University of Asia Pacific
Department of Electrical & Electronic Engineering

EEE 401: Energy Conversion and Special Machines

Module 1: Solar Energy

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ENERGY SOURCES

Classification

- ✓ Renewable and Non Renewable
- ✓ Commercial and Non Commercial
- ✓ Primary and Secondary

WHY RENEWABLES ?

1. They are sustainable resources
2. They can contribute to the overall economic growth
3. They usually have low environmental impacts
4. They contribute to the welfare of isolated communities
5. They can contribute to regional and global applications
6. To reduce the impact of climate change
7. To promote sustainable development

RENEWABLE ENERGY RESOURCES: CONSTRAINTS

- Non-availability/ magnitude of resources throughout the year
- Relatively high capital cost
- Current utilization methods
- Low awareness and large scale exploitation may lead to localized environmental impacts

OBJECTIVE OF THIS MODULE

After end of this module one can learn-

- ✓ How to estimate solar radiation at a location?
- ✓ Thermal collectors principles and working
- ✓ Photovoltaic principles
- ✓ Where they can be applied? How ?
- ✓ Simple design of thermal and PV systems

SOLAR RADIATION
Sun Earth angles
Extraterrestrial radiation, clear sky radiation and attenuation of beam radiation
Solar radiation on the earth's surface

DETERMINATION OF SOLAR RADIATION

To use any energy resource, we need to know:

its availability, quantification, quality
for what application/use it is to be used ?
is it appropriate ?
is it environment friendly ?
resource base and its qualification

- **Quantity** **Fossil:** Reserves, calorific value, mc, ash,..
  Renewable: Unlimited, density,..
- **Quality** **Fossil :** Calorific value, mc, ash,..
  Renewable : Density,..
- **For Whom?** Designer of solar systems
  Architects, air conditioning engineers
  Energy conservation specialists
  Water resource management

DETERMINATION OF SOLAR RADIATION (cont'd)

To know this, we need to study:

Basic sun earth angles

- latitude ,
- longitude
- (equation of time)
- (solar and watch time)
- hour angle
- Declination

Derived angles

- incidence
- altitude
- azimuth
- tilt
- sunrise and sunset

SUN EARTH ANGLES

SUN PATH DIAGRAM

Apparent daily path of the Sun in the sky throughout the year for an observer in the Northern Hemisphere (left) and Southern Hemisphere (right).

FACTORS AFFECTS SOLAR RADIATION

The solar radiation on the earth's surface varies-

(i) During the day (from morning to noon and from noon to evening with the maximum usually at noon.)

This is called hourly variation.

This is due to the motion of the sun from east to west during the course of the day and is true for all locations.

(ii) Daily, which is primarily due to the presence of clouds

(iii) Monthly (or seasonal variation), due to the location and the sun's position.

(iv) From location to location.

FACTORS AFFECTS SOLAR RADIATION (cont'd)

(v) depending on the orientation of the surface, i.e., whether the surface receiving the radiation is placed horizontally or is tilted from the horizontal, etc.

This could be seasonal in nature or even during the day and dependent on the location.

Some of these factors could be obtained by a knowledge of the sun earth angles.

LATITUDE and LONGITUDE

The position of a location on the earth's surface is known by the coordinates **latitude and longitude.**

LATITUDE (ϕ) is,

- The angular distance of a point (on the surface of the earth) from the equator.
- The angular distance could either be north or south of the equator.
- It tells us how far north (or south) the location is from the equator.
- North latitudes are taken to be positive, while south latitudes are taken as negative.

LATITUDE and LONGITUDE (cont'd)

LONGITUDES or MERIDIANS are,

- Semi great circles passing through the poles of the earth.
- The zero (0) meridian passing through Greenwich near London is called the prime meridian
- The angle between the prime meridian and the meridian passing through the location
- Locations east of Greenwich are denoted by degrees East, while the locations west of Greenwich are denoted by degrees West.

LATITUDE and LONGITUDE (cont'd)

C,	Center of the earth
P, Q,	north and south poles respectively
G,	Greenwich, a location in the northern hemisphere (near London) through which the prime meridian is assumed to pass
H,	a location on the surface of the earth in the northern hemisphere and east of Greenwich
U,	a location in the southern hemisphere
AJBDA,	plane of the equator
PGJQ,	prime meridian

HKL, plane of a latitude
PHBQ, meridian of longitude (L)
Angle HPG, longitude of location H (east of Greenwich)
K, a location in the northern hemisphere and west of Greenwich

LATITUDE and LONGITUDE (cont'd)

DEFINITIONS

- ✓ **Beam Radiation:** The solar radiation received from the sun without having been scattered by the atmosphere. (Beam radiation is often scattered to as direct solar radiation; to avoid confusion between subscripts for direct and diffuse, we use term beam radiation)

- ✓ **Diffuse Radiation:** The solar radiation received from the earth after its direction has been changed by scattering by the atmosphere. (Diffuse radiation is referred to in some meteorological literature as sky radiation or solar sky radiation; the definition used here will distinguish the diffuse solar radiation from infrared radiation emitted by the atmosphere.

- ✓ **Total solar radiation:** The sum of the beam and the diffuse solar radiation on a surface. (The most common measurement of solar radiation are total radiation on a horizontal surface, often referred to as global radiation on the surface).

DEFINITIONS (cont'd)

- **Air Mass, m:** The ratio of the mass of atmosphere through which beam radiation passes to the mass it would pass through of the sun were at the zenith (directly overhead). It is denoted by m.

  Useful notation:

  m =0 ; extraterrestrial radiation
  m = 1 ; at sea level, when the sun is at its zenith
  m = 2 ; when the zenith angle is 60°

  So, $m = \frac{1}{\text{Cos } \theta_Z}$; θ_Z is zenith angle

- **Irradiance, W/m^2:** The rate at which the radiant energy is incident on a surface of unit area. The symbol G is used for solar irradiance, with appropriate subscripts for beam or diffuse radiation.

- **Irradiation, J/m^2:** The incident energy per unit area of a surface, found by integration of irradiance over a specified time (hour or day). It is also called as insolation.

NOMENTCLATURE

H denotes daily radiation Values.

I refers to instantaneous or hourly radiation values.

Subscripts are commonly used to distinguish different radiation terms.

(a) Type of radiation

b - beam component

d - diffuse component

t or **g** - total or global (or it is omitted)

Example: I_d denotes hourly diffuse radiation on a horizontal surface

(b) Depending on surface orientation

h - radiation on horizontal surface (or it is omitted)

T - radiation on tilted surface

Example: H_T denotes daily global radiation on a tilted surface

NOMENTCLATURE (cont'd)

(c) Others

o - extraterrestrial radiation
sc - solar constant

In solar energy studies, it is often convenient to use monthly average or monthly mean values of different time scales (hourly or daily). These are denoted by a bar ("-") above the parameter. Thus,

H denotes the monthly average daily radiation
$\bar{I}$ denotes the monthly average hourly radiation
$\bar{I}_d$ denotes the monthly average hourly diffuse radiation on horizontal surfaces.

DECLINATION (δ)

- It is the angular distance, north (or south) of the equator of the point, when the sun is at its zenith (or) when the sun is directly overhead at any location during solar noon, the latitude of that location gives the declination.

- At locations north of the Tropic of Cancer, the sun always appears in the south, while at locations south of the Tropic of Capricorn, the sun always appears to the north.

- The declination varies throughout the year, but all places on the earth will have the same declination for a given day and is given

$$\delta = 23.45 \text{ Sin } \{360 (284 + N) / 365\} \text{ degrees}$$

where, N is the day number of the year.

DECLINATION (cont'd)

DECLINATION (cont'd)

HOUR ANGLE (ω)

- It is the angular displacement of the sun east or west of the local meridian due to the rotation of earth on its axis at 15° per hour.
- Hour angle tells us how close the time is to solar noon. Solar noon is the time when the sun is directly overhead.
- Hour angle is always with reference to the particular location
- It does not depend on any other parameters (geographical or otherwise) such as GMT, latitude, etc.
- At solar noon, the hour angle is zero, when the sun reaches its highest point in the sky.
- In the morning it is negative, while in the afternoon, it is positive.
- The hour angle can be calculated from,

$$\omega = 15\,(t-12)$$ degrees, where t is solar time in hours.

HOUR ANGLE (cont'd)

Therefore,

At noon, hour angle ω = 0

At 11 am solar time, hour angle (ω) = -15 degrees

At 2.30 pm solar time, hour angle (ω) = +37.5 degrees

For the time 8-9 am, the hour angle is taken as the mid point of the hour i.e., at 8.30 am.

Therefore, **the hour angle (ω) = -52.5 degrees**

HOUR ANGLE (cont'd)

AB: A vertical plane containing the sun and the location of interest (Hour angle is zero) Sun is overhead or it is on the vertical plane containing the meridian (solar noon).

AC: Sun's position in the morning. Hour angle is given by the angle formed by planes AB and AC .

Morning values are taken as - ve

SOLAR TIME and WATCH TIME

SOLAR TIME

- This is based on solar day which is defined as the time interval between two successive passages of the sun across the meridian of the observer.

- Solar time is the time specified in all sun-angle relationships, i.e., <u>all calculations in solar energy are based on solar time only.</u>

- The movement of the sun is symmetrical about solar noon.

SOLAR TIME and WATCH TIME (cont'd)

WATCH TIME

- This is based on longitudes and is dependent on the standard meridian for each country (region).
- The reference meridian is the Greenwich meridian.
- It does not depend on the sun's position. The day length is not symmetrical to the solar noon.
- The earth makes a complete rotation on its axis once in 24 hours, thereby moving across 360° longitude. The rotational speed is therefore, 4 minutes per meridian (longitude) or 15° per hour.

SOLAR TIME and WATCH TIME (cont'd)

RELATIONSHIP

Solar time will be different from watch time due to:

(i) Due to longitudinal differences between the local longitude (Llo) and the standard longitude (Lst)

$$\Delta = 4(Lst - Llo) \quad \text{minutes}$$

(ii) Due to the fact that the rotational and angular velocities of the earth is not always constant (equation of time (EOT)). This could be estimated from:

$$EOT = 9.87 \sin 2B - 7.53 \cos B - 1.5 \sin B \quad \text{minutes}$$

where, $B = 360\,(N-81)/364$

N = day number of the year

SOLAR TIME and WATCH TIME (cont'd)

RELATIONSHIP

(iii) The difference between the solar time (ST) and watch time (WT) for locations east of Greenwich (say, Asian, African and Australian locations), as

$$\text{Solar Time} = \text{Watch Time} + \text{EOT} - \Delta$$

while for locations west of Greenwich (say, the Americas) it is

$$\text{Solar Tine} = \text{Watch Time} + \text{EOT} + \Delta$$

DERIVED ANGLES

These are used to define the sun's position in relation to the surface.

AZIMUTH ANGLE (γ)

- It is the angle on the horizontal plane measured from south to the horizontal projection of the sun's direct rays (or)
- It is also the angle of sun from South measured horizontally (in the northern hemisphere).
- East of south is taken as negative and west of south as positive.
- Azimuth angle of a surface in the northern hemisphere facing direct south is zero.

SLOPE or TILT ANGLE (β)

- It is the angle the surface makes with the horizontal plane.

DERIVED ANGLES (cont'd)

INCIDENCE ANGLE (θ)

- For any surface, it is the angle between the sun's direct rays (I_b) and the normal to the surface.

ZENITH ANGLE (θ_z)

- The zenith angle (θ_z) is the incidence angle for a horizontal surface i.e. it is the angle between I_b and a line perpendicular to the horizontal surface.

ALTITUDE ANGLE (α)

- It is the angle on a vertical plane between I_b and the projection of the sun's rays on the horizontal plane

i.e. $\alpha = 90 - \theta_z$

DERIVED ANGLES (cont'd)

INCIDENCE ANGLE

DAY LENGTH MEASUREMENT

DAY LENGTH

- Day length is the time between sun rise and sun set and therefore will be equal to m / 2 ϖ_s(degrees)
- Hour angle is related to time as 15°= 1 hr. So, in terms of time, Daylength = (2/15) ϖ_s hrs.
- For tilted surfaces, the sunrise hour angle (ϖ_s) is given by

$$\varpi_S = \text{Min of } \{\text{Cos-1 } (-\tan \varphi \tan \delta) \text{ or Cos-1 } (-\tan \varphi - \beta) \tan \delta)\}$$

MEAN DAY OF THE MONTH

Recommended Average Days for Months and Values of n by Months[a]

Month	n for *i* th Day of Month	For the average day of the month		
		Date	n, Day of Year	d, Declination
January	i	17	17	-20.9
February	31+ i	16	47	-13
March	59 + i	16	75	-2.4
April	90 + i	15	105	9.4
May	120+ i	15	135	18.8
June	151+ i	11	162	23.1
July	181 + i	17	198	21.2
August	212 + i	16	228	13.5
September	243 + i	15	258	2.2
October	273 + i	15	288	-9.6
November	304+ i	14	318	-18.9
December	334 + i	10	344	-23

[a] From Klein (1977)

SUN PATH DIAGRAM

- ✓ This is used to know the position of sun in the sky relative to a location at a given instant of time.
- ✓ The sun path diagram could be drawn for a given location (lattitude) of time (hour, day and month).

⌖ Observer at that location

Note: Concentric circles: altitude angle
Radial line: azimuth angle

SOLAR CONSTANT

The solar constant (I_{SC}) is the total amount of electromagnetic energy of all wavelength that falls on a unit area normal to the sun in unit time at the top of the earth's atmosphere when the earth is at its mean distance from the sun.

- The intensity of solar radiation varies inversely to the square of the distance from the sun.
- The value of $\mathbf{I_{SC}}$ = **1367** W/m².
- The average sun-earth distance is called an astronomical unit or AU, 1 AU = 149.6 million km.
- The distance between the sun and the earth varies every day and is a minimum on January 4 and a maximum on July 6.

ATTENUATION OF EXTRATERRESTRIAL RADIATION

Extraterrestrial Radiation is the maximum possible radiation, acts as a reference.

✓ **Two Mechanisms of Attenuation:**

(a) scattering by

air molecules,
water vapor and
dust;

(b) absorption by

water vapor,
ozone and
carbon dioxide.

CLEARNESS INDEX

- K or K_T
- hourly or daily.

The hourly clearness index (k) during a particular hour is the ratio of the hourly global radiation on horizontal surface to the hourly extraterrestrial radiation on horizontal surface (during the same time period).

$K = I / I_0$

and the monthly average hourly clearness index (k) is : $\bar{k} = \dfrac{\bar{I}}{\bar{I}_0}$

The daily clearness index (K) gives the ratio of the daily global radiation on a horizontal surface to the daily extraterrestrial radiation on a horizontal surface.

$K = H / H_0$

the monthly average daily clearness index (K or K_T) is given by $\bar{K} = \dfrac{\bar{H}}{\bar{H}_0}$

SOLAR RADIATION ON THE EARTH'S SURFACE

Direct, diffuse, and total solar radiation.

MEASURING INSTRUMENTS

- **SUNSHINE RECORDER**

  The determination of sunshine duration is one of the oldest measurement by which the solar radiation was estimated

- **Pyranometers**

  Pyranometer measure the total or global solar radiation and when provided with a shading ring, measure the diffuse radiation.

- **Pryheliometer**

  Pyrheliometer is an instrument for measuring the intensity of direct solar radiation at normal incidence and can be a primary standard instrument.

  Pyrheliometer must follow the sun to measure only the direct sunlight and avoid the diffuse component. This is done by using a collimator tube over the sun and tracking the sun continuously.

SOLAR THERMAL COLLECTION AND UTILIZATION
Solar thermal collector: basic principle of operation
Energy analysis of flat plate collectors
Concentrating collectors
Applications of solar thermal systems

INTRODUCTION OF SOLAR THERMAL COLLECTORS

- How much radiation fall on surface
  - Horizontal, tilted
  - How this is used by a solar collector

- Needs a study of
  - Optics – for input
  - Heat transfer – for useful energy, and losses

SOLAR THERMAL CONVERSION

There are two basic types of collectors:

(a) Flat plate collectors

(b) Concentrating collectors

- **Flat plate collectors:** the solar radiation falls directly on the surface that serves to absorb the radiation. These collectors are normally fixed and used for relatively low temperature applications.

- **Concentrating collectors:** the solar radiation is first received by one or more reflecting or refracting surfaces which serve to convey it to a relatively small absorbing surface. These collectors are normally require continuous or intermittent orientation towards the sun and are used for relatively high temperature applications.

FLAT PLATE COLLECTOR

WORKING PRINCIPLE OF A FLAT PLATE SOLAR COLLECTOR

FLAT PLATE COLLECTOR

- ✓ A flat-plate solar collector consists of a waterproof, metal or fiberglass insulated box containing a dark-colored absorber plate, the energy receiver, with one or more translucent glazing.

- ✓ Consists of a black surface behind glass that gets super-hot in the sun. Glass is transparent to visible radiation (aside from 8% reflection loss).

- ✓ Absorber plates are typically made out of metal due to its high thermal conductivity and painted with special selective surface coatings in order to absorb and transfer heat better than regular black paint can.

- ✓ The glazing covers reduce the convection and radiation heat losses to the environment.

FLAT PLATE COLLECTOR EFFICIENCY

- An important indicator of the performance of a solar collector is its efficiency, which is defined as the percentage of intercepted solar energy transferred to the working fluid.
- Two-pane design only transmits about 85% of incident light, due to surface reflections
- Collector is not a perfect absorber, and maybe absorbs 95% of incident light.
- Radiative losses total maybe 1/3 of incident power and Convective/Conductive losses are another 5-10%.
- Bottom line is approximately 50% efficiency at converting incident solar energy into stored heat.

SOLAR DOMESTIC WATER HEATING

There are five major components in solar water heating systems-

- ✓ Collector(s) to capture solar energy
- ✓ Circulation system to move a fluid between the collectors to a storage tank
- ✓ Storage tank
- ✓ Backup heating system
- ✓ Control system to regulate the overall system operation

SOLAR DOMESTIC WATER HEATING (Cont'd)

There are two basic categories of solar water heating system–

- Direct or open loop system
- Indirect or closed loop system

- Direct System

  The water that will be used as domestic hot water is circulated directly into the collectors from the storage tank (typically a hot water heater which will back up the solar heating).

- Indirect System

  Indirect or closed loop systems use a heat exchanger that separates the potable water from the fluid, known as the "heat-transfer fluid" (HTF), that circulates through the collector.

ROOFTOP SOLAR DOMESTIC WATER HEATING

DIRECT WATER HEATING SYSTEM

INDIRECT WATER HEATING SYSTEM

- Indirect solar water heating system without heating backup.

INDIRECT WATER HEATING SYSTEM (cont'd)

- Indirect solar water heating system with heating backup.

INDIRECT WATER HEATING SYSTEM (cont'd)

- Indirect or closed loop systems use a heat exchanger that separates the potable water from the fluid, known as the "heat-transfer fluid" (HTF), that circulates through the collector.
- After being heated in the panels, the HTF travels to the heat exchanger, where its heat is transferred to the potable water.
- The controller in these systems will activate the pumps to the collectors and heat exchanger when design temperature differences are reached.
- An indirect system that exhibits effectiveness, reliability, and low maintenance.
- A refrigerant system is generally more costly and must be handled with care to prevent leaking any refrigerant.

HEAT TRANSFER RELATIONS FOR FLAT PLATE COLLECTORS

1. CONDUCTION

- At the back and sides
- Fluid flow through pipes (water) (negligible)
- Fluid flow through duct (air) (negligible)

2. CONVECTION

- Between absorber plate and cover plate
- Between cover plate and ambient
- In riser tubes

3. RADIATION

- Between absorber plate and cover plate
- Between cover plate and sky.

ENERGY BALANCE EQUATION

$$Q_U = Q_{in} - Q_{loss}$$

$$= A_c H (\tau\alpha) - A_c U_L (T_p - T_a)$$

Q_{in}

A_c Collector area

H, Radiation incident on collector (or H_T)

$(\tau\alpha)$, a factor to take into account the transmission of cover and the absorption of plate (instantaneous or average)

Qloss

U_L overall heat loss coefficient

T_p plate temperature (mean)

T_a ambient temperature (mean)

ENERGY BALANCE EQUATION (Cont'd)

For Flat Plate Collector,

Ac	Measured
$(\tau\alpha)$	Not possible to measure directly
T_p	Not possible to measure directly
T_a	Measured
U_L	Not possible to measure directly
Qu	$mCp\ (T_{fo} - T_{fi})$, can be measured

ENERGY BALANCE EQUATION (Cont'd)

The steady state useful energy gain (Qu) for the collector is given by

$$Q_u = mC_p\left(T_{f,out} - T_{f,in}\right)$$

where,

m is the mass flow rate of fluid

Cp is the specific heat of the fluid

Tf,out, Tf,in are the fluid temperature at outlet and inlet of the collector

The instantaneous collector efficiency is then given by

$$\eta_c = \frac{Q_u}{A_c . I_T} = \frac{\frac{(m)}{A_c} C_p\left(T_{f,out} - T_{f,in}\right)}{I_T}$$

where,

Ac is the area of the collector

IT is the total incident radiation on the collector

PROBLEM

The daily hot water requirement per person is 50 liters. If $\overline{H}$ for April is 24 MJ/m^2, what is the solar collector area requied for a family of four persons if the hot water is requied at 65°C while the ambient temperature can be assumed to be constant at 22°C. The solar collector is 50 % efficient

SALIENT FEATURES OF SOLAR WATER HEATING SYSTEM

- Around 60 deg.–80 deg. Celsius temperature can be attained depending on solar radiation, weather conditions and solar collector system efficiency.

- Can be installed on roof-tops, building terrace and open ground where there is no shading, south orientation of collectors and over-head tank above SWH system.

- Hot water for homes, hostels, hotels, hospitals, restaurants, dairies, industries etc.

ADVANTAGES OF SHWS

Fuel Savings

A 100 liters capacity SWHs can replace an electric system for residential use and saves 1500 units of electricity annually.

Avoided utility cost on generation

The use of 1000 SWHs of 100 liters capacity each can contribute to a peak load shaving of 1 MW.

Environmental benefits

A SWH of 100 liters capacity can prevent emission of 1.5 tonnes of carbon dioxide per year.

Life

15-20 years.

Approximate cost

Tk.15000-20,000 for a 100 liters capacity system and Tk. 110-150 per installed liter for higher capacity systems.

DESIGN CONSIDERATIONS

- Collector tilt:
  - ✓ The flat plate collector is generally fixed permanently by considering the season of predominant hot water use.
  - ✓ For a year round use, the collector tilt is kept equal to the latitude, while for winter use, the collector tilt is (lat + 10°) and for summer use, it is (lat -10).

- The orientation: facing direct south (in the northern hemisphere).
- The collector area depends on the daily hot water demand, which depends on the local customs.

- The following could be taken as a 'guideline‘:
  1. Conservative 30 - 40 lit/person/day
  2. Average 40 - 60 lit/person/day
  3. High 60 - 120 lit/person/day

DESIGN CONSIDERATIONS

- For natural convection systems, the bottom of the storage tank should be at least 30 cm above the top of the collector.

- The daily overall system efficiency of a domestic solar hot water system is about 30 - 40%.

- The flow rate through a natural circulation system is about 40 lit/m2 hr in bright sunshine and around noon, the normal temperature difference between the collector outlet and inlet is about 100C.

- Storage tank capacity: Sized to allow two days hot water to take care of any day being completely cloudy. The storage tank capacity of 2.5 times the daily requirement is generally sufficient.

CONCENTRATING COLLECTOR

CONCENTRATING COLLECTOR

- Concentrating, or focusing, collectors intercept direct radiation over a large area and focus it onto a small absorber area.

- These collectors can provide high temperatures more efficiently than flat-plate collectors, since the absorption surface area is much smaller. However, diffused sky radiation cannot be focused onto the absorber.

- Most concentrating collectors require mechanical equipment that constantly orients the collectors toward the sun and keeps the absorber at the point of focus.

WHY CONCENTRATING COLLECTORS?

- Flat plate collectors are the most common but are only suitable for applications requiring temperatures of the order of up to about 80-85°C.

- But, when higher delivery temperatures are required, as the input radiation cannot be increased, the reduction of heat losses could be possible by reducing the surface area of the absorber.

- In order to do that, an optical device could be placed between the radiant source and the absorbing surface.

TERMINIOLOGY USED IN CONCENTRATING COLLECTORS

Receiver: It is the part of the system that absorbs the solar radiation and converts it into other energy forms (heat). It usually consists of the absorbing surface, insulation, etc.

Concentrator: This is the optics of the system that directs the solar radiation onto the receiver.

Aperture: This refers to the opening in the concentrator through which the solar radiation enters the concentrator.

Collector: This refers to the total system including the receiver and the concentrator.

Concentration Ratio: It is the ratio of the collector aperture area to the absorber area. For flat plate collector CR ≈ 1.

TYPES OF CONCENTRATING COLLECTOR

a) Parabolic trough system

b) Parabolic dish system

c) Power tower system

PARABOLIC TROUGH SYSTEM

- Parabolic troughs are devices that are shaped like the letter “u”.
- The troughs concentrate sunlight onto a receiver tube that is positioned along the focal line of the trough.

PARABOLIC DISH SYSTEM

- A parabolic dish collector is similar in appearance to a large satellite dish, but has mirror-like reflectors and an absorber at the focal point. It uses a dual axis sun tracker.

PARABOLIC DISH SYSTEM

POWER TOWER SYSTEM

- A heliostat uses a field of dual axis sun trackers that direct solar energy to a large absorber located on a tower. To date the only application for the heliostat collector is power generation in a system called the power tower.

POWER TOWER SYSTEM

POWER TOWER SYSTEM

CONCENTRATED SOLAR POWER

A CSP has essentially four basic components- Concentrator, Receiver, Transport or storage and a Power converter unit.

SOLAR THERMAL APPLICATIONS

- **Electricity generation**
- **Water heating systems**
  Domestic and industrial hot water systems
- **Air heating systems**
  Drying
  Space heating
- **Solar cooling**
  Refrigeration and air conditioning
- **Cooking**, etc.

PHOTOVOLTAIC EFFECT AND SOLAR CELLS

- Generation of electromotive force as a result of the absorption of ionizing radiation is photovoltaic effect.
- Devices that use the photovoltaic effect to generate a voltage when sunlight is the source of ionizing radiation are called solar cells.
- An individual cell typically produces power at about 0.5V with the current directly proportional to the cell's area.
- The individual cells are connected in series-parallel combinations to meet the voltage, power and reliability requirements of the particular application.

PROPERTIES OF LIGHT

- Energy is not indefinitely indivisible. The smallest amount of energy that can be transferred in a form of energy and a quantum of light is called a photon.

- The photon must be treated not only as particle but also as a wave. The wavelength of photon depends on its energy (the greater the energy, the shorter its wavelength).

- The energy of a photon (E) is proportional to the frequency (γ) of light and is related by $E = h\gamma$; h is Planks' constant or $E = hc/\lambda$.

- In the atom, an electron either absorbs a quantum of energy or it does not (there is no middle way).

PROPERTIES OF LIGHT (cont'd)

- Therefore, the energy of an electromagnetic wave of wavelength (λ) is carried by particles (photons) of momentum h/λ.

- Radiation thus has a wave characteristic and as energy is transferred in discrete amounts. This gives light a dual nature.

- Thus, light must be treated not only as 'wave' but also as a stream of 'particles', each of which carries a discrete quantity of energy.

LIGHT INTERACTION IN SEMICONDUCTORS

- Radiation from the sun can be considered as a stream of energy called photons, each one carrying an energy exactly equal to $h\gamma$.

- Once light has entered the semiconductor, the individual photons strike the electrons within the semiconductor. As momentum is conserved, the electrons receive almost all the energy of the photon.

There are two possibilities-

LIGHT INTERACTION IN SEMICONDUCTORS

(i) If the photon has less energy than the forbidden energy gap, it cannot interact with the electron (in the valence band) because after collision the electron would have absorbed all the energy, but since the energy received is less than the forbidden energy gap, the electron remains in the valence band and the energy gained is lost by collision with the lattice atoms.

The net result is that there is an increase in the temperature of the semiconductor.

(ii) When the photon has energy greater than the forbidden gap, the electron (in the valence band) that receives this energy has now sufficient energy to 'jump' the forbidden energy gap and enter the conduction band.

LIGHT INTERACTION IN SEMICONDUCTORS

- The electron now has an energy $E_g = (E_c - E_v)$ greater than before the collision. The hole, thus created in the valence band will rise to the top of the valence band.

- Therefore, due to the action of the photon, an electron hole pair has been generated and this electron-hole pair created has gained an energy E_g from the photon.

P-N JUNCTION IN SOLAR CELL

- If a p-type and n-type semiconductor materials are joined together, a p-n junction is made at the boundary.

- A junction could be the result of a single semiconductor crystal being part p-type and part n-type, or being composed of two different semiconductor compounds, or by applying a metal to the surface of the semiconductor.

SUNLIGHT TO ELECTRICITY IN SOLAR CELL

PV cell formed by n- and p-layers

PHOTOVOLTAIC PROCESS

- When a photon of light strikes a semi-conductor (p-n), Particles of light called "photons" bounce into negatively charged electrons around the silicon atoms of the cell, and knock these electrons free from their silicon atoms.

- The energy of the photon is transferred to the electron. There are over a billion photons falling on the cells every second, to there are lots of electrons knocked loose! Each electron is pushed by an internal electric field that has been created in the factory in each cell. The flow of electrons pushed out of the cell by this internal field is what we call the "electric current".

- When some of these charges migrate across the p-n junction and remain, a voltage is created across the junction.

PHOTOVOLTAIC PROCESS (cont'd)

- Metal contacts on both sides of the cell are connected to an electrical circuit to which a load can be connected.

- So, the basic steps in the operation of a solar cell are:

  ✓ the generation of light-generated carriers;
  ✓ the collection of the light-generated carries to generate a current;
  ✓ the generation of a large voltage across the solar cell; and
  ✓ the dissipation of power in the load and in parasitic resistances.

PHOTOVOLTAIC PROCESS (cont'd)

How Solar Cells Change Sunlight Into Electricity

- Light knocks loose electrons from silicon atoms
- Freed electrons have extra energy, or "voltage"
- Internal electric field pushes electrons to front of cell
- Electric current flows on to other cells or to the load
- Cells never "run out" of electrons

SOLAR CELL STRUCTURE

- When sunlight strikes the solar cell, electrons (red circles) are knocked loose. They move toward the treated front surface (dark blue color).
- An electron imbalance is created between the front and back.
- When the two surfaces are joined by a connector, like a wire, a current of electricity occurs between the negative and positive sides.

COMMON PV TERMINOLOGY

- **Solar cell:** The PV cell is the component responsible for converting light to electricity. Silicon is the most common material produce PV effect, where DC current is produced. Solar cells are designed to absorb as much light as possible and are interconnected in series and parallel electrical connections to produce desired voltage and current.

- **PV module:** PV module is composed of interconnected solar cells that are encapsulated between a glass cover and weatherproof backing.

- **PV array:** PV modules are connected in series and parallel to form an array of modules, thus increasing total available power output to the needed voltage and current for a particular application.

COMMON PV TERMINOLOGY (cont'd)

- **Peak Watt (W_P):** PV modules are rated by their total power output, or peak Watts. A peak Watt is the amount of power output a PV module produces at STC (Standard Testing Conditions) of a module operating temperature of 25°C in full noontime sunshine (irradiance) of 1,000 W/m².

  **Keep in mind that modules often operate at much hotter temperatures than 25°C in all but cold climates, thus reducing crystalline module operating voltage and power by about 0.5% for every 1°C hotter. Therefore, a 100 W module operating at 45°C (20° hotter than STC, yielding a 10% power drop) would actually produce about 90 W. Amorphous modules do not have this effect.

CELL, MODULE & ARRAY

Solar Cells
(4 Cells)

Solar Panel
(Module)

Solar PV Array
(Multiple modules)

SOLAR CELL

What Are Solar Cells?

- Thin wafers of silicon
  - Similar to computer chips
  - much bigger
  - much cheaper!
- Silicon is abundant (sand)
  - Non-toxic, safe
- Light carries energy into cell
- Cells convert sunlight energy into electric current- they do not store energy
- Sunlight is the "fuel"

BASIC MATERIAL OF SOLAR CELL

- The element Silicon is the second most abundant element on the earth's surface, next to Oxygen. Silicon and Oxygen together make sand (Silicon Oxide, SiO2). The Oxygen is removed at high temperatures, and leaves behind the Silicon

- So the basic material of solar cells is abundant and safe

- Solar cells need the sunlight as their fuel which is delivered for free all over the world.

EQUIVALENT CIRCUIT OF A SOLAR CELL

- From the equivalent circuit it is evident that the current produced by the solar cell is equal to that produced by the current source, minus that which flows through the diode, minus that which flows through the shunt resistor.

where,

I = output current

I_L = photogenerated current

I_D = diode current

I_{SH} = shunt current

Equivalent circuit of solar cell

Schematic symbol of solar cell

SOLAR MODULE

Connect Cells To Make Modules

- One silicon solar cell produces 0.5 volt
- 36 cells connected together have enough voltage to charge 12 volt batteries and run pumps and motors
- Module is the basic building block of systems
- Can connect modules together to get any power configuration

SOLAR MODULE

- A group of PV cells connected in series and/or parallel.
- Cells are too small to do much work. They only produce about 0.5 volt, and we usually need to charge 12 volt batteries.
- A typical module has 36 cells connected in series, plus to minus, to increase the voltage. 36 times 0.5 volt yields 18 volts. However, the voltage is reduced as these cells get hot in the sun and 12-volt batteries typically need about 14 volts for a charge, so the 36 cell module has become the standard of the solar battery charger industry.

SOLAR ARRAY

- These individual solar cells are arranged together in a PV module and the modules are grouped together in an array.

- Some of the arrays are set on special tracking devices to follow sunlight all day long.

FACTORS AFFECTING ELECTRICAL CHARACTERISTICS OF MODULES

- The magnitude of the current from a solar cell module depends on the following factor:

  - ✓ The amount of sunshine
  - ✓ The temperature of the cell
  - ✓ Number of cells of the module
  - ✓ Effect of cell area
  - ✓ Type of silicon
  - ✓ Blocking diode

FACTORS AFFECTING ELECTRICAL CHARACTERISTICS OF MODULES (cont'd)

✓ The influence of radiation-

Solar cell I-V characteristics for different irradiation values

Solar cell power characteristics for different irradiation values

FACTORS AFFECTING ELECTRICAL CHARACTERISTICS OF MODULES (cont'd)

The power produced by a crystalline PV module is affected by two key factors: solar irradiance and module temperature.

- ✓ The lower the irradiance is, the lower is the current output and thus the lower is the peak power point. Thus, the amount of current produced is directly proportional to increases in solar radiation intensity.

- ✓ Voltage essentially constant; its behavior is essentially constant as solar radiation intensity is changing.

FACTORS AFFECTING ELECTRICAL CHARACTERISTICS OF MODULES (cont'd)

✓ The temperature of the cell-

Solar cell I-V characteristics temperature dependency

Solar cell power characteristics temperature dependency

FACTORS AFFECTING ELECTRICAL CHARACTERISTICS OF MODULES (cont'd)

The effect of module temperature-

- ✓ As the module operating temperature increases, module voltage drops while currents essentially holds steady.
- ✓ PV module operating voltage is reduced on average for crystalline modules approximately 0.5% for every degree Celsius above STC (i.e. 25°C).
- ✓ Thus, a 100 Wp crystalline module under STC now operating at a more realistic 55°C with no change in solar irradiance will lose about 15% of its power rating and provide about 85 W of useful power.

FACTORS AFFECTING ELECTRICAL CHARACTERISTICS OF MODULES (cont'd)

✓ Number of cells in the module-

FACTORS AFFECTING ELECTRICAL CHARACTERISTICS OF MODULES (cont'd)

- ✓ **Effect of cell area:** The maximum current I_{sc} is dependent of the cell area. At all irradiation levels, cells with larger area have a higher I_{sc} than small cells.

- ✓ **Type of silicon:** Single crystal silicon generates the highest current, polycrystalline cells slightly less and thin film cells generate only one half of a single crystal silicon cell.

- ✓ **Blocking diode:** PV modules allow a small current to flow from battery to them at night. This is called dark current leakage and this is prevented by using a blocking diode. This diode requires about 0.7V and so two extra cells are required to compensate this voltage.

SAMPLE MANUFACTURER'S SPECIFICATION

The table below shows a example of manufacturer's specification for a 53 W_p PV Module.

Operating point	Model BP VLX-53
P_{mp}	53 W_p (peak Watts)
V_{mp}	17.2 V
I_{mp}	3.08 A
V_{oc}	21.5 V
I_{sc}	3.5 A
Standard test conditions (STCs)	1,000 W/m^2, 25°C

SAMPLE MANUFACTURER'S SPECIFICATION (Cont'd)

Electrical Specifications
(STC* = 25 °C, 1000W/m² irradiance and AM=1.5)

Max System Voltage (IEC/UL)	1000V / 600V
Maximum Power P_{max}	100 W (-3%, +3%)
Voltage at Maximum Power Point V_{mpp}	18.00
Current at Maximum Power Point I_{mpp}	5.56
Open Circuit Voltage V_{oc}	22.10
Short Circuit Current I_{sc}	5.91
Module Efficiency (%)	15.7
Temperature Coefficient of V_{oc}	-0.084 V/°C (-0.38% /°C)
Temperature Coefficient of I_{sc}	3.2×10^{-3} A/°C (0.05% /°C)
Temperature Coefficient of P_{max}	-0.50 W/°C (-0.50% /°C)

*Standard Test Conditions

Mechanical Specifications

Characteristic	Details
Cell Size	125mm x 125mm (4.93" x 4.93")
Module Dimension (L x W x T)	**1020 x 670 x 35 mm (40.28 x 26.4 x 1.4 in)**
No. of Cells	72
Weight	8.0 kg (17.6 lbs)
Cable Length	900mm (35.4") for positive (+) and negative (-)
Type of Connector	MC-IV
Junction Box	IP65 Rated
No. of Holes on Frame	**4 installation holes, 2 grounding holes, 8 air holes**

SOLAR CELL PARAMETERS

Five basic parameters for solar cell are-

- ✓ Short-circuit current (I_{sc})
- ✓ Maximum power current (I_{mp})
- ✓ Open-circuit voltage (V_{oc})
- ✓ Maximum power voltage (V_{mp})
- ✓ Maximum power (P_{mp})

SOLAR CELL PARAMETERS

Short-circuit current (I_{sc}) is the maximum current generated by a cell or module and is measured when an external circuit with no resistance is connected (i.e. solar cell is shorted). Its value depends on the cells surface area and the amount of solar radiation incident upon the surface. It is the maximum current generated by the cell.

Maximum power current (I_{mp}) is the maximum current specified in Amperes and generated by a cell or module corresponding to the maximum power point on the current-voltage (I-V) curve.

Open-circuit voltage (V_{oc}) is the maximum voltage generated by the cell. This voltage is measured when no external circuit is connected to cell.

SOLAR CELL PARAMETERS (Cont'd)

Maximum power Voltage (V_{mp}) is the maximum voltage specified in Volt corresponds to the maximum power point on the current-voltage (I-V) curve.

Maximum power (P_{mp}) is the maximum power available from a PV cell or module and occurs at the maximum power point on the I-V curve. It is the product of the PV maximum power current (I_{mp}) and maximum power Voltage (V_{mp}). This is referred to maximum power point.

If a module operates outside its maximum power value, the amount of power delivered is reduced and represents needless energy loss. Thus, this is the desired point of operation for any PV module.

I-V Curves

The I-V curve is obtained experimentally by exposing the PV cell or module to a constant level of irradiance while maintaining a constant cell temperature, varying the load resistance, and measuring the current produced.

Typical I-V and power curves for a crystalline PV module operating at 1,000 W/m² (STC)

I-V Curves (Cont'd)

The I-V curves typically passes through the two end points- I_{sc} and V_{oc}

- ✓ The short circuit current (I_{sc}) is produced with the positive and negative terminals of the cell shorted. The voltage between the terminals is zero, corresponding to zero load resistance.

- ✓ The open circuit voltage (V_{oc}) is produced across the positive an negative terminals under open circuit conditions. The current is then zero, corresponding to infinite load resistance.

- ✓ Therefore power is the product of voltage times current, the maximum power point (**P_{mp}**) occurs on the I-V curve where the product of current (**I_{mp}**) times voltage (**V_{mp}**) is maximum.

I-V Curves (Cont'd)

The I-V curve has utmost interest in solar energy-

- ✓ The solar cell usually operated over a wide range of voltages and currents. By simply varying the load resistance from zero (a short circuit) to infinity (an open circuit), it is possible to determine the highest efficiency as the point where the cell delivers maximum power.

- ✓ This point represents the maximum efficiency of the solar cell in converting sunlight into electricity.

I-V Curves (Cont'd)

The **short circuit current** (Isc) and the **open circuit voltage** (Voc) generation-

ELECTRICAL CHARACTERISTICS OF SOLAR CELL

Fill Factor (FF): The "fill factor", more commonly known by its abbreviation "FF", is a parameter which, in conjunction with V_{oc} and I_{sc}, determines the maximum power from a solar cell.

- ✓ The FF is defined as the ratio of the maximum power from the solar cell to the product of V_{oc} and I_{sc}.

$$FF = \frac{V_{MP} I_{MP}}{V_{OC} I_{SC}}$$

- ✓ Cell quality is maximum when FF approaches unity.

ELECTRICAL CHARACTERISTICS OF SOLAR CELL

Fill Factor (FF): Graphically, the FF is a measure of the "squareness" of the solar cell and is also the area of the largest rectangle which will fit in the I-V curve.

Graph of cell output current (red line) and power (blue line) as function of voltage.

High FF

Low FF

ELECTRICAL CHARACTERISTICS OF SOLAR CELL

Efficiency (η): Efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun. In addition to reflecting the performance of the solar cell itself, the efficiency depends on the spectrum and intensity of the incident sunlight and the temperature of the solar cell.

The efficiency of a solar cell is determined as the fraction of incident power which is converted to electricity and is defined as:

$$P_{max} = V_{OC} I_{SC} FF$$

$$\eta = \frac{V_{OC} I_{SC} FF}{P_{in}}$$

PV MODULES CONNECTION

PV modules are connected in series to obtain higher output voltages and in parallel to obtain greater current.

Analogy of series and parallel connection of modules

PV MODULES CONNECTION (cont'd)

Connection of PV modules in series and parallel, increasing both voltage and current

ADVANTAGES OF PHOTOVOLTAIC SYSTEMS

- Highly reliable and life is > 25 years (at present).
- Installation and maintenance are easy.
- No moving parts.
- Simple to operate.
- Require no fuel and no running cost.
- Being modular can be increased in smaller steps.
- Silent in operation and no pollution.

SOLAR ELECTRIC SYSTEM COMPONENTS

- ✓ Solar modules

  to convert the solar radiation to electricity

- ✓ Storage batteries

  to store the electricity for use at night or during cloudy weather. Lead acid batteries are the most popular.

- ✓ Control unit (manual or automatic)

  for the protection of batteries, system etc.

- ✓ Distribution system

- ✓ Electric appliances (Loads)

STORAGE BATTERIES

- Batteries are generally used to store electricity and supply it to the load. The main ones used in solar electric systems are the lead acid and the nickel cadmium batteries.

- Batteries are rated by the capacity given by ampere hour (Ah) and it gives a measure of how much electricity or charge can be stored in the battery.

- For example, a battery with a capacity of 80 Ah can supply 8 ampere current for 10 hours or a 4 ampere current for 20 hours.

- The state of charge at any moment is the amount of charge left that can be used compared to fully charged capacity. 100% refers to a fully charged battery, 50% to a half discharged battery and so on.

STORAGE BATTERIES (cont'd)

- The sequence of discharging (to the load) and then charging up (from the PV array) to the state of charge is called a cycle.

- A shallow cycle is one when the battery is discharged by only a few percent, while a deep cycle indicates a depth of discharge of 50% or more.

- The number of cycles that can be obtained from a battery before its capacity is reduced to 80% is called the cycle life. This depends on the cycle depth, discharge current and the temperature.

- Charging efficiency compares the amount of charge used by the loads to the amount of charge needed to recharge the battery back to its original level. A charging efficiency of 100% means that all the charge going in can be recovered during discharge.

CHARGE CONTROLLER

- A charge controller cuts off power supply to and from the battery beyond certain preset levels thus ensuring the proper band of charge level.

- When the battery voltage rises to a pre-set level of charging it limits the charging current to stop further charging. Similarly, when it reaches the pre-set level of discharging it disconnects the load from battery and prevents the battery from further discharging.

CHARGE CONTROLLER (cont'd)

- High voltage disconnect: When the charge level of the battery reaches to the maximum level, charge controller disconnects the battery from the module (or stops further charging). The voltage at which this occurs is called high voltage disconnect (HVD).

- Low voltage disconnect: When the charge level of the battery reaches the minimum level, the charge controller disconnects the load from the battery. The voltage at which this occurs is called low voltage disconnect (LVD).

INVERTERS AND CONVERTES

- Inverters accept an electrical current in one form and output the current in another form. An inverter converts DC into AC. There are also DC–DC converters, which step up or step down the voltage of a DC current.
- An inverter needs to meet two needs: peak or surge power and continuous power:
  - ✓ Surge is the maximum power that the inverter can supply, usually for only a short time. Some appliances, particularly those with electric motors, need a much higher power level at startup than they do when running.
  - ✓ Continuous is the power that the inverter has to supply on a steady basis. This is usually much lower than surge power. For example, this would be what a refrigerator pulls after the first few seconds it takes for the motor to start.

SIZING A SOLAR PHOTOVOLTAIC SYSTEM

- The **first step** is to know the energy (electrical) requirements for each day.
  - ✓ It should be ascertained whether the load is a dc or ac and the voltage necessary.
  - ✓ For each load, with the wattage used, estimate the number of hours of operation it will be in use during a day and thus the watt hours used during the day. Thus, the daily total watt hour demand is calculated.

SIZING A SOLAR PHOTOVOLTAIC SYSTEM (cont'd)

- The **next step** is to estimate the solar radiation availability for the location at the tilt angle of interest.

  - ✓ In photovoltaic system analysis, the concept of peak sun hours or peak hours per day is used, which gives the equivalent time in hours at peak sun condition (i.e. 1kW/m^2) that yields the same total radiation.
  - ✓ In the calculation of daily radiation, usually the lowest value of radiation (either for a day or for a month) is taken so that a conservative estimate is made on the calculation of the array size.

SIZING A SOLAR PHOTOVOLTAIC SYSTEM (cont'd)

- The **next step** is to estimate the solar array required for supply electrical energy-
  - ✓ Total energy demand per day in Wh.
  - ✓ Total system efficiency
  - ✓ Peak sunshine hours at tilt for design month, obtained from solar radiation data.
  - ✓ Maximum power output of selected PV module at STC.

SIZING A SOLAR PHOTOVOLTAIC SYSTEM (cont'd)

- The **next step** is to estimate the battery sizing and the number of batteries needed for the application. The following parameters are needed to know before starting battery size calculation-
  - ✓ Maximum depth of discharge (DOD), which ranges 25-35% for automotive and 50- 80% for deep cycle batteries.
  - ✓ Charging efficiency, which is usually considered to be 80%.
  - ✓ Days of Autonomy.
  - ✓ System voltage.
  - ✓ Daily load requirement.

- The **next step** is to estimate a charge controller sizing.

- The **next step** is to estimate a inverter and converter sizing.

SIZING A SOLAR HOME SYSTEM

The required array size could be obtained using following formula-

- ✓ Required array size (Wp) = Daily load in Wh ÷ (Total system efficiency x Peak sunshine hours)
- ✓ Number of modules in parallel = Required array size in Wp ÷ Maximum power output at STC of selected PV module
- ✓ Number of modules in series = Battery voltage ÷ Maximum voltage of selected PV module at load x derating factor
- ✓ Total number of modules = Number of modules in parallel x Number of modules in series

Example:

Required array size (Wp) = 1707.5 Wh ÷ (57% x 4.9) = 611 Wp
Number of modules in parallel = 611 Wp ÷ 75Wp = 8
Number of modules in series = 12 V ÷ 16.9V x 0.8 = 0.88 ≈ 1
Total number of modules = 8 × 1 = 8

SIZING A SOLAR HOME SYSTEM (Cont'd)

The following parameters are needed to know before starting battery size calculation-

- ✓ Maximum depth of discharge (DOD), which ranges 25-35% for automotive and 50-80% for deep cycle batteries.
- ✓ Charging efficiency, which is usually considered to be 80%.
- ✓ Days of Autonomy
- ✓ System voltage
- ✓ Daily load requirement

- Battery Capacity (Ah) = [Daily load requirement (Wh) x Days of Autonomy] ÷ [Battery charging efficiency (%) x DOD (%) x System voltage]

SIZING A SOLAR HOME SYSTEM (Cont'd)

- Considering daily load requirement 1000 Wh, charging efficiency of battery 80%, days of autonomy of 3 days, maximum depth of discharge (DOD) 70% and system voltage as 24 volts for the system-

Battery Capacity (Ah) = [1000 Wh X 3] ÷ [80% X 70% X 24V] = 224 Ah.

- Number of batteries: The convenient size (volt and capacity) of battery should be selected based on the available manufacturers specification and economics. For example, we choose 12 volt 100Ah batteries.

- **The term days of autonomy means the number of days a battery bank can provide can supply to the appliances without recharged by the solar panels.**

SIZING A SOLAR HOME SYSTEM (Cont'd)

- ✓ Number of batteries in parallel = 224 Ah ÷ 100Ah (individual battery capacity in Ah) = 2.24 ≈ 3 (approximated to nearest higher capacity)
- ✓ Number of batteries in series = 24 volt (system voltage) ÷ 12 volt (individual battery voltage) = 2
- ✓ Total number of batteries = Number of batteries in parallel X Number of batteries in series = 3 X 2 = 6

SIZING A SOLAR HOME SYSTEM (Cont'd)

Important facts during battery sizing-

- ✓ **To build battery bank, try first to select a battery that is rated close to the Ah capacity.** Ignore voltage for a moment. If can't find one that's very close, look for one that has a capacity either one-half or one-third of needed Ah. These fractions represent the number of series strings of such batteries need, in parallel, to complete battery bank (1/2 = 2 strings, 1/3 = 3 strings).

- ✓ Once find a candidate battery, divide the system voltage by the battery's voltage. This will give the number of such batteries would need in each series string.

- ✓ It's best to keep the number of parallel strings of batteries to three or fewer. If parallel more than three strings of batteries, it will risk shortening battery life due to uneven charging.

SIZING A SOLAR HOME SYSTEM (Cont'd)

Charge Controller sizing

1. **Calculating the Controller Array Current:** This is the input current that comes from the solar array.
   - ✓ The minimum capacity of charge controller array current (Amps) = Module Short Circuit Current x Modules in parallel x Safety Factor. Which is array short circuit current. (Each PV module specifications mentioned short circuit current).
   - ✓ To be on the safe side, it is advised to multiply the result by a safety factor of 1.25 to 1.3.

1. **Calculating the Controller Load Current:** This is the current that is pulled from the batteries through the controller.
   - ✓ Total DC Connected Watts / DC System Voltage = Max. DC Load Current

SIZING A SOLAR HOME SYSTEM (Cont'd)

Charge Controller Specifications

Solar Charge Controller	Power Tarom 2070	Power Tarom 2140	Power Tarom 4055	Power Tarom 4110	Power Tarom 4140
system voltage	12 V / (24 V)		48 V		
max. module input short circuit current	70 A	140 A	55 A	110 A	140 A
max. load output current	70 A	70 A	55 A	55 A	70 A
max. self consumption	14 mA				
end of charge voltage (float)	programable: 13.7 V (27.4 V)		54.8 V		
boost charge voltage	programable: 14.4 V (28.8 V)		57.6 V		
equalisation charge	programable: 14.7 V (29.4 V)		58.8 V		
reconnection setpoint (SOC / LVR)	programable: > 50 % / 12.6 V (25.2 V) / 50.4 V				
deep discharge protection (SOC / LVD)	programable: < 30 % / 11.1 V (22.2 V) / 44.4 V				
ambient temperature allowed	-10 °C...+60 °C				
terminal size (fine / single wire)	50 mm² / 70 mm²				
enclosure protection class	IP 65				
weight	10 kg				
dimensions l x w x h (l) x 330 x 157	330 mm	360 mm	330 mm	360 mm	360 mm

Technical data at 25 °C / 77 °F

SIZING A SOLAR HOME SYSTEM (Cont'd)

Inverter sizing

- ✓ An inverter is used in the system where AC power output is needed. The rating of the inverter should never be lower than the total watt of appliances. The inverter must have the same nominal voltage as battery.
- ✓ For stand-alone systems, the inverter must be large enough to handle the total amount of Watts will be using at one time. The inverter size should be 25-30% bigger than total Watts of appliances. In case of appliance type is motor or compressor then inverter size should be minimum 3 times the capacity of those appliances and must be added to the inverter capacity to handle surge current during starting.

SIZING A SOLAR HOME SYSTEM (Cont'd)

Inverter sizing

- ✓ Since an inverter is needed to operate AC loads, efficiency of inverter needs to be considered during calculation of AC loads. For example, if an AC load of 10 Watt is connected to the battery through an inverter of efficiency 80%, the consumption of that load has to be considered as 12.5 Watt (10W ÷ 80%).

- ✓ In addition, for safety, the inverter should be considered 25-30% bigger size. From previous example the inverter size should be about 12.5+ 25% = 15.7W or greater.

SIZING A SOLAR HOME SYSTEM (Cont'd)

TILT ANGLE FOR SOLAR MODULE

- Solar modules produce the most power when they are pointed directly at the sun. For installations where the solar modules are mounted to a permanent structure, the solar modules should be tilted for optimum winter performance.

Latitude Site	Tilt Angle
0-15°	15º
15-25°	Same as Latitude
25-30°	add 5° to local latitude
30-35°	add 10° to local latitude
35-40°	add 15° to local latitude
40° +	add 20° to local latitude

Source: http://www.oksolar.com/technical/angle_orientation.html

PV SYSTEM BLOCK DIAGRAM

PV system schematic incorporating a stand-alone inverter to meet AC loads.

PHOTOVOLTAIC TECHNOLOGY

- First Generation
  - ✓ Single crystal silicon wafers (c-Si)
- Second Generation
  - ✓ Amorphous silicon (a-Si)
  - ✓ Polycrystalline silicon (poly-Si)
  - ✓ Cadmium telluride (CdTe)
  - ✓ Copper indium gallium diselenide (CIGS) alloy
- Third Generation
  - ✓ Nanocrystal solar cells
  - ✓ Photoelectrochemical (PEC) cells
  - ✓ Gräetzel cells
  - ✓ Polymer solar cells
  - ✓ Dye sensititized solar cell
- Fourth Generation
  - ✓ Hybrid - inorganic crystals within a polymer matrix

PHOTOVOLTAIC EFFICIENCY

Commercial Module Efficiency								
Technology	Thin Film					Crystalline Silicon		CPV
	(a-Si)	(CdTe)	CI(G)S	a-Si/ µc-Si	Dye s. cells	Mono	Multi	III-V Multijunction
Cell efficiency	4-8%	10-11%	7-12%	7-10%	2-4%	16-22%	14-18%	30-38%
Module efficiency						13-19%	11-15%	~25%
Area Needed per KW (for modules)	~ 15 m²	~ 10m²	~ 10m²	~12m²		~7m²	~8m²	

Source: EPIA 2010, Photon international, March 2010, EPIA analysis
Efficiency based on Standard Test conditions.

Source: http://shareholdersunite.com/2011/03/07/solar-cell-efficiency/

REFERENCES

1. Solar Energy Renewable Energy and the Environment. Robert Foster, Majid Ghassemi, Alma Cota. Tylor & Fracis Group, CRC Press, 2010.
2. Solar Engineering of Thermal Process (3rd Edition). John A. Duffie, William A. Beckman. John Wiley & Sons, Inc., 2006.
3. www.pveducation.org/pvcdrom/introduction/solar-energy