a constant current to suit a constant torque pump. This type of load is not well matched to the output of solar cells, because the current generated is directly proportional to the light intensity. So it is not suitable drive this pumps coupled directly with a photovoltaic source [11][17].

In general at high speeds positive displacement pumps can be more efficient than rotodynamic pumps. But at low heads (below about 15 meters), positive displacement pumps are less efficient because the total hydrostatic forces are lower than the frictional forces. Therefore, in that situations they are less likely employed. Commercially available positive displacement pumps are:

- *Diaphragm pumps (often called submersible positive displacement pumps)* are used to pump small quantities of water from deeper wells. They are generally employed when surface pumps are unsuitable because the suction head is too high. Diaphragm pumps generally use DC motors. They need periodic maintenance depending on the depth of head pumped and their operational hours.
- *Jack pumps* are usually used for medium applications at medium depth. They require regular maintenance, especially because the leathers on the plunger at the end of the long sucker rod can wear out easily. The leather is used to create seal against the cylinder.
- *Piston pumps* are generally connected to a surface--mounted motor. They can be used both for shallow wells and for surface water sources, because the suction head of these devices is limited at 6 meters. They are not tolerant to silt, sand, or abrasive particles because the piston seals are easily damaged. However filters may be used to remove the dirt.
- *Rotary vane pumps* (sometimes called helical rotor pumps) move water by a rotating dispenser. Such pumps are mostly surface--mounted depending by suction head limitations. It is limited to 6 at meters. They produce a continuous or sometimes a slightly pulsed water output. As main advantage they can pump higher volumes of water per day even at

low motor speeds. Rotary vane pumps are not tolerant to silt, sand, or abrasive particles, so filters may be used to remove dirt. However the unique advantage of helical rotor pumps over centrifugal pumps is their ability to operate efficiently over a wide speed ranges and heads, whereas the efficiency of centrifugal pumps deteriorates from the rated speed.

5.2.3 Net Positive Suction Head (NPSH)

For any cross-section of the hydraulic system, the NPSH parameter displays the difference between the actual pressure (meters of head) of the water in the pipeline and the water's vapor pressure at a given temperature. NPSH is an important parameter to consider for the hydraulic circuit design, whenever the liquid pressure drops below the vapor pressure the liquid boiling occurs, *Figure 19*. That process is called cavitation and vapor bubbles may reduce or stop the liquid flow until to damage the system. Two aspects of this parameter must be considered to choice the pump, one is the $NPSH_A$ (available) and one is the $NPSH_R$ (required).

According to the latest edition of the Hydraulic Institute Standards, Net Positive Suction Head available ($NPSH_A$) is defined as: "the total suction head in feet of liquid absolute, determined at the suction nozzle and corrected to datum, less the vapor pressure of the liquid in feet absolute".

In somewhat simpler terms, $NPSH_A$ is the absolute pressure in feet of liquid at pumping temperature available at the pump suction flange, above vapor pressure. Mathematically this looks like [31]:

$$NPSH_A = \pm h_s - h_l + h_a - h_v \quad (6.1)$$

Where:

- h_s = Static suction head (+) or static suction lift (-) [m]. It is the difference between the inlet of the pump and the water level into the well.
- h_l = Suction line losses (friction, entrance and fittings) [m].
- h_a = Absolute pressure at the liquid's free surface, in meter of liquid pumped. for open tank is used the atmospheric pressure, while for closed pressurized tanks the absolute static pressure inside the tank must be used [30]. Typical values of atmospheric pressure depending by the

altitude of location are in the *Table 6.*

- h_v= Vapor pressure of liquid at pumping temperature, in meter of liquid. Vapor pressure is defined as that pressure exerted by the gaseous state of a liquid that is in equilibrium with its liquid phase. Better still, try this definition: Vapor pressure is that pressure at which a liquid begins to vaporize, i.e. boil. Typical values of vapor pressure depending by the water temperature are in the *Table 7.*

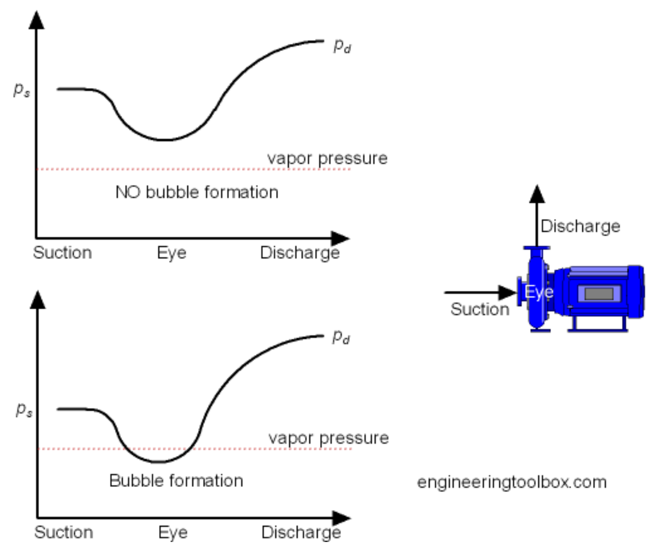


Figure 19: Cavitation pressure condition [30]

NPSHR is "required" by the pump because each pump model has a specific range of values for that parameter. In general the pump performance curves plot NPSHR versus flow. That data are usually provided by the pump manufacturer. Therefore it can have different representation depending by pump the manufacturer. In case is not provided by the manufacturer, it can be experimentally determined by several methodologies. One procedure is operate the pump under study with clear water while incrementally reducing NPSHA by throttling a suction valve. The on--set of cavitation is then observed and recorded at controlled flow rates. The on--set of cavitation is officially defined as corresponding to a 3% drop in total developed pump pressure. Obviously there is sufficient cavitation that is already occurring to produce this 3% reduction in discharge pressure.

Table 2: Typical values of atmospheric pressure depending by the altitude [32]

Altitude[m]	h_0 [m]	Altitude[m]	h_0 [m]
0	10.33	1600	8.57
100	10.22	1700	8.46
200	10.11	1800	8.35
300	10	1900	8.24
400	9.89	2000	8.13
500	9.78	2100	8.02
600	9.67	2200	7.91
700	9.56	2300	7.8
800	9.45	2400	7.69
900	9.34	2500	7.58
1000	9.23	2600	7.47
1100	9.12	2700	7.36
1200	9.01	2800	7.25
1300	8.9	2900	7.14
1400	8.79	3000	7.03
1500	8.68	3100	6.92

Table3: Typical values of vapor pressure depending by the water temperature [32]

T_w [°C]	h_v [m]
0	0.07
2	0.08
4	0.09
6	0.1
8	0.11
10	0.13
12	0.14
14	0.16
16	0.18
18	0.2
20	0.23
22	0.26
24	0.29
26	0.32
28	0.36
30	0.41

The actual start of cavitation is known as incipient cavitation and it always occurs well before the point of $NPSH_R$ is reached. As regard the pump selection, theoretically to preclude pump cavitation:

$$NPSH_A \geq NPSH_R \quad (6.2)$$

Practically, in order to compensate for system variations and incorrect analytical assumptions:

$$NPSH_A \gg NPSH_R \quad (6.3)$$

The available $NPSH_A$ of the system should always exceed the required $NPSH_R$ of the pump to avoid vaporization and cavitation of the impellers eye. The available $NPSH_A$ should in general be significant higher than the required $NPSH_R$ to avoid that head loss in the suction pipe and in the pump casing, local velocity accelerations and pressure decreases, start boiling the fluid on the impeller surface. Generally when the $NPSH_A$ is calculated it can be divided for a safety factor which is in the range from 1,3 to 1,7 [10] in that way is obtained the maximum value acceptable for the $NPSH_R$.

Pumps with double-suction impellers have lower $NPSH_R$ than pumps with single-suction impellers. A pump with a double-suction impeller is considered hydraulically balanced but is susceptible to an uneven flow on both sides with improper pipe-work [31].

5.3 Motor-pump configuration options

Five different physical configurations are the most commonly employed [10]:

- *Submerged multistage centrifugal motor pump set.* This scheme is often used for medium depth wells with centrifugal pumps which are automatically primed and safer from damage a theft. This layout can use AC or DC motors. If an AC motor is chosen, an inverter has to be used as well. Generally for existent system the PV array is usually less than 1500 Wp [11]. In this configuration, both pump and motor are suspended in the water. Therefore the submersible motors are smaller in diameter and much longer than ordinary motors to adapt to the well shape. However due to their smaller diameter, they are less efficient motors than surface motor. Submersible motors can be also classified depending by the operating condition in dry or wet motors.
- Dry motors are hermetically sealed with a high dielectric oil to exclude water from the motor.
- Wet motors are open to the well water so if they run in dry condition can overheat and burn out. Therefore, the length of riser pipe must be sufficient to keep the motor always completely submerged [37]. *Figure 20.*

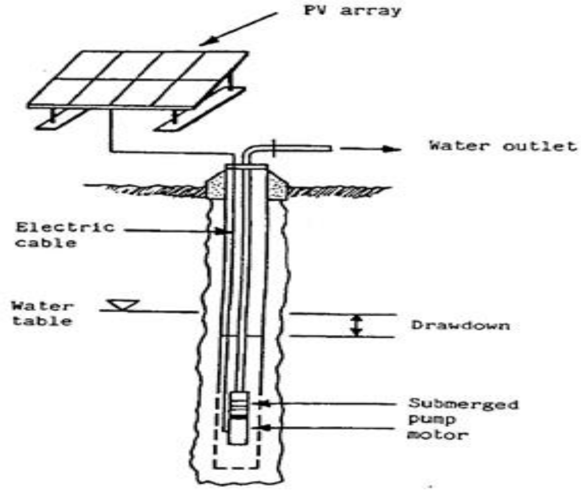


Figure 20: Submerged multistage centrifugal motor pump--set [adapted from 43]

- *Submerged pump with surface motor*. This kind of subsystem is advantageous for motor cost maintenance because it is easily accessible by technicians. However this configuration results globally unsuitable for high cost systems and the efficiency problems due to the power losses in the shaft bearings [17]. *Figure 21.*

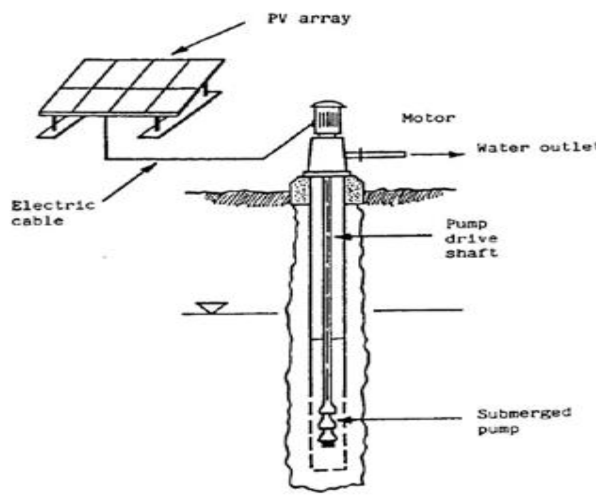


Figure 21: Submerged pump--set with surface motor [adapted from [43]

- *Floating motor--pump.* This design is recommended to surface water resources (lakes, rivers, canals…) and it is very suitable for irrigation scopes. Generally it uses a DC motor and often the solar energy array support incorporates a handle or “wheel barrow” type trolley to enable transportation*. Figure 22.*
- *Reciprocating positive displacement pump (volumetric pump):* This motor--pump layout is very suitable for high head and low flow applications. In latter conditions the frictional forces are lower than the hydrostatic forces, making positive displacement pumps more efficient than

centrifugal for these situations. *Figure 23.*

- *Surface suction pump set*: This type of pump set is usually not recommended except when an operator is always present to control the pump operation. Typical self--start and priming problems can be prevent by the use of primary chambers and non--return valves. Both centrifugal and positive displacement can be suitable pump types. It is not possible to have suction heads of more than 8 m. *Figure 24.*

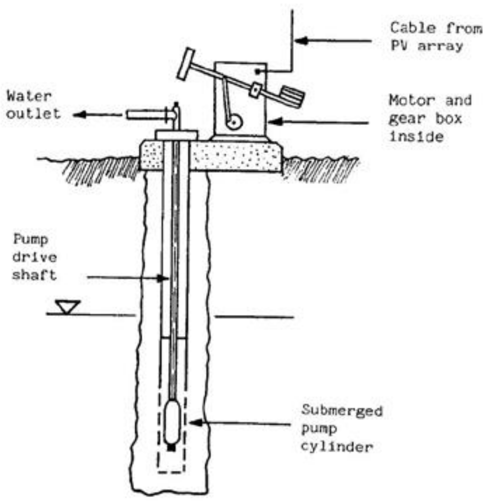


Figure 23: Positive displacement pump pump [adapted from [43]

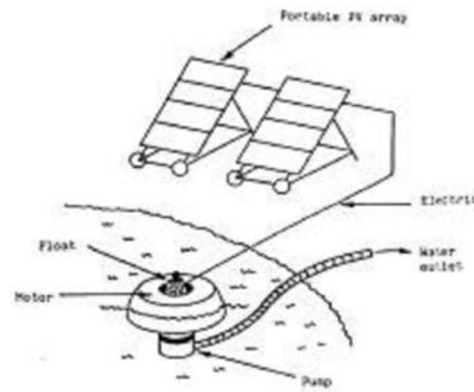


Figure 22: Floating motor [adapted from [43].

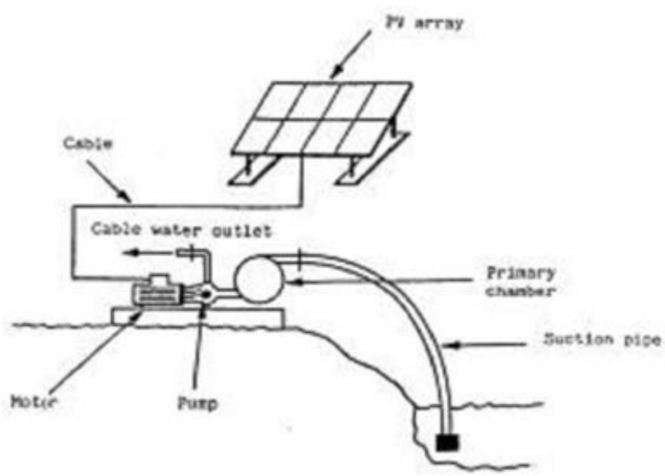


Figure 24: Surface suction pump set [adapted from [43]

Summarizing the guidelines for the motor--pump choice, the main aspects which the designer should consider are: daily water demand, the pumping head, suction head (for surface mounted pump--set), and water source features. Generally, positive displacement pumps are best suitable for low flows (less than 15 m^3 day^{-1}) and high pumping heads (30-150m). Submersible centrifugal pumps are best for high flow rate (25-100 m^3 day^{-1}) and medium heads (10-30m). As help to select the appropriate motor pump layout can be used the graph *Figure 25* where different suitable solution are showed depending by the head and the daily water demand [11][27].

Once the power needed (load) to the pump to lift the water is determinate, it is possible to evaluate the most suitable motor considering also its efficiency, reliability, cost and availability. In general it is possible to indicate some wattage range for each family of motor, as follow: permanent magnet DC motors under 2,250 W (3 horsepower), wound-field DC motors for 2,250-7,500 W (3-10 horsepower), and AC motors above 7,500 W (10 horsepower) [27].

The DC motors represent the most attractive typology, PV panels supply direct current. this kind of motors can be connected directly to the motor without the use of inverter so less costs and energy loss [31]. However recent developments in induction motor technology, made the AC motors an attractive solution. Induction motors are more robust, require less maintenance and are commercial available at lower costs than DC motors [28][38].

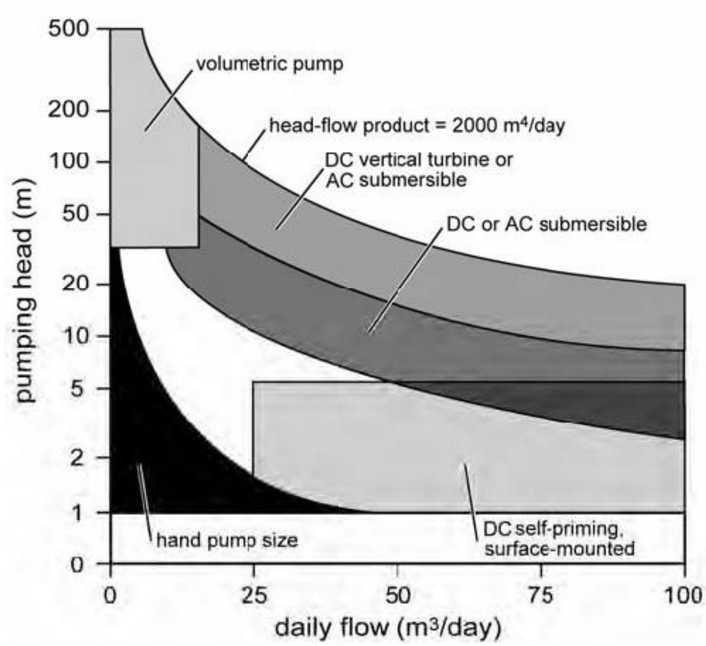


Figure 25: Approximate ranges of applications of photovoltaic water pumping configurations [11]

6. PV SYSTEM AND MOTOR--PUMP MATCHINE

Depending on the motor type used to drive the pump (AC motor or DC motor) are necessary different matching configurations. A variety of matching element is available, and they must be included between generator and the motor to enable proper operation system and to optimize the performance of pumping system. For the simplest case the matching element is just a cable which connects the generator directly with the DC motor. In other cases, according to the motor chosen is possible to use a DC/DC converter for MPPT tracking or, alternatively, a DC/AC inverter for AC motors. According to [11], the Photovoltaic power source can be connected to the pump motor by the following layouts:

- Direct coupling;
- Fixed DC input converter (MPPT);
- AC coupling with an inverter

In addition the direct coupling can have two variations, i.e. with array reconfiguration or with booster.

6.1 Direct coupling

In this configuration between the PV array and the pump there is only a cable. That is possible just with DC motor--pumps.

The I--V operating point results of the intersection of the pump curve with the PV array curve. If the pump curve is too high (array current under--sized), the pumping threshold will be high, penalizing low irradiances (winter season, bad days and morning/evening). On the other hand if it is too low, the system can't use its full power potential during the bright sun hours. Therefore the optimal sizing depends either on the irradiance distribution (i.e. location, orientation, meteorological data), and on the periods at which the water needs are the more important [10].

6.1.1 Direct coupling with array configuration

Mismatch losses can be improved by performing a PV--array reconfiguration. Considering two identical groups of PV--modules, at low irradiance all groups are connected in parallel, providing the high current needed for the pump priming. When a selected irradiance level is reached, the groups switch to series connected configuration, doubling the voltage and reducing the current of the PV array. The switch is done by an electronic device of rather simple technology [10].

6.1.2 Direct coupling with booster

It is an improvement of the direct coupling configuration. It can be necessary with DC displacement pumps, indeed most of them have an high starting torque resistance, therefore it is necessary give a significant peak of current (at low voltage) to overcome the initial internal friction forces. The PV array could provide this current probably only during the bright sun hours with the maximum level of insolation. To overcome this limitation is usually mounted an electronic device called "Booster", which stores the PV energy in a big capacity and gives it back as a peak of current [10].

6.2 MPPT – Maximum power point tracker

In general the maximum power point varies with radiation and temperature therefore it could be difficult to maintain optimum matching at all radiation levels. To overcome this aspect and at same time to improve the performance of a PV pumping system, a DC–DC converter called “maximum power point tracker” (MPPT) can be used. These electronic devices mounted between the array and motor--pump can match continuously the output characteristics of a PV array to the input characteristics of a DC motor [8]. MPPT absorbs the power of the PV array at a fixed voltage and current (for maximum output), and returns the current as to the DC--motor of the pump (for higher pump output). A MPPT has built--in control logic by a microprocessor, it analyzes the array voltage and current at frequent intervals, computes optimal current/voltage point corresponding to the available power and the motor needs and compares it with the previous value. The efficiency of these devices can be expected over the 95% and generally MPPT are cheap devices [33]. Of course, a converter is not necessary if the desired voltage can be provided from the array, by suitable arrangements of modules.

6.3 Inverters

An inverter is a device which converts DC to AC current. It is required when the photovoltaic system is equipped with AC motors. Inverters can treat the power output of array over a wide range of irradiation value; they normally include a MPPT to optimize the energy yield. The choice of inverter is closely related to the DC operating voltage of the system. For that reason the selection of theinverter input voltage is a primary decision, because it often imposes the system DC voltage. The operating voltage is chosen for a PVPS in relation of the motor voltage requirements and the total current, indicative values are shown in *Table 8.* Depending by the AC power demand, DC loads operate usually at 12 V or its multiples as 24, 36 or 48 V, etc, generally DC PV systems smaller than 1 kW operate at 12 V [28].

Table 4*: Selecting system voltage [28]*

AC power demand [W]	Inverter input voltage (DC voltage)
<1500	12
1500--5000	24 or 48
>500	48 or 120

It is recommended to keep the current below 20 with a 100 A limit for any section of system, in that way is possible to use the standard and most commonly available electrical hardware and wires. In case of AC motor the system voltage should be selected after an analysis of inverter characteristics Tab.1 and also considering option futures enlargement of system [34]. In general stand--alone inverters can operate at 12, 24, 48 or 120 V DC input and creates 120 or 240 volts AC at 50 or 60 hertz. However to choose the inverter the most suitable, it is recommended to analyze all the aspects of the AC load, not only how much power but also what variation in voltage, frequency and waveform can be tolerated. On the input side, the DC voltage, surge capacity and acceptable voltage variation must be considered. Some of those parameters are listed on sheet given by the manufacturers. It is necessary to take in account that the choice of inverter will affect the performance, reliability and cost of PV system. The shape of the output waveform is an important parameter. Inverters are sometimes classified according to the type of waveform produced; square wave, modified sine wave and sine wave, *Figure 26*. The output waveform depends on the conversion method and the filtering used on the output waveform. The latter is used to eliminate peaks and unwanted frequencies that result when the switching occurs. Modified sine wave inverters offer improved voltage regulation by varying the duration of the pulse width in their output. Efficiencies can reach 90%. This type of inverter is suitable for most of motors. However, these inverters will not operate a motor as efficiently as a sine wave inverter because the energy in the additional harmonics is dissipated in the motor windings. They can operate the AC motor within their power rating. In general, any inverter should be oversized 25% or more to increase reliability and lifetime [14]. This also allows for modest growth in load demand. The efficiency of the conversion reached is around 98% for over much the range, but it tends to fall down if the inverter operated below about 25% of its maximum power rating [21].

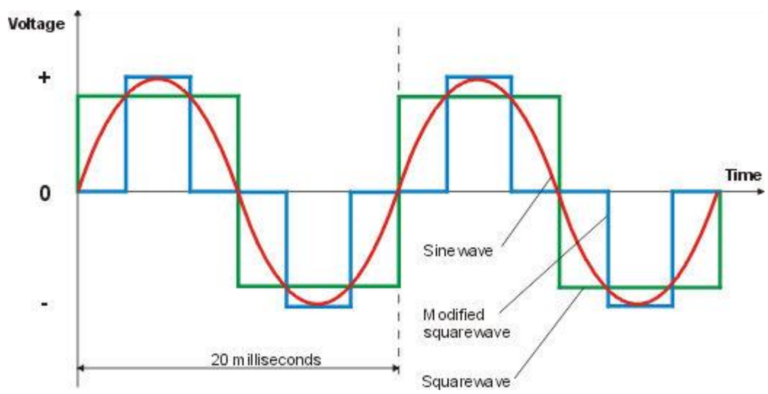


Figure 26: Type of waveform produced by inverters [35]

6. 4 Variable Frequency Drive

A Variable Frequency Drive (VFD) is a type of motor controller that drives an electric motor by varying the frequency and voltage supplied to the electric motor. Other names for a VFD are variable speed drive, adjustable speed drive, adjustable frequency drive, AC drive, microdrive, and inverter.

Frequency (or hertz) is directly related to the motor's speed (RPMs). In other words, the faster the frequency, the faster the RPMs go. If an application does not require an electric motor to run at full speed, the VFD can be used to ramp down the frequency and voltage to meet the requirements of the electric motor's load. As the application's motor speed requirements change, the VFD can simply turn up or down the motor speed to meet the speed requirement.

6.4.1 How does a Variable Frequency Drive work?

The first stage of a Variable Frequency AC Drive, or VFD, is the Converter. The converter is comprised of six diodes, which are similar to check valves used in plumbing systems. They allow current to flow in only one direction; the direction shown by the arrow in the diode symbol. For example, whenever A-phase voltage (voltage is similar to pressure in plumbing systems) is more positive than B or C phase voltages, then that diode will open and allow current to flow. When B-phase becomes more positive than A-phase, then the B-phase diode will open and the A-phase diode will close. The same is true for the 3 diodes on the negative side of the bus. Thus, we get six current "pulses" as each diode opens and closes. This is called a "six-pulse VFD", which is the standard configuration for current Variable Frequency Drives.

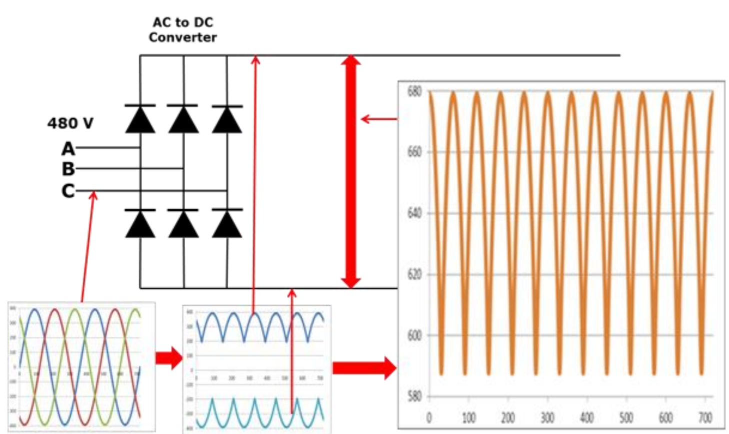


Figure 27: AC to DC Converter [46]

Let us assume that the drive is operating on a 480V power system. The 480V rating is "rms" or root-mean-squared. The peaks on a 480V system are 679V. As you can see, the VFD dc bus has a dc voltage with an AC ripple. The voltage runs between approximately 580V and 680V.

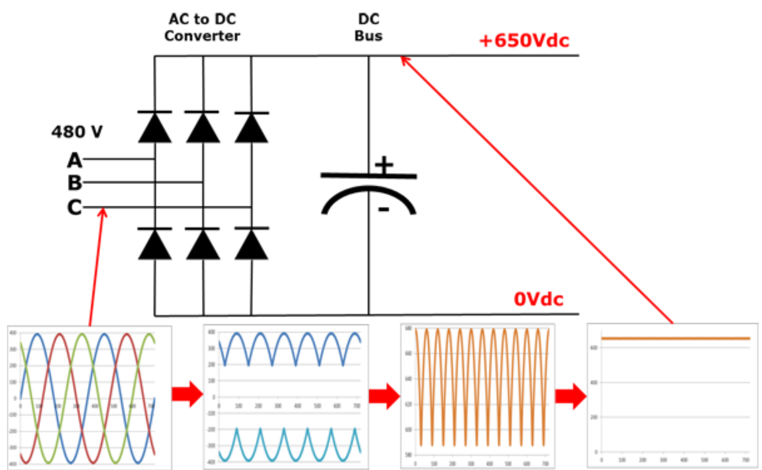


Figure 28: Functions of a Capacitor in the AC to DC Converter [46]

We can get rid of the AC ripple on the DC bus by adding a capacitor. A capacitor operates in a similar fashion to a reservoir or accumulator in a plumbing system. This capacitor absorbs the ac ripple and delivers a smooth dc voltage. The AC ripple on the DC bus is typically less than 3 Volts. Thus, the voltage on the DC bus becomes "approximately" 650VDC. The actual voltage will depend on the voltage level of the AC line feeding the drive, the level of voltage unbalance on the power system, the motor load, the impedance of the power system, and any reactors or harmonic filters on the drive.

The diode bridge converter that converts AC-to-DC, is sometimes just referred to as a converter. The converter that converts the dc back to ac is also a converter, but to distinguish it from the diode converter, it is usually referred to as an "inverter". It has become common in the industry to refer to any DC-to-AC converter as an inverter.

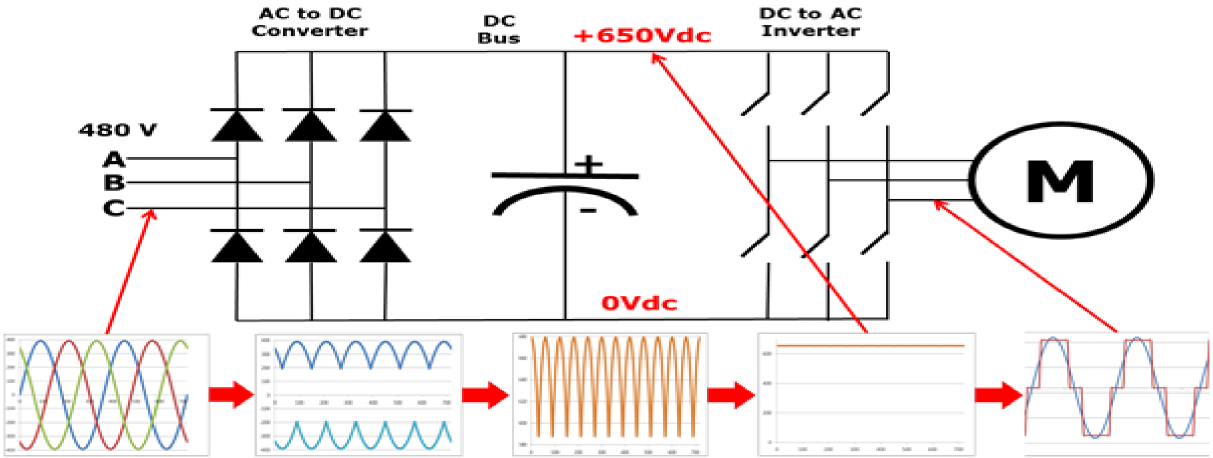


Figure 29: Working Principle of a Variable Frequency Drive, VFD [46]

When we close one of the top switches in the inverter, that phase of the motor is connected to the positive dc bus and the voltage on that phase becomes positive. When we close one of the bottom switches in the converter, that phase is connected to the negative dc bus and becomes negative. Thus, we can make any phase on the motor become positive or negative at will and can thus generate any frequency that we want. So, we can make any phase be positive, negative, or zero.

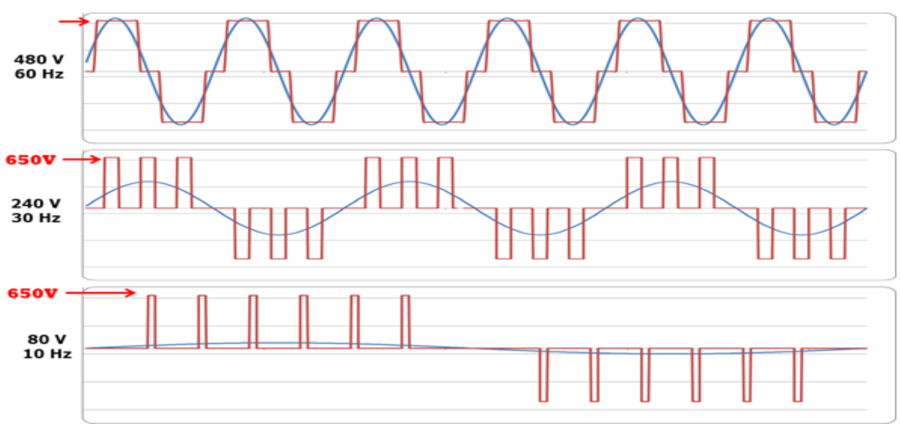


Figure 30: Output in a Variable Frequency Drive, VFD [46]

Notice that the output from the VFD is a "rectangular" wave form. VFD's do not produce a sinusoidal output. This rectangular waveform would not be a good choice for a general purpose distribution system, but is perfectly adequate for a motor. The blue sine-wave is shown for comparison purposes only. The drive does not generate this sine wave.

If we want to reduce the motor frequency to 30 Hz, then we simply switch the inverter output transistors more slowly. But, if we reduce the frequency to 30Hz, then we must also reduce the voltage to 240V in order to maintain the V/Hz ratio (see the VFD Motor Theory presentation for more on this). How are we going to reduce the voltage if the only voltage we have is 650VDC?

This is called Pulse Width Modulation or PWM. Imagine that we could control the pressure in a water line by turning the valve on and off at a high rate of speed. While this would not be practical for plumbing systems, it works very well for VFD's. Notice that during the first half cycle, the voltage is ON half the time and OFF half the time. Thus, the average voltage is half of 480V or 240V. By pulsing the output, we can achieve any average voltage on the output of the VFD.

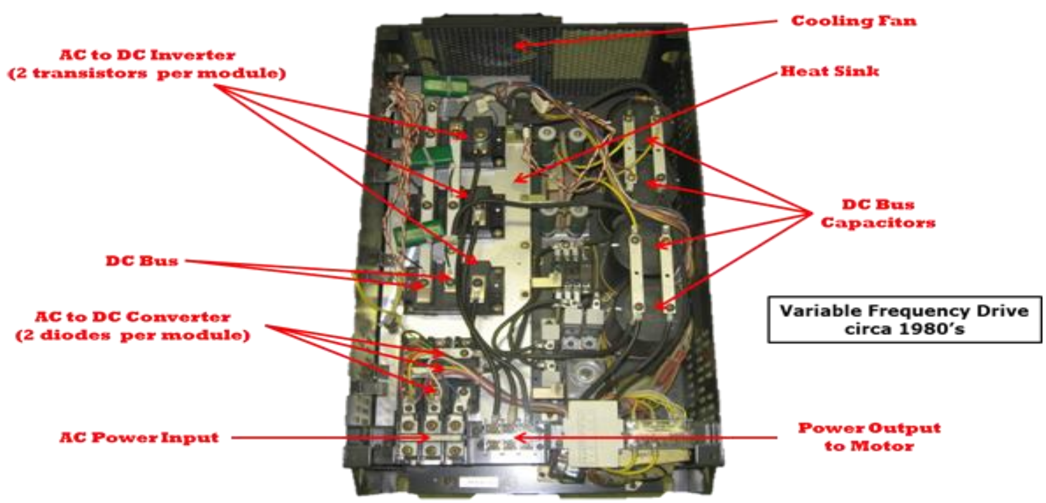


Figure 31: different parts of a Variable Frequency drive [46]

6.4.2 Why should a VFD be used?

6.4.2.1 Reduce Energy Consumption and Energy Costs

If you have an application that does not need to be run at full speed, then you can cut down energy costs by controlling the motor with a variable frequency drive, which is one of the benefits of Variable Frequency Drives. VFDs allow you to match the speed of the motor-driven equipment to the load requirement. There is no other method of AC electric motor control that allows you to accomplish this.

Electric motor systems are responsible for more than 65% of the power consumption in industry today. Optimizing motor control systems by installing or upgrading to VFDs can reduce energy consumption in your facility by as much as 70%. Additionally, the utilization of VFDs improves product quality, and reduces production costs. Combining energy efficiency tax incentives, and utility rebates, returns on investment for VFD installations can be as little as 6 months.

6.4.2.2 Increase Production Through Tighter Process Control

By operating your motors at the most efficient speed for your application, fewer mistakes will occur, and thus, production levels will increase, which earns your company higher revenues. On conveyors and belts you eliminate jerks on start-up allowing high through put.

6.4.2.3 Extend Equipment Life and Reduce Maintenance

Your equipment will last longer and will have less downtime due to maintenance when it's controlled by VFDs ensuring optimal motor application speed. Because of the VFDs optimal control of the motor's frequency and voltage, the VFD will offer better protection for your motor from issues such as electro thermal overloads, phase protection, under voltage, overvoltage, etc.. When you start a load with a VFD you will not subject the motor or driven load to the "instant shock" of across the line starting, but can start smoothly, thereby eliminating belt, gear and bearing wear. It also is an excellent way to reduce and/or eliminate water hammer since we can have smooth acceleration and deceleration cycles.

7. DESIGN AND CALCULATION PROCEDURE FOR PVPS

The different approaches to the PVPS design can be categorize into: dynamic modeling and steady modeling. Using the dynamic modeling, the system can be sized maximizing the global efficiency. That is possible, analyzing how the components' performances vary depending by the time. However to permit this calculation it is necessary to know detailed technical parameters and factors for each component, such as operating principles of diodes, ideality factor, the shunt and series resistance, etc. They are operative principles not usually contents on product's catalogues and they are also difficult information to obtain from the manufacturer. Therefore the application of the dynamic modeling has considerable flexibility limitations [18][39]. The purpose of this thesis work has been to develop an immediate and feasible design method, so a 'steady' method instead of a 'dynamic' method has been developed. It uses constant values of efficiency for each subsystem and all the data are available from literature or components catalogues. It consists on the creation of a clear mathematical relationship between the solar radiation energy, the PV array power and the required hydraulic energy which is necessary to satisfy the daily water demand. This method is enough easy to be applied by field technicians and end users.

Key Design Information	
Application	Irrigation
Site	Dhaka, Bangladesh
Location/Elevation	Lat. 23 Deg 11 mts. N, Long. 89 Deg 10 mts.E
Environment	Farmland
Temperature Range (°C)	6 to 42
Maximum Wind Speed (m/s)	8
Availability Required	Critical
Days of Storage	Day to Day Usage
Source	Borehole
Dynamic Head (m)	meters
Water Required (LpD)	Cubic meters

7.1 Hydraulic energy

As first step for the sizing of system, it is necessary to calculate the hydraulic energy E_h [kWh/day]. It is defined as the required energy needed to raise the daily required volume V_w [m^3/day], against the total dynamic head *TDH* in meters. It is given by:

Determine total daily water requirement

Daily water requirement in litre or in m^3/day

Determine Total Dynamic Head (TDH)

The total dynamic head *TDH* is the head required to pump the water from the water source to the storage tank. It is the sum of four components: the static water level h_{sl}, the drawdown h_{down}, the discharge head h_d and the friction head h_f, as it is shown in *Figure* 32.

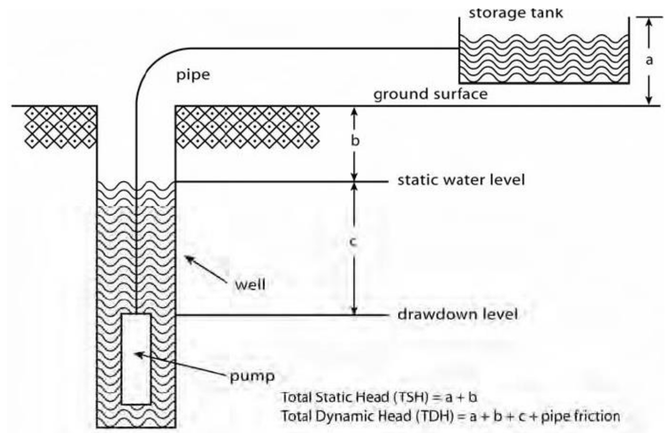


Figure 32: Total dynamic head composition [45]

The friction head is calculated as explained in *Chapter 5*, while the other heads are measured directly in situ. It is possible to describe them as well and system characteristics:

- *Static water level* is the height between ground surface and the table of groundwater.
- *Discharge head* is the height between the ground surface and the reservoir pipe outlet.
- *Drawdown* is an effect of the pumping operations. The water level in the borehole tends to drop. The extracted water volume is balanced by the water which flows 'downhill' from the surrounding water table. Greater is the flow extracted more is the drop of the level it depends also from soil characteristics as the permeability [43]. Drawdown data are given by pumping test; it is measured after 48 hour of pumping operation at the peak water demand [40].
- Total vertical lift in meter.
- Total static lift in meter

So, Total Dynamic Head (TDH) = Sum of Total vertical lift in (meter) and Total static lift in (meter)

Determine the hydraulic energy required per day

Hydraulic energy req. to raise water = Mass x Acceleration due to gravity (g) x TDH

= Density x Volume x Acceleration due to gravity (g) x TDH

= Watt hour/day

Where:

- ρ = Water density [= 1000 Kg m^{-3}].
- g = Acceleration due to gravity [9.81 m s^{-2}].

Determine solar radiation data

For Bangladesh daily global solar irradiance in $KWh/m^2/day$

Determine Motor and Pump size

Total wattage of PV panel= Total hydraulic energy/ number of hours of peak sunshine per day in Watt-peak

Total wattage of PV panel (Considering system losses) = Total PV panel wattage/ pump efficiency in Watt-peak

Power rating of Motor= Total wattage of PV panel (Considering system losses) /746 in Hp

7.2 Array sizing

Average Inverter voltage= sum of maximum & minimum inverter voltage/2

Number of panels in Series= Average Inverter Voltage/ voltage of a single panel under normal operating condition

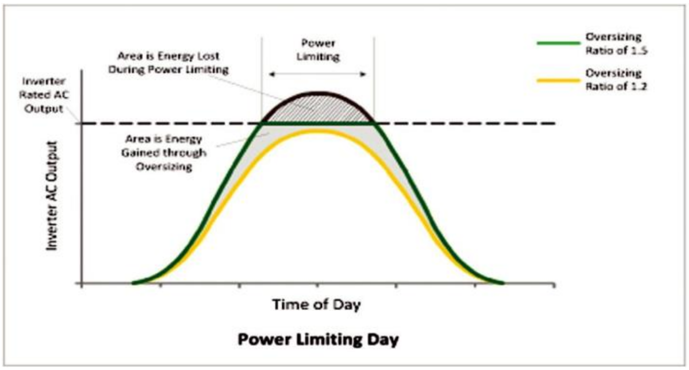
Number of panels in Parallel = (1200* Power Rating of Motor* 1.2)/Average Inverter Voltage*Current of a single panel under normal operating condition

Array Rated Power = Average Inverter Voltage * Number of Panels in Parallel * Current of a single panel under normal operating condition

Efficiency = Total wattage of PV panel/ Array Rated Power

7.3 Array Oversizing

The main driver of system design is the high cost of PV modules. The goal is to ensure maximum energy harvest from each module in the system. By doing so, it is ensured the optimal use of this high-cost system component. Best design practices is to place modules to avoid shading from obstructions and between racking rows, and to size the array to the largest capacity so the inverter spent little to no time power limiting. Power limiting is an inverter function that occurs when the available power from the array is greater than the inverter's rated input power. Power limiting is often called "clipping" due to the flattening effect on the system's daily production profile, as shown in Figure 33 and 34.



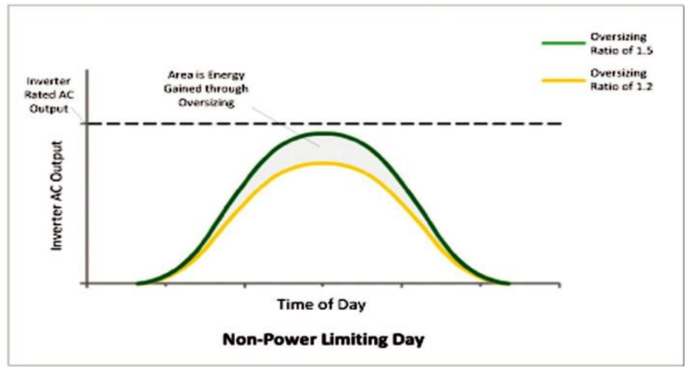


Figure 33: Daily Production Profile Power Limiting Day   Figure 34: Daily Production Profile Non-Power Limiting Day [43]

During power limiting, the inverter controls the input power from the array by shifting the array's operating point to a higher-voltage and lower-current operating point along the array's current-voltage (I-V) curve, thereby deviating from the maximum power point of the array.

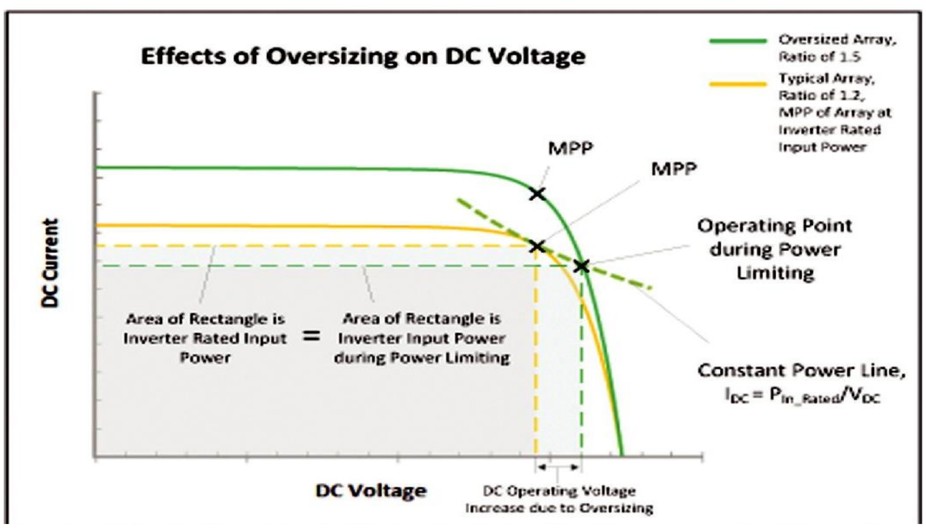


Figure 35: Array I-V Curves And Operating Points Of Typical And Oversized Arrays [43]

By maximizing production per module, achieve the optimal specific yield of the system is achieved. Specific yield is the system's annual energy harvest per kW of installed DC capacity. Specific yield is expressed in units of annual kWh/kW. Optimizing specific yield typically results in array-to-inverter ratios ranging from 1:10 to 1:25, depending on project location and DC derating factors. With lower PV module prices, the incremental cost of adding additional DC capacity to a system has greatly decreased. Since a larger array feeding a fixed size inverter will result in greater system annual production, the increased annual energy harvest is spread across the system's fixed/semi-fixed costs, which include inverters, AC collection system, permitting, interconnection fees, engineering and overhead. As a result, project financials have shifted in favor of increased Array-to-Inverter ratios.

What Factors Limit Oversizing

Oversizing exposes the inverter to the following:

- Increased available power from the array
- Increased available short-circuit current from the array
- Slightly increased full-power input voltage during power limiting
- Increased operational hours at full power

Although the inverter has the ability to control the current from the array during normal power-conversion operation, during a DC-side fault, the inverter's capability to control the current from the array is through interruption at best. The scenario that subjects the inverter to the highest short-circuit current is a low-impedance fault ("bolted fault") within the inverter's DC section between the ungrounded and grounded circuitry, or between ungrounded circuitry and ground. During these scenarios, the inverter is exposed to the full short-circuit current of the array. The inverter's DC side components, including bus bars, cables and switches, must be rated to carry and interrupt (in the case of electromechanical switches) the array's available short-circuit current. The weakest link in this circuit dictates the maximum short-circuit current that the inverter is rated to handle. Based upon the desired string count and string size, the maximum Array-to-Inverter ratio can then be determined.

7.4 Effect Of Oversizing On Inverter Life

Large array-to-inverter ratios cause the inverter to work harder for longer hours. In addition, most commercial three-phase inverters operate less efficiently when operating above the maximum power point voltage, resulting in greater internal-heat rejection. Common sense tells us that this can cause some of the temperature-sensitive components to age faster compared to a lightly-loaded scenario.

The good news is that inverters have thermal-management architectures to control internal temperatures to protect the inverter during prolonged periods of full-power operations. These measures also act to help preserve the life of temperature sensitive components. Inverters sense temperatures of critical components and have programmed set points that trigger increased blower fan speed and power limiting as means of regulating internal temperature.

In addition, inverters have critical temperature limits that, once reached, result in inverter shutdown. Inverters also include one or more temperature switches as a backup safety mechanisms in the event of an uncontrolled temperature increase due to failures in the inverter's thermal-management-control systems. The inverter's maximum ambient operating temperature for full-rated power and other factors that affect the inverter's operating temperature and cooling ability, including inverter shading, elevation and mounting location (indoor/outdoor, ventilated/ conditioned).

7.5 Overall efficiency of the system

The overall efficiency of the PV pump system can be calculated from the hydraulic energy and the

Array rated power P_{in}. That is:

Overall efficiency of PV pump = {(Total Wattage PV panel)/ (Array Rated Power)}* 100

7.6 Storage tank

The water storage is a very important part of pumping system for irrigation. If we considered systems without batteries, it is the only way to store energy. An advantage of reservoir design for irrigation is that the evapotranspiration of plants is proportional to the solar intensity. Therefore plants need less water during those periods when less water is pumped. It limits the needed volume, bringing cost savings for structures. However, several days' water storage in a tank are recommended. Three days is a typical storage size, but local climatic conditions can vary the optimum size. The volume of the tank is calculated multiplying the daily water volume needed for the design month for the number of autonomy request days *N*. As design month must be chosen the driest month. As general rule, it is in summer and it has the monthly highest value of solar radiation [21]

$$V_{tank} = N * V_W$$

8. MODEL VALIDATION

The calculation procedure has been implemented by C++. That calculation software is composed of inputs and outputs,

Inputs include

- Daily water Requirement
- Autonomy days
- Total vertical Lift
- Total static Lift
- Peak Sunshine Hour
- Pump Efficiency
- Inverter Voltage max
- Inverter Voltage min
- Please Enter Single Panel Voltage
- Single Panel Current

Outputs include

- Total Dynamic Head
- Flow Rate

- Hydraulic Energy Required
- Total Wattage PV Panel
- "Total Wattage PV Panel with Loss
- Power Rating of the Motor
- Average Inverter Voltage (V
- Number of solar modules in
- Number of solar modules in parallel
- Solar Array rated Power
- Efficiency
- Volume of storage tank

The input data to do the design simulation must be inserted with good accuracy. One cases study has been selected:

8.1 Case Study: Location, Dhaperhat, Sadullapur, Gaibandha

Pump Capacity : 7.5 HP

PV Capacity : 9.75 Kw

Pump Controller Capacity: 7.5 HP;

WaterOutput: 750950 Lit/day

Static Water Level : 13M; Boring: 46M

Solar Modules : 9750 Wp

Drive : 7.5 Hp / 5.5kW / 3 phase

Pump : 7.5 Hp submersible / 3 phase

Cables : 4 Sqmm(Drive to pump)

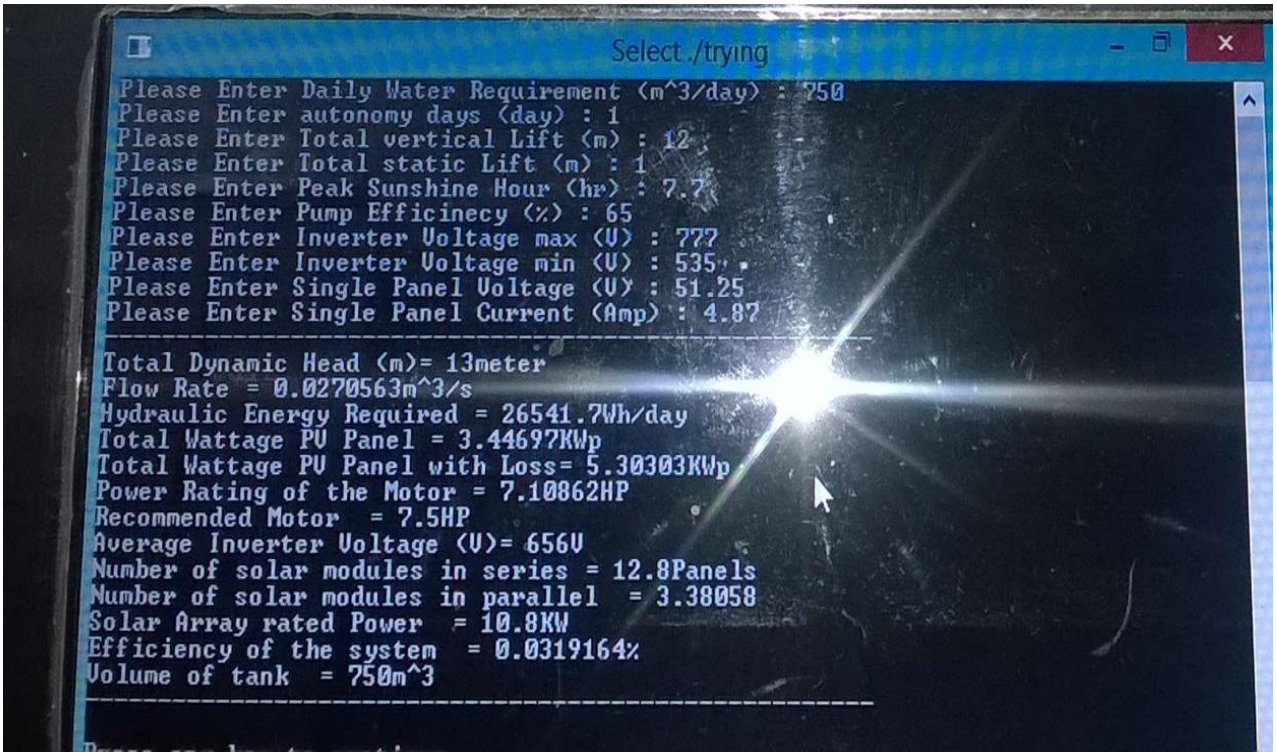
Water source : Borewell Total depth : 150Ft • Water table: 20Ft • Pump installed at : 50Ft

Water Level Censor : Not installed

Solar Array details

Make : OSDA, China Wattage : 250Wp Type : Monocrystalline No of panels in series : 13 (3 strings) No of panels in parallel : 3 (1 string) Vmp : 51.25 V Imp : 4.87A Warranty : 20 years

Console Output from the coded software



9. Effect on the Environment- Carbon study

Currently [43], 35,322 deep tubewells, 1,523,322 shallow tubewells and 170,570 low lift pumps are working in Bangladesh to provide water for irrigation. About 79% of the total cultivated area in Bangladesh is irrigated by groundwater, whereas the remaining is irrigated by surface water. More than 90% of the pumps within Bangladesh are run by diesel engines. The remaining 10% use electricity. Despite subsidies on electricity, diesel pumps are preferred by farmers due to low capital cost and mobility ease within small and fragmented farm lands. Each year, on average, about 980 million kwh of electricity is used by electric tubewells with an estimated subsidized cost of USD 50 million. The annual diesel consumption for groundwater extraction is of the order of 4.6 billion liters, costing USD 4.0 billion in aggregate. This in turn produces 235200 tonnes of carbon dioxide per year.

1 kwh of energy produces 0.24 kg of carbon dioxide (Diesel fuel) [42]

To produce 980 million kwh of energy 235200 tonnes of Carbon dioxide is produced annualy.

10. RECOMMENDATIONS

Diesel causes Carbon dioxide pollution at a cost of 4.0 billion USD per year, by the use of PVPS, we can, not only save the environment of huge amount of pollution but we can also put an end to the recurring cost of diesel with a payback in six years. With the carbon market in effect PVPS can aid Bangladesh to trade to benefit Bangladesh in monetary value.

1. Subsidize PVPS Schemes.
2. Remove Subsidies for diesel and increase subsidies for PVPS
3. Carbon trading can be done for 23520 tonnes.
4. Make and implement Policies to Monitor Ground water removal for sustainable development.
5. This model can be modified and can be used to charge batteries for other purposes (Provide electricity to houses and other institutions), which can further reduce cost and can be used to provide electricity in the rural and remote areas.

11. Limitation

What is the impact of the wire diameter on the efficiency of my small photovoltaic or wind system? Many of us already know that higher is the diameter of an electrical wire, lower is the resistance that the wire opposes to the passage of current. For example [41], a wire of 6 mm ^{2} diameter opposes less resistance than a wire cross-section 4 mm ^{2}. Less resistance means that, according to Ohm's Law, we would have less power loss along the same wire and therefore more useful electrical energy for our needs. For distances up to 50 meters, the standard UNEL 35023, requires that the minimum diameter of an electric wire must not be less than 0.25 mm ^{2} / A (ie 4A/mm ^{2}). So an electric wire of 1mm ^{2} is good for a change of currents up to 4A, a wire instead of 2.5 mm ^{2} up to 10A, 4mm ^{2} wire up to 16A, and so on. This is true for wire lengths up to 50 meters. For the design, the legislation requires the use of wires with a minimum cross section of 1.5 mm ^{2}. The resistivity of copper is 0.0175 ohm × mm ^{2} / m. So a copper wire of one meter long and of section size of 1mm ^{2} has an electrical resistance of 0.0175 ohms. It is understandable, therefore, that if we have a 1kW inverter and a battery bank voltage of 24V, we will have a loss on that cable about 30W, but if quadruple the diameter of the wire (4mm ^{2}), the loss is reduced four times too. In fact, the loss will be 7.5 W (75% less). The section of a wire is an important parameter in the design of an efficient photovoltaic system. No considerations have been done in the wire--to--wire efficiency. As this can change the power required from the array. This can produce different results for the calculated array size. but it has been compensated for by array oversizing.

12. CONCLUSIONS

The reason for developing this software is, it is customized according to need and a standard is set for PVPS design. The other software like RET and Groundfos takes into account of sunshine duration of about 4.5 hours for Bangladesh but an extra three of sunlight could be utilized for pumping ground water, which is taken into consideration by allowing the individual, based on his experience, to extend the sunshine duration to reduce cost. PVPS are system employed for farm scopes. They are used to pump water from the water source (Ex: well), to a surface tank. Then the water it is used for irrigation scopes. PVPS are stand--alone systems powered by a PV array, so they don't need connection with the electric grid and they don't used fossil fuels. A design model for PVPS for irrigation has been developed based on literature studies of real cases. It has been constituted by a mathematical sizing method implemented by C++ coding software, together with the needed guidelines to choose the most suitable devices (PV panels array, and motor--pumps). In addition to the immediate input variables of sun radiation and water demand, other needed information must to be individuated, they regarded the groundwater resource, the hydraulic system and the makeup of PV array. The design methodology has been validated applying it to two real cases of study. The two cases are respectively described into two different references and the same inputs data were used for validation. The obtained outputs by the design method have been compared with the reference's data. It has been verified the similitude between the output data and the corresponding references values. It has also observed that the design model can size PVPS with a certain margin of safety. The results have showed that a 20% increase in the array design will increase the durability of the system as well eliminate the decreasing efficiency of the solar modules. Since the water level is taken from geological data, but in practical the Water level is found comparatively very well above that point so the motor-pump is not oversized. But the boring and pump is placed at the distance mentioned in the geological data because of the working principle of the submersible pump. Therefore to choice the most suitable motor--pump lay out is very important to analyze carefully the in situ the work conditions. In addition, it can be very useful to know the detailed performance of the available devices in the manufacturer catalogues. The payback for the PVPS to Diesel system is six years (Conservative), and the PVPS is designed for 15 to 20 years maximum with a recurring cost of the controller every seven years. So for long term investment with PVPS is beneficial both for individual, Government and Environment. Though Government should implement policies to monitor depletion of Ground Water resource otherwise it can pose major threat to the environment like desertification. Other drawbacks include high initial cost requires large space for solar array setup.

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14. APPENDIX

```
#include "stdio.h"

#include <iostream>

using namespace std;

float motor_HP(float motor_KW){

  if(motor_KW<1){

     return 1;}

  else if ((motor_KW>1) && (motor_KW<=2)){

     return 2;}

  else if ((motor_KW>2) && (motor_KW<=3)){

     return 3;}

  else if ((motor_KW>3) && (motor_KW<=4)){

     return 4;}

  else if ((motor_KW>4) && (motor_KW<=5.5)){

     return 5.5;}

  else if ((motor_KW>5.5) && (motor_KW<=6)){

     return 6;}

  else if ((motor_KW>6) && (motor_KW<=7.5)){

     return 7.5;}

  else if ((motor_KW>7.5) && (motor_KW<=10)){

     return 10;}

  else if ((motor_KW>10) && (motor_KW<=12.5)){

     return 12.5;}

  else if ((motor_KW>12.5) && (motor_KW<=15)){

     return 15;}

  else if ((motor_KW>15) && (motor_KW<=20)){
```

```
        return 20;}
    else {
        return 100;}
    }
int main () {
    float DWR, TVL, TSL, TDH, FR, PSH, HER, TWPV, TWPVL, PE, PRM, SPC, AIV, SPV, NPp,
NPs,Vmax, Vmin, AD, ARP, Es, Vt;
    cout << "Please Enter Daily Water Requirement (m^3/day) : ";
    cin >> DWR;
    DWR=(DWR*7)/ (7-AD);
    cout << "Please Enter autonomy days (day) : ";
    cin >> AD;
    cout << "Please Enter Total vertical Lift (m) : ";
    cin >> TVL;
    cout << "Please Enter Total static Lift (m) : ";
    cin >> TSL;
    TDH=TVL+TSL;
    cout << "Please Enter Peak Sunshine Hour (hr) : ";
    cin >> PSH;
    cout << "Please Enter Pump Efficinecy (%) : ";
    cin >> PE;
    PE=PE/100;
    cout << "Please Enter Inverter Voltage max (V) : ";
    cin >> Vmax;
    cout << "Please Enter Inverter Voltage min (V) : ";
    cin >> Vmin;
```

```
AIV=(Vmax+Vmin)/2;
cout << "Please Enter Single Panel Voltage (V) : ";
cin >> SPV;
cout << "Please Enter Single Panel Current (Amp) : ";
cin >> SPC;
cout << "----------------------------------------------------\n";
cout << "Total Dynamic Head (m)= " << TDH << "meter\n";
FR=DWR/(3600*PSH);
cout << "Flow Rate = " << FR << "m^3/s\n";
HER=1000*DWR*9.8*TDH/ 3600;
cout << "Hydraulic Energy Required = " << HER << "Wh/day\n";
TWPV=HER/(PSH*1000);
cout << "Total Wattage PV Panel = " << TWPV << "KWp\n";
TWPVL=TWPV/PE;
cout << "Total Wattage PV Panel with Loss= " << TWPVL << "KWp\n";
PRM=TWPVL*1000/746;
cout << "Power Rating of the Motor = " << PRM << "HP\n";
PRM=motor_HP(PRM);
cout << "Recommended Motor  = " << PRM << "HP\n";
cout << "Average Inverter Voltage (V)= " << AIV << "V\n";
NPs=AIV/SPV;
cout << "Number of solar modules in series = " << NPs << "Panels\n";
NPp= (1200*PRM*1.2)/(SPC*AIV);
cout << "Number of solar modules in parallel  = " << NPp << "\n";
ARP= (AIV*NPp*SPC)/1000;
cout << "Solar Array rated Power  = " << ARP << "KW\n";
```

```
    Es = (TWPV/(ARP*1000) )*100;
    cout << "Efficiency of the system  = " << Es << "%\n";
    Vt = (DWR*AD);
    cout << "Volume of tank  = " << Vt << "m^3\n";
    cout << "-------------------------------------------------------\n";
    std::cin.get();
return 0;
}
```