# Solar Energy and Photovoltaic Systems

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*Abstract*—**The spectrum of solar energy is quite wide and its intensity varies according to the timing of the day and geographic location. We review solar energy conversion into electricity with particular emphasis on photovoltaic systems, solar cells and how to store electricity.**

***Index Terms*—Solar-spectrum, solar cells, positioning, storage.**

## I. INTRODUCTION

In 1953, an article in a magazine with a title "Why Don't We Have ..Sun Power" with a statement " Every hour, it floods the earth with a deluge of thermal energy equal to 21 billion tons of coal". In fact according to latest figures published, the surface of the earth receives about 124 exa ($10^{18}$) Watts or 3,850 zetta ($10^{24}$) Joules per year of solar power [1].

The spectrum of the solar light coming from sun covers from about 250 nm to about 2500 nm in wavelength, as can be seen in the figure (1). By the way visible light of human beings covers from 400 to 700 nm, at which band the light is very dense, about 1.5 W/m2/nm at 400 nm, going up to about 1.75 W/m2/nm at about 550 nm and then comes back to 1.5 W/m2/nm at 700 nm as can be deduced from the figure.

Solar thermal heating is the result of the whole solar spectrum, for this reason, even white painted cars, get hot, because though most of the visible light is reflected, but the other parts of the spectrum, heats the car. Though mirrors reflect most of the wide spectrum of sun, but the glass covering the mirror, gets hot.

There are two methods for converting solar power into electricity, thermal which is based on concentrating solar power by mirrors or other type of reflectors to produce high temperature to generate water vapour or other liquids with high pressure to rotate turbines to generate electricity

or by making use of photovoltaic (PV) effect to convert solar power to electric power directly. A photovoltaic complete system usually consists of the followings:

Photovoltaic units, batteries, charging controllers, inverters, load controllers, circuit breakers and wiring.

We shall explain the principle of solar thermal technology, but we shall go into detail about PV system.

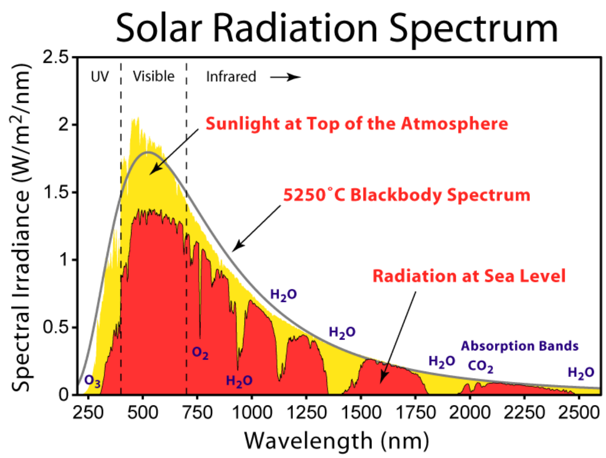

Figure 1. [2]

## II. SOLAR THERMAL ELECTRICITY GENERATIONS

This method is based on concentrated solar thermal (CST) technology by using mirrors to concentrate sunlight. There are several ways to do that. Some use curved mirrors which are usually parabolic mirrors that track the movement of the sun and focus the sunlight at pipes filled by water or other liquids. The other type of designs use long flat rotating mirrors, which are cheaper.

Andasol-1Plant in Gaudix and Astexol-2 Plant in Andalosia of Spain with a capacity of about 50 MW use the Parabolic Trough design which consists of long parallel rows of modular solar collectors, as can be seen in Figure (2). Tracking the sun from East to West by rotation on one axis, the high precision reflector panels concentrate the solar radiation coming directly from the sun onto an absorber pipe located along the focal line of the collector. A heat transfer medium, a synthetic oil like in car engines, is circulated through the absorber pipes at temperatures up to 400°C and generates live steam to drive the steam turbine generator of a conventional power block.


Figure 2. [5]

The two plants mentioned above are in operation. Two more similar plants will be constructed in 2011 in Solana-Spain of 250 MW with six hours of molten salt thermal energy capability [5][6].

Concentrating solar power systems are a fast growing source of sustainable energy.

Full-scale parabolic trough systems consist of many such troughs laid out in parallel over a large area of land. Since 1985 a solar thermal system using this principle has been in full operation in California in the United States. It is called the SEGS system. Other CSP designs lack this kind of long experience and therefore it can currently be said that the parabolic trough design is the most thoroughly proven CSP technology.

The Solar Energy Generating System (SEGS) is a collection of nine plants with a total capacity of 350MW. It is currently the largest operational solar system (both thermal and non-thermal). A newer plant is Nevada Solar One plant with a capacity of 64MW. Heat storage enables better utilization of the steam turbine. With day and some night time operation of the steam-turbine Andasol 1 at 50MW peak capacity produces more energy than Nevada Solar One at 64 MW peak capacity, due to the former plant's thermal energy storage system and larger solar field.

553MW new capacity is proposed in Mojave Solar Park, California. Furthermore, 59MW hybrid plant with heat storage is proposed near Barstow, California. Near Kuraymat in Egypt, some 40MW steam is used as input for a gas powered plant. Finally, 25MW steam input for a gas power plant in Hassi R'mel, Algeria.

One of the technologies used in solar thermal electricity generation and storage is based on parabolic trough. For example at Kramer Junction a company called Acciona Solar Power project SGX2 installed such a system [5]. The system is composed of hemispheric reflector with aperture width of 5.77 m, aperture area of 470 m2 and weight of 22 kg/m2 and peak optical efficiency of 77% with total output of 64 MW. The reflector is a glass mirror.

To increase efficiency of parabolic trough collectors, selective coating on the receiver is applied to increase solar absorption more than 96% ($\alpha \geq 0.96$) and reduce thermal remittance to less than 7% ($\epsilon \leq 0.07$) at 400˚C with thermal stability above 500˚C [7]. Applying such kind of technology reduces the cost of electricity production.

The main advantage of solar thermal energy generation is that it absorbs the whole solar spectrum, for this reason its efficiency is more than 90% in reflection of solar power but not in production of electricity which is in the range of about 30-40%.

## III. Solar Photovoltaic Electricity Generation

### *A. Introduction*

There are many types of technologies used to produce electricity based on solar photovoltaic principle. Crystalline silicon at the moment is the main technology used commercially, but there are other technologies under intense research work to produce more efficient solar cells.

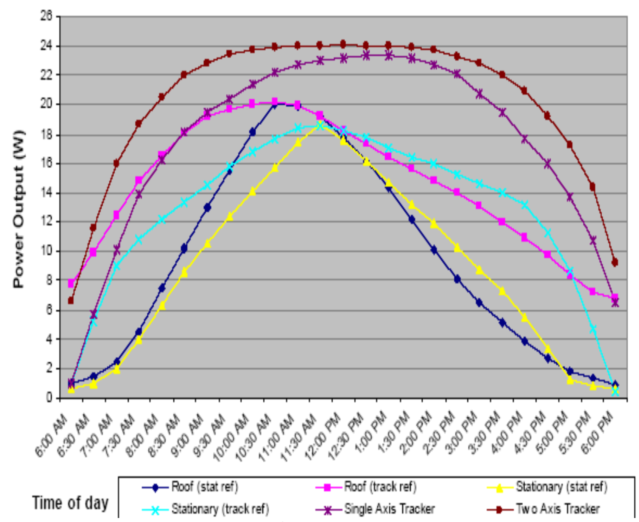


Figure 3. [3]

Solar Power level during day time at solar cells with two axis trackers, single axis trackers, on roof with tracking, on roof with no tracking and stationary. [3]

The efficiency of silicon solar cells is in the range of 13-18%. The average of sun light power or solar power covering all the spectrum is about 1KW/m2 peak, that is in the direction of the sun and when the sun has reached its peak power, not early in the morning or late in the evening as seen in figure (3); the average solar power with no tracking between 6 AM to 6 PM is about half the peak power . For this reason, usually the day time is considered to start at 8 AM and ends at 4 PM. As can be seen from this figure, by using good tracking system, the average solar power between 8 AM and 4 PM is about more than 90% of the peak. But that depends on the location of the area, how far it is from the equator and seasonal timing. Solar cells made of 1 m2, produce about 140-170 W peak, for the reason mentioned above, but the average (with no tracking facilities) solar power produced within the 8 hours mentioned above is about 70-85 W/m2.

By the way, the cost of photovoltaic systems came down especially during the past ten years. As technology is advancing, efficiency of most systems is going up and thereby the cost is coming down [8].

*B. Crystalline Silicon Photovoltaic cells*

Silicon cells are manufactured with two adjacent layers, the first is made of silicon doped with small amount of phosphorus which has one more electron in its outer orbital than silicon. When a phosphorus atom takes place of a silicon atom, the extra electron is transferred to the crystal lattice. As these electrons with negative charge are free to move, so this material is known as n-type silicon. P-type silicon gets its positively charged particles from tiny amounts of boron, an element that has one less electron than silicon in its outer shell. In this case there are not enough electrons to form all the covalent bonds required, so the electrons move around to try to fill this deficiency, which is called a hole. Holes act like free, positively charged particles. When p-type and n-type materials are placed together, they form a p-n junction as shown in Figure (4). Electrons and holes attract each other, congregate by the interface, and leave the p-type and n-type regions with negative and positive charges, thus creating the required electric field.

When light shines on crystalline silicon, electrons within the crystal lattice may be freed. But not all photons — as packets of light energy are called — are created equal. Only photons with a certain level of energy can free electrons in the semiconductor material from their atomic bonds to produce an electric current.

This level of energy, known as the "bandgap energy," is the amount of energy required to dislodge an electron from its covalent bond and allow it to become part of an electrical circuit. To free an electron, the energy of a photon must be at least as great as the bandgap energy. However, photons with more energy than the bandgap energy will expend that extra amount as heat when freeing electrons. Crystalline silicon has a bandgap energy of 1.1 electron-volts (eV). (An electron-volt is equal to the energy gained by an electron when it passes through a potential of 1 volt in a vacuum.) The bandgap energies of other effective PV semiconductors range from 1.0 to 1.6 eV as shown in Figure (5). In this range, electrons can be freed without creating extra heat.

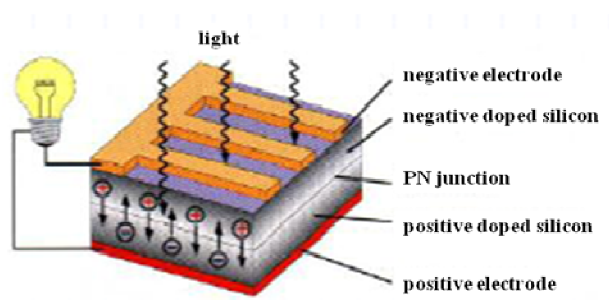


Figure 4. [3]

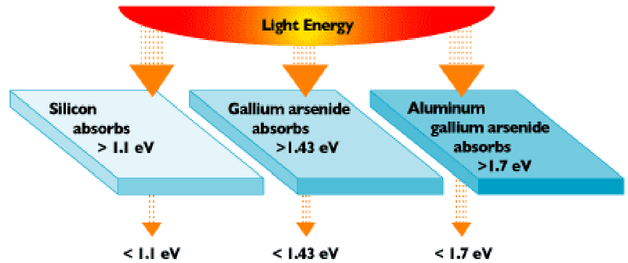


Figure 5. Basically, a solar cell is a P-N junction that absorbs light, releases electrons and holes, creating a voltage in the cell, which is then applied to a load [3].

In 2002, researchers in Materials Sciences Division (MSD) in Lawrence Berkeley National Laboratory discovered that the band gap of indium nitride is 0.7 eV, that means a single system of alloys incorporating indium, gallium and nitrogen can convert virtually the full spectrum of sunlight to electric current [8]. But they discovered too, that lattice matching between the three semiconductors has to be met, otherwise, the system would not work.

Later it was discovered that:

- GaInP2 (band gap:1.8 eV) covering wavelength 300-700 nm
- GaAs (band gap:1.42 eV) covering wavelength 650-900 nm
- Ge (band gap :0.67) covering wavelength 900-1650 nm

which have lattice matching that can cover a large portion of the band. Figure (6) shows the efficiencies of different types of cells.

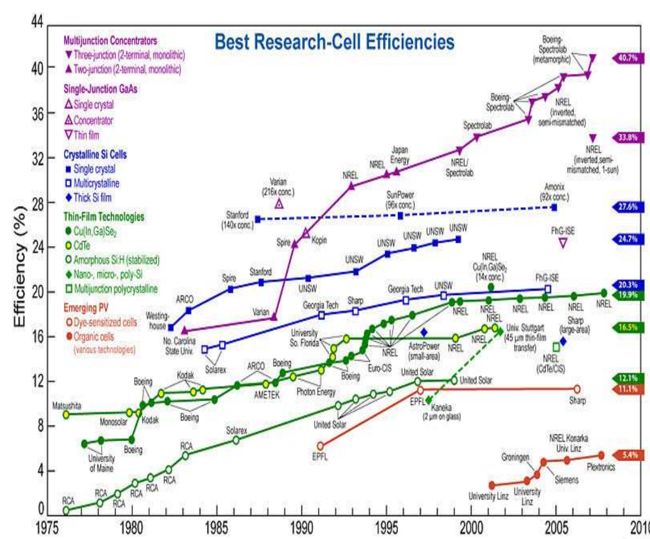


Figure 6. [8]

Solar Cell Efficiency of (1) Multijunction concentrators (2) Single and multicrystaline silicon (3) Thin film Technology such as Cu(In,Ga)Se2, CdTe (4) Organic and Dye-sensitized, [9].

*C. Effects of latitude, altitude and clouds on Solar power*

Solar power is maximum during summer because the sun goes up and minimum during winter as it goes down. For example, in Baghdad which is at latitude 33˚ 21' north, so at noon on 21 of March and on 21 of Sept the sun makes an angle of 33˚ 21' with the vertical axis or 66˚ 69' above the horizon. While on the 21 of June at noon it makes an angle of (33 -10) or 23˚ 21' with vertical or 76˚ 69' above the horizon according to STD tables and on 21 of Dec it makes an angle of 56˚ 69' with the horizon. While in Mosul which is at latitude 36.5, these angles are 36.5, 26.5 and 46.5 degrees with the vertical axis. But on all days around the year, the sun makes larger angle with the vertical axis early in the morning and then it goes up as we approach mid-day and then it goes down again as we approach sun set.

Duration of the day on 21st of June according to STD in Baghdad is 14.22 hours and on 21st of August it is 13.13 hours.

Duration of the day is connected with the rotation of the sun. In the region between 32˚ and 36˚ in the north, on 21st of April and 21st of September the sun starts in the morning from a direction of about 90˚ in the west then at noon its direction is exactly to the south and then at sun set its direction is 90˚ to the East, so during these days the sun (horizontally) it moves 180˚. On 21st of June, it starts from a direction of about 120˚ from the East and it disappears at 120˚ to the west that is on such a day it moves 240˚. On 21st of December, it starts from a direction of about 60˚ from the East and disappears at 60˚ to the West, that is, it moves only 120˚ during that day. These effects we have to take into account in designing a PV system.

According to International Standard, sun power at noon is 1000 W/m2 at 25 ˚C and this power decreases as we approach sun set and sun rise also as we move north and south from the equator.

In USA, they have measured the daily insolation which is the solar radiation reaching the ground on many locations during the whole year [10]. The average in June it varies between 6.5 KW/m2 to 11.1 KW/m2 and the average in December it varies between 1.1 KW/m2 to 8.9 KW/m2. While the yearly daily average varies between 3.6KW/m2 and 8.9 KW/m2, these numbers give us a view of what do we expect to receive in Iraq and the whole Middle East.

The more we go to the south and the more the elevation of the place, the higher its daily insulation.

The reason of the effect of elevation is due to absorption of air and clouds of solar power. Oxygen absorbs solar power at wavelength of about 780 nm while H2O absorbs solar power at many wavelengths which are:

920, 1100-1150, 1350-1450, 1800-1950 and 2500-2750 nm, for this reason if we go up to a height of say 36,000 KM above the Earth surface, solar power is much stronger. Also in dry areas such as in the Middle East especially in summer, solar power is quite strong, more than STC standard.

The spectrum of the sun power is between 200 to 2500 nm, with most power concentration is within the range of 300 to 1500 nm. Visible light spectrum is between 400 to 700 nm. Blue light is of high frequency, that is of short wavelength while red light is of lower frequency, that is of longer wavelength while other colors fall in between.

Enhanced concentration on silicon modules by addition of mirrors to enhance irradiance in addition of tracking systems is under intense research work which was started in 2008 [11]. But the concentration is low compared with that used in solar thermal systems. For example Abengoa has already installed many such systems in Spain, Portugal and Italy [12].

D. *Typical Solar Cell Specification*

A typical solar cell has the following specification: *Efficiency: 15 to 17.2%*

- Power Maximum (Pmax): 3.65 to 4.186 W
- Open Circuit Voltage (Voc): 0.608 to 0.632 V
- Short circuit current (Isc): 7.95 to 8.49 A
- Maximum power voltage (Vmp): 0.495 to 0.521 V
- Maximum power current Imp: 7.34 to 8.04 A
- Dimension: 156×156 ± 0.5 mm
- Thickness: 0.24 ± 0.04 to 0.16 ± 0.03 mm
- Connections Front: two 2.0 mm wide bus bar (silver) with distance of 75 mm
- Connections Back: 4.5 mm wide bus bar with silver/aluminum soldering pads and aluminum back surface field
- Typical temperature coefficients:
  - Voltage: −2.11 mV/K
  - Current: + 2.79 A/K
  - Power: −0.45 %/K.

As can be seen as the temperature of solar cells go up, the voltage and power drop down.

Solar modules are manufactured by connecting several solar cells together. If 10 solar cells are connected in series, we get a module of 4.95 to 5.21 V and of a current equal to 7.34 to 8.04 A with peak power of 36.5 to 41.86 Wp.

Solar panels are manufactured by connecting several modules together. If 6 such solar modules are connected in series, we get a solar panel of 29.70 to 31.26 V with no change in the current that of 7.34 to 8.04 A and of power equal to 219 to 251.16 Wp.

The area of such solar panels is equal to more than 60×156×156= 1.460 m2 because connecting solar cells together to form a solar module takes space and connecting several modules to form a solar panel takes even more space. For this reason the area of such a solar panel is about 1642×992=1.629 m2 which means an increase of about 10%.

*E. Photovoltaic Module Testing*

A comprehensive report about module testing was issued by National Renewable Energy Lab. in Oct. 2008 with evaluation of IEC 61215 Standard for testing and life estimation of such modules [13].The report is based on 177 references. The report's conclusion is that accelerated stress tests need more research work.

*F. Factors that affect Solar panel Performance*

Five major factors affect the performance output of photovoltaic panels: load resistance, sunlight intensity, cell temperature, shading and crystalline structure.

Load Resistance: A load or battery determines the voltage at which the panel will operate. For example in a nominal 24 V battery, the battery voltage is usually between 23 and 28 V. For the batteries to charge, the panels must operate at a slightly higher voltage than the battery bank voltage. PV systems should operate at voltages close to the maximum power point of the array. If a load's resistance is well matched to a panel's I-V performance, the panel will operate at or near the maximum power point, resulting in highest possible efficiency. As the load's resistance increases, the panel will operate at voltages higher than the maximum power point, causing efficiency and current output to decrease.

For this reason, a control device that tracks the maximum power point must be used to continuously match voltage and current operating requirements of the load.

*Intensity of Sunlight:* The current of a solar panel is proportional to the intensity of solar radiation, but the voltage does not change appreciably.

*Cell Temperature:* As the cell temperature rises above the standard operating temperature of 25˚C, the panel operates less efficiently and the voltage decreases. In this case heat can be considered as resistance to flow of electrons. Effective current may also decrease. A panel between 80 to 90˚C, losses 0.5% in efficiency per every degree rise in temperature. So airflow above and under the panel is critical to remove heat. For this reason mounting scheme that can remove heat is important. In solar systems with no batteries, temperature rise is more noticeable.

*Shading:* Even partial shading of photovoltaic panels will result in dramatic output reduction. Even if one cell is shaded, the module (containing 12 cells) might have its output reduced by 75%. But in the Middle East, high buildings are not much, so shading effect is not so problematic [14].

*G. Mounting solar Panels and Tracking*

An array consists of two or more photovoltaic panels wired to achieve a desired voltage and current. An array is usually mounted at a fixed angle from the horizontal, facing due south. Because the sun's position changes throughout the day and year, the array will receive varying amounts of sunlight. Mounting system types can maximize the received solar power. The types of mounts are:

*Pole mount:* This system uses a mounting hardware bolted directly to a vertical pole that is securely cemented in the ground. Pole mounts can be used to mount arrays of up to twenty-four modest sized modules, that is about four solar panels.

*Ground mount:* This system uses a ground mounted array support structure with a frame bolted directly to prepared footings. Standard support frames are commercially available or may be fabricated on site.

*Roof mount:* There are four types:

- Rack mount: It is supported by a metal framework at a predetermined angle.
- Direct mount: The panels are mounted directly to the conventional roof covering
- materials with no frame and mounting rails
- Integrated mount: In this system, the solar panels replace the conventional roof.

*Tracking Mounts:*

- Single axis: Most single axis trackers passively follow the sun's azimuth but not altitude. They are cost effective, with no motors or gears but use changing weight of a gaseous refrigerant sealed within tubes to track the sun. Sunlight heats the refrigerant on one side causing the refrigerant to boil, expand as a gas and condense on the other side which results in a weight shift and causes the tracker to move. When the tracker faces the sun, both sides are evenly heated and remains in its position until the sun's position changes, causing the tracker to shift again.
- Dual axis: track the sun's azimuth and altitude using a linear actuator for each axis, the motors of which are controlled by a sensor for each axis. The power of these motors comes from one of the arrays.

- Tracking units enhance performance by about 25-30% annually and in winter by about 15% and in summer by about 40%, but with extra cost. So such system is ideal for loads that work in summer such as cooling and air-conditioning [14] [16].

## IV. Batteries

In photovoltaic system, the energy is stored in batteries during the day so as to be used at night. Also, as photovoltaic system's power output varies throughout any day, a battery storage system can provide a relatively constant source of power.

Batteries are not hundred percent efficient. Some energy is lost as heat and in chemical reactions. Therefore, additional photovoltaic modules are needed to compensate for the loss.

Utility grid-connected photovoltaic systems do not require batteries, though they can be used as an emergency backup power source.

The following types of batteries are commonly used in PV systems: Lead acid which are either liquid vented or sealed VRLA- Valve Regulated Lead Acid) and Alkaline batteries which are also of two types, Nickel-Cadmium and Nickel-Iron.

### *A. Lead-Acid Batteries*

Automotive batteries are not suitable for such applications because they are designed to discharge large amounts of current for a short duration to start an engine and then be immediately recharged by the vehicle's alternator. Photovoltaic systems require a battery to discharge small amounts of current over long durations and to be recharged under irregular conditions. These batteries are deep cycle which can be discharged down as much as 80%, they can last for 3 to 10 years, while car batteries can last for only a few photovoltaic cycles under these conditions [14][15].

#### A.1 Liquid Vented

Like automobile batteries, are built of positive and negative plates, made of lead and lead alloy placed in an electrolyte solution of sulphuric acid and water. A 12 V battery consists of 6 cells each of 2 volt. As with automobile battery, a voltage controller is used to regulate the voltage. When a battery nears full charge, hydrogen gas is produced and vented out of the battery. When cold the battery has less capacity, but high temperatures shorten battery life.

#### A.2 Sealed Lead-Acid Batteries (VRLA)

They have no caps and thus no access to the electrolyte. They are not totally sealed, there is a valve which allows excess pressure to escape in case of over charging. This is referred to as a valve regulated lead acid battery (VRLA).

There are two types of sealed batteries used in PV systems, gel cell and absorbed glass mat (AGM). In gel cell batteries, the electrolyte is gelled by adding silica gel that turns the liquid into a gelled mass. AGM batteries use a fibrous silica mat to suspend the electrolyte. This mat provides pockets that assist in the recombination of gasses generated during charging and limit the amount of hydrogen gas produced.

### *B. Alkaline Batteries*

Most common alkaline batteries are nickel-cadmium and nickel-iron. Each cell has a nominal voltage of 1.2 V and the charge termination point is 1.65-1.8 V per cell. They are expensive but they can tolerate extremely cold temperature.

### *C. Battery Capacity*

Battery capacity is given in amp-hour (AH), a battery of 100 AH, in theory can deliver one amp for 100 hours or two amps for 50 hours before the battery is considered fully discharged. To increase battery capacity, they can be connected in parallel. Two 100 AH 12 V batteries wired in parallel provide 200 AH at 12 V. To get higher voltage, they have to be connected in series, two 100 AH 12 V batteries wired in series provide 100 AH at 24 V.

It is advisable to minimize excessive paralleling because this increases the total number of battery cells, thereby increasing the potential for failure from a bad cell.

It is advisable to specify a larger battery capacity than is needed because batteries lose their capacity as they age. But this has to be carefully studied as during reduced insulation (solar power level), the batteries will not be fully charged.

A battery capacity is related to rate of discharge, for example, 6 V battery may have 180 AH capacity if discharged over 24 hours and will have 192 AH if discharged at a rate of 72 hours.

For this reason a battery capacity is usually given in the form of C/20 for example, meaning a capacity of C if discharged over a rate of 20 hours.

Depth of discharge (DOD) refers to how much capacity is withdrawn from a battery. Most PV systems are designed for discharges of 40-80%.

Battery life is related to how deep the battery is cycled. If a battery is discharged to 50% every day, it will have double its life if discharged to 80%. Lead-acid batteries should never be completely discharged. Shallow cycling means discharging to 10-20% with the advantage that the battery will have a long life. If a battery is cycled 10% DOD, it will have about five times the life of 50% cycle. The best total capacity of a batteries in PV system is to based on 50% depth of discharge.

A battery that experience shallow cycling of 25% DOD would last about 4000 cycles, while if cycled to 80% DOD, it would last for only 1,500 cycles. If one cycle equalled one day, the shallow cycled battery would last for 10.95 years, while deeply cycled battery would last for only 4 years.

Manufacturers usually rate their battery capacity at 25 ˚C. As the temperature drops down, battery capacity decreases. At zero degree, a battery capacity drops to about 65-85% its fully rated capacity. For this reason the required battery capacity must be based on 25 ˚C, if the temperature drops down, the total battery capacity must be increased by a factor of 1.19 at 10 ˚C, 1.3 at 4.4 ˚C, 1.4 at -1.1 ˚C, 1.59 at -6.7 ˚C for example [14][16][17].

## V. Charging and Load Controllers

Photovoltaic charging controllers are voltage regulators. Their primary function is to prevent overcharge by sensing battery voltage. When the batteries are fully charged, the controller will stop or decrease the amount of current flowing from the PV array into the batteries. They are of different sizes . For example one manufacturer produces 12 V and 24 V battery charge controllers with sizes from 10 to 100 A (120 W to 2.4 KW); 48 V from 15 to 300 A (720 W to 14.4 KW); 96 V, 110 V and 220 V from 30 to 200 A (2.88 to 44 KW).

Some charging controllers have additional features:

- Lights. They indicate when the batteries are fully charged, when the battery voltage is low.
- Meters. One of which is a voltmeter with emphasize on battery voltage, high, normal or low, the other is an ammeter which indicates whether the array is working normally.
- Temperature compensation. When the battery temperature is less than 15 ˚C or more than 35 ˚C, the charging voltage should be adjusted. Some controllers have a temperature sensor to automatically change the charging voltage[16].

## VI. Inverters

There are two types of inverters, single phase 230 V AC, 50 Hz and three phase 380 V, 50 Hz. The power that such inverters can handle depends very much on the input DC voltage as shown below (this an example of the range of a manufacturer list):

*Single Phase:*

- 12 V DC from 200 W to 500 W,
- 24 V DC from 200 W to 2 KW
- 48 VDC from 0.5 to 10 KW,
- 110 VDC from 1 to 30 KW
- 220 VDC from 1 to 100 KW

*Three Phase:*

- 48 VDC from 3 to 10 KW,
- 110 VDC from 3 to 100 KW.
- 220 VDC from 3 to 250 KW,
- 540 VDC from 45 to 500 KW

### A. Inverter Features

*Efficiency:* From 80 to more than 94%. But efficiency is connected with the load. If the load is small compared with the inverter peak output, the efficiency comes down [14][15]. For example a 4000 watt inverter will have efficiency of 61% if operated with a load of 25 W, 85% with a load of 100 W, 94% with a load of 400 W, 90% with a load of 1,600 W, 83% with a load of 3200 W and 75% with a load of 6400 W.

*Harmonic regulation:*

- Should have low output peaks to minimize harmful heating effects.
- Should be based on modular circuitry to be replaced easily, with guard protective System.

*Load controller:* to shut off the load in case the battery voltage comes too low.

*Parallel operation:* Multiple inverters can be connected in parallel to increase servicing more load.

*Series Operation:* To enable inverters to work on higher voltage load.

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