Chapter Six

Non-reactive Energy Sources

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Outline

- Definitions
- Water power
- Geothermal power
- Wind power
- Solar energy

Definition

- Non reactive energy sources involves the utilization of energy directly without being released as thermal energy from chemical or nuclear reaction.

Non-reaction energy sources

Non-reaction energy sources includes:

- Water power
  - hydroelectric power from falls & rivers
  - Tidal power
  - Wave power
  - Ocean thermal current
- Geothermal energy
- Wind energy
- Solar energy

Utilization

- Energy from the source can be used to generate electricity directly;
- or as mechanical power (for example windmill for water pumping).
- Some can be used for heating as in solar energy and geothermal energy.
- Other sources can be used in thermal power cycles such as ocean them current and geothermal energy.

Utilization

- Flowing water contributes significantly to the electricity generation, while other sources are of minor contribution and in the stages of development.
- Because of the increasing price of conventional fuel and energy sources and the dwelling supply of the fossil fuels, interest in the above renewable resources is increasing.
- The largest part of the renewable energy utilization cost is the fixed cost (capital cost).

Advantages

- The advantages of the above non-reactive energy sources include the absence of various polluting effects of the fossil fuel system or the nuclear radiation waste of nuclear reactors.

Outline

- Definitions
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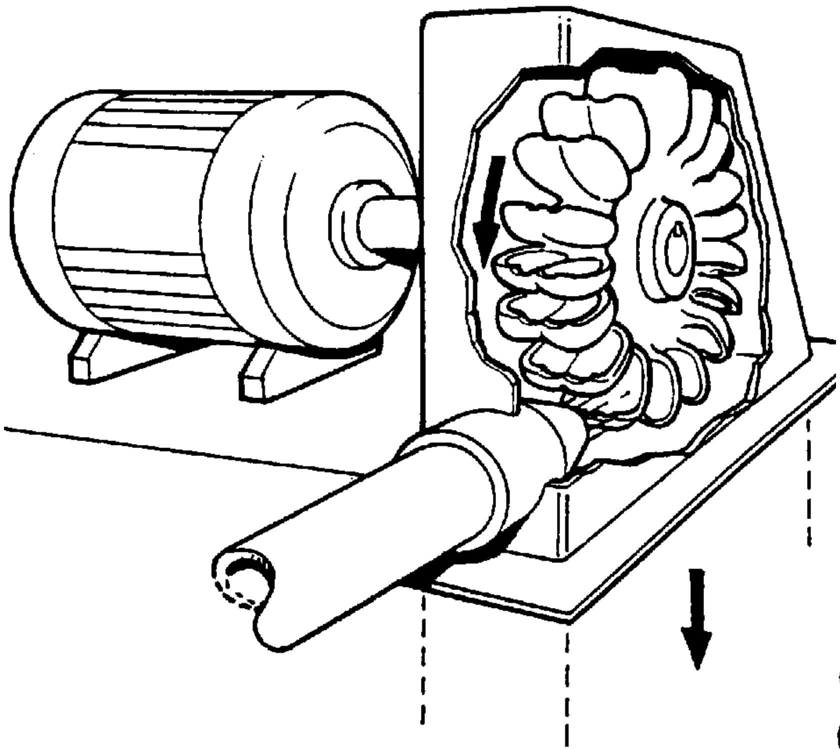
Hydroelectric power plants

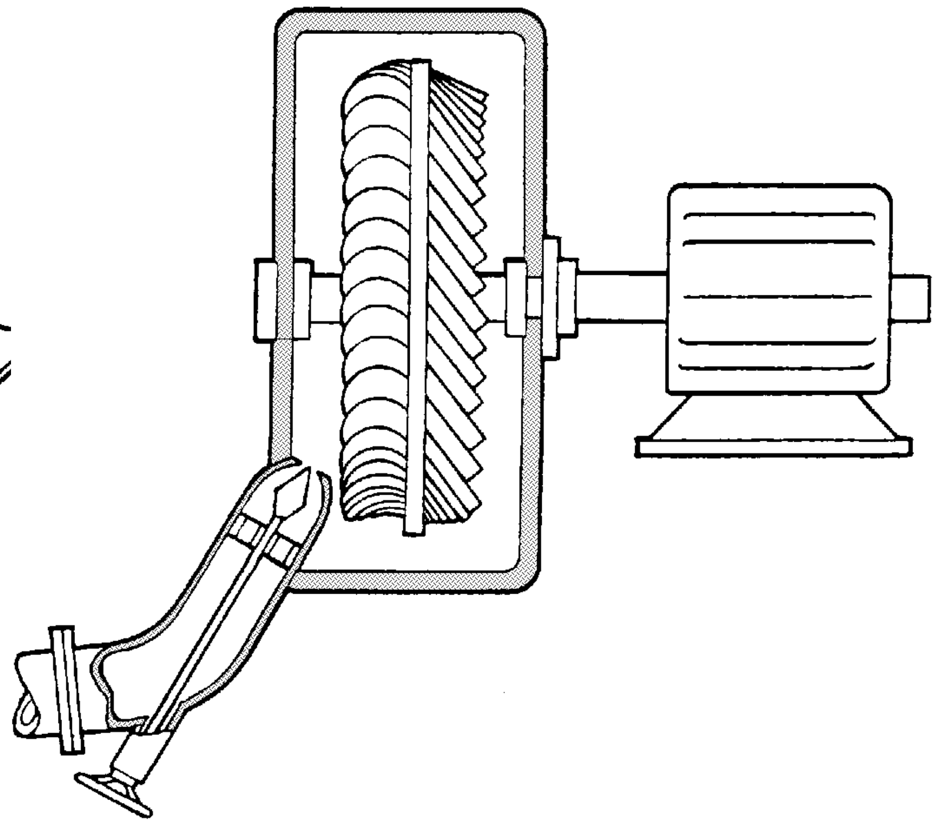
- Hydroelectric power involves the utilization a fall of a river by erecting a dam at a suitable point in the river and creating a head of water, then making use of the potential energy of the falling water.
- Hydroelectric power is a highly effective energy conversion system with no environmental pollution, and usually it is more economical than fossil fuel system.

Types of Turbines

- Installed turbine type depends mainly on the operating head and water flow rates.
- Two main types of turbines are employed.
  - Impulse Turbine is used for high water heads and low water flow rates. The head is converted into kinetic energy as it passes through nozzle of turbine, then kinetic energy of water rotates the blades.
  - Reactive Turbines are used for low water heads and large flow rates. Three types are available:
    - Radial turbine (Francis).
    - Propeller type (Kaplan).
    - Mixed flow (Deriaz Type).

Impulse Turbines: Pelton & Turgo

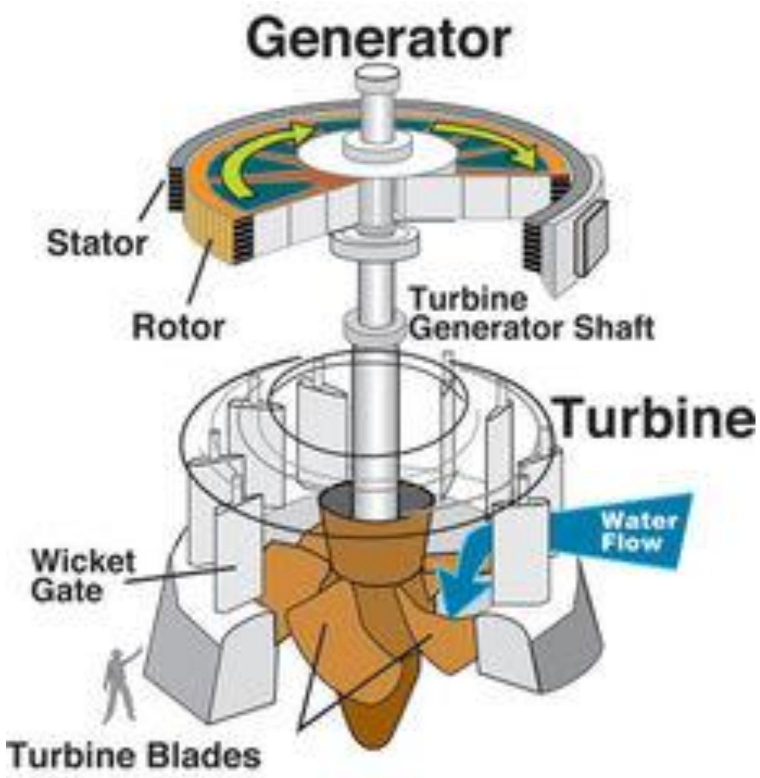


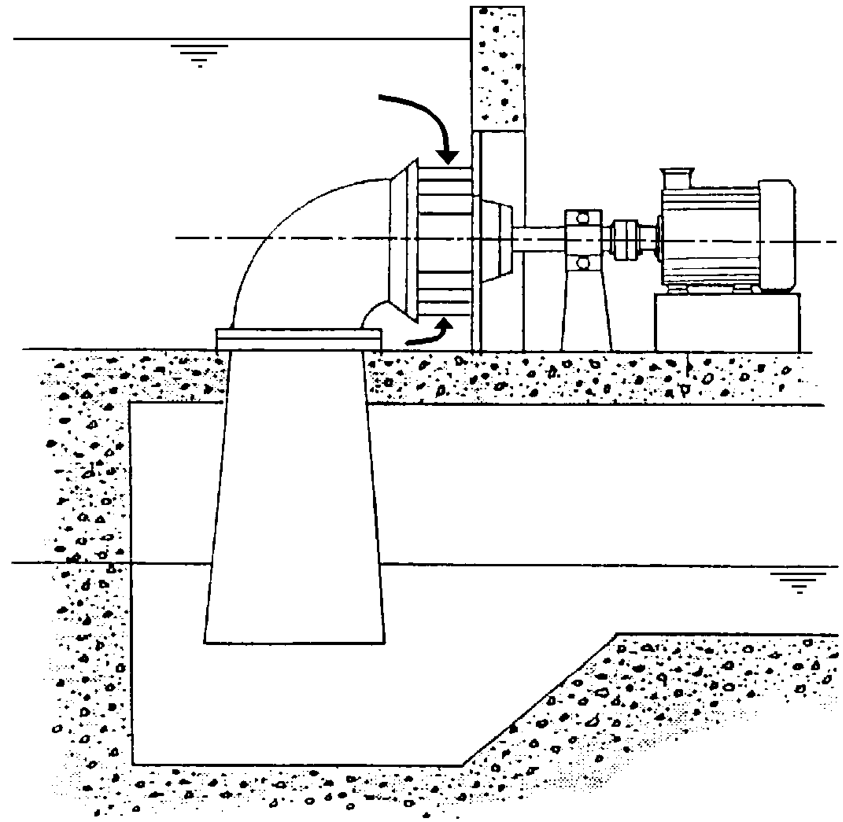


Reaction turbines

- They are distinguished from the impulse type by having a runner that always functions within a completely water-filled casing.
- All reaction turbines have a diffuser known as a ‘draft tube’ below the runner through which the water discharges.

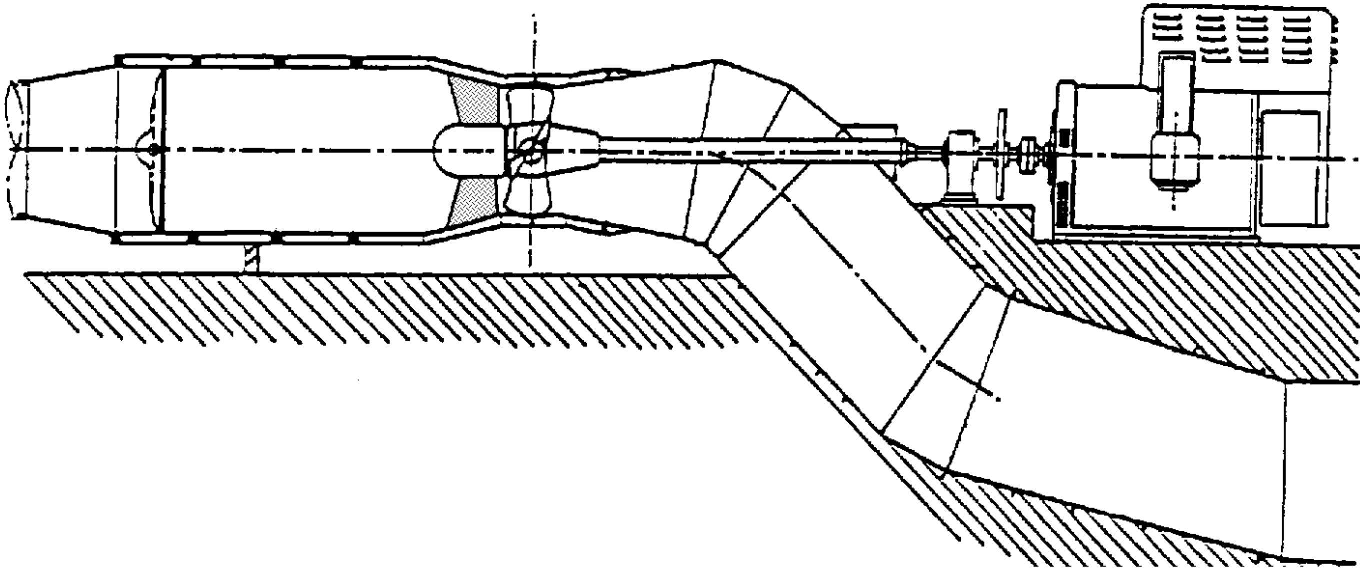
Francis Turbine





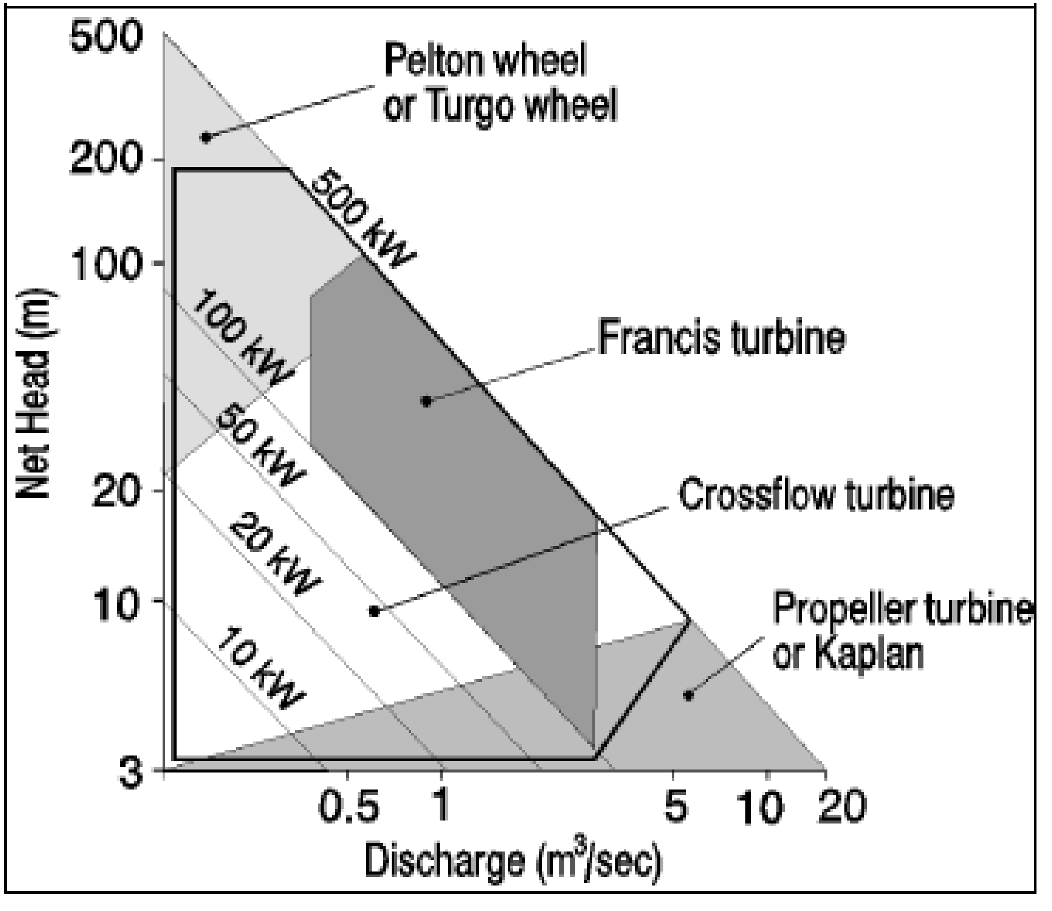
Propeller & Kaplan turbines

- In some cases the blades of the runner can also be adjusted, in which case the turbine is called a *Kaplan*.



Selecting turbine

- The turbine to be selected is based on the available head and flow rate.



Proposed Major Hydro-electric Project

Name	Maximum Capacity	Country	Construction starts	Scheduled completion
Red Sea dam	50,000 MW	Middle East	Unknown	Unknown
Grand Inga	40,000 MW	Republic of the Congo	2010	Unknown
Baihetan Dam	12,000 MW	China	2009	2015
Wudongde Dam	7,000 MW	China	2009	2015
Maji Dam	4,200 MW	China	2008	2013
Songta Dam	4,200 MW	China	2008	2013
Liangjiaren Dam	4,000 MW	China	2009	2015
Jirau Dam	3,300 MW	Brazil	2007	2012
Pati Dam	3,300 MW	Argentina		
Santo Antônio Dam	3,150 MW	Brazil	2007	2012
Guanyinyan Dam	3,000 MW	China	2009	2015

Power analysis

- First law for steady flow

  $m(h1 - h2) + m([C1^2 - C2^2]/2) + Q - w + mg\ \Delta z = 0$

  But $h = u + P/\rho$
- Take ''1'' at surface of water in reservoir.

  ''2'' at surface of water in tailrace of turbine.
- Then: $m(u1 - u2) + (P1 - P2)/\ \rho + m\ ([C1^2 - C2^2]/2) + Q - w + mg\ (z1 - z2) = 0$
  - Usually P1 = P2 = atmosphere
  - C1 = 0 and usually:

    m (u1 – u2) + Q are replaced by:

  $mg\ \Delta z$ = loss head as a result of friction,

Maximum turbine power

- then:
  $m[g(z1 – z2) – C_2^2/2 - g\ \Delta zf] – w = 0$
- Maximum power when assuming C2 = 0
  $W_{max} = mg\ (z1 – z2) = \rho ghQ$
  Where:
  ρ = density.
  Q = discharge or volume flow-rate.
  h = water head.
- Assuming ρ = 1000 kg/m3, g = 10 m/s,
  then wmax = 10hQ kW, where h in meter and Q in m3/s.

Microhydro Water Power

- For cases of rated power less than 100kW. This obtained from low heads or small flow rates of the water.
- Impulse turbine are used for microhydro because it has higher efficiency at partial loads, also it is simple control arrangements.
- Pelton wheel turbine is used for microhydro.

Tidal Power

- Tides: are caused by the attraction of the moon and the sun, it draws water a way from earth piling it up causing high (flood) tide. The fall of the water is known as ebb tide.
- Flood tide occurs twice during each lunar day (24 hour + 51 min) low tide follows high tide by 6 hours and 12.8 minutes.
- Variation in the water level between high and low tides depends on the relative positions of moon and sun

Utilizing tidal effects

- Tidal effects are enhanced through water ways, rivers and bays. Average tidal rise is 6 – 10 m high, hence special low head and large flow rate turbines are used such as “bulb type” and “slant axis “ turbines.
- Economic tidal power utilization requires;
  - High tidal variation.
  - Pool or narrow enough mouth so that it can be dammed.
  - Deep enough so that turbine can be set below the low tide.
  - Problems of silting and adverse effects on ecology and navigation are solved.

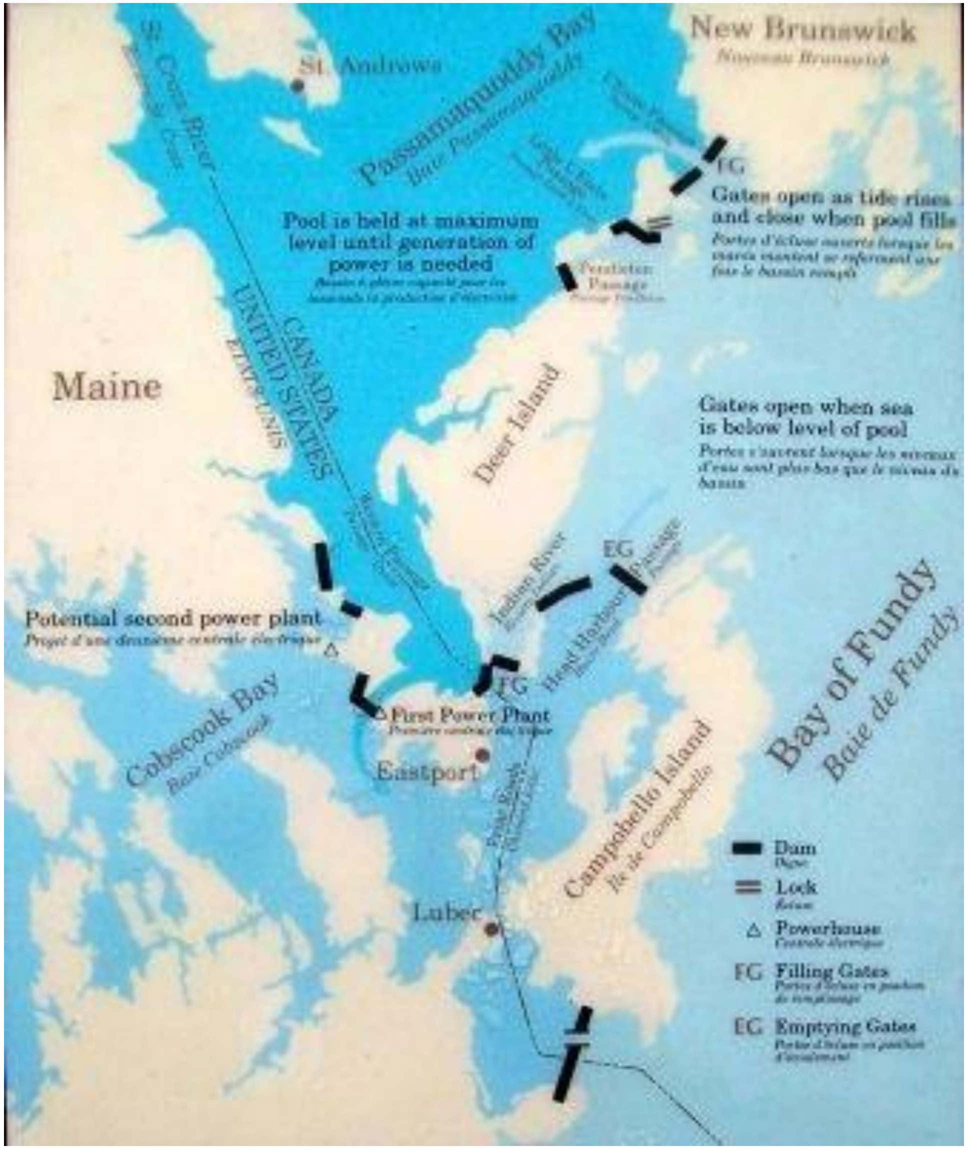
Potential sites

- La Rance river, northwest coast of Brittany “on the English channel”, France .A 240MW plant operating since 1966, average head of 28 feat.
- Passamaquoddy; fundy bay between Canada and U.S.A, being studied, average head 18.1 ft.
- Hopewell Canada, tidal range 11m.

The largest tidal power station in the world (and the only one in Europe) is in the Rance estuary in northern France, near St. Malo. It was built in 1966

A major drawback of tidal power stations is that they can only generate when the tide is flowing in or out - in other words, only for 10 hours each day.

Passamaquoddy tides are among the highest in the world, and range from a maximum rise and fall near 9.1 metres to a minimum rise and fall of about 3.7 metres . With a twice-daily average change in water level of 6 metres the tides are ideal for power production with the 2 billion cubic metres of seawater that enters and leaves the bay twice each day



Tidal power analyses

- Potential energy of tidal water is converted to electrical energy using low head hydro turbine.
- Water is stored in a basin during the high tide (gates are opened), then gates are closed and water flows through the turbine during the low tide.
- Let A: area of basin

  ΔZ: tidal range.

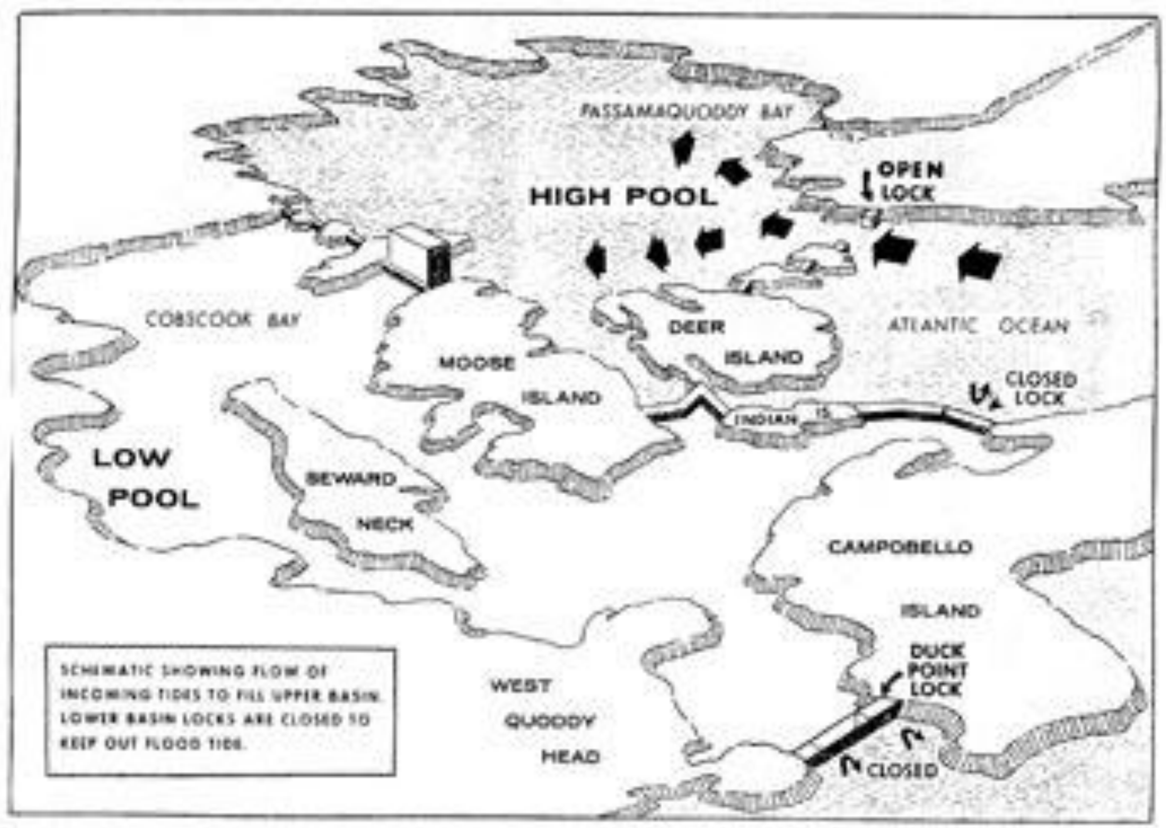
  τ: duration of tidal cycle τ = 12.43 hours.

  ρ: density of water.
- Then water flow rate is $m = 2\rho (A \Delta Z / \tau)$.
- This assumes power to be generated during flood and ebb. Assuming average head on turbine $\Delta Z/2$, then theoretical maximum power = Wmax

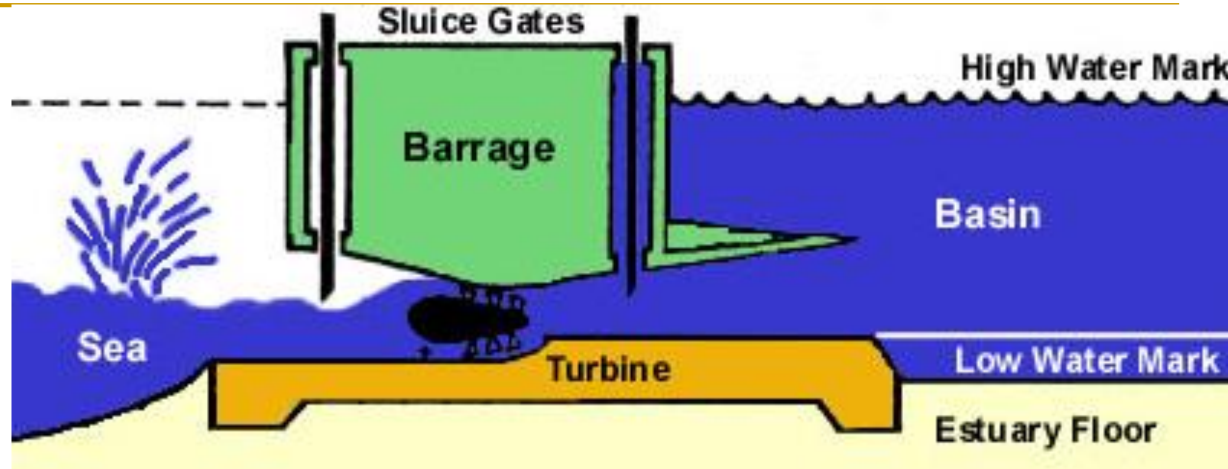
  $$W_{max} = mg(\Delta Z/2) = \rho A g (\Delta Z)^2 / \tau$$

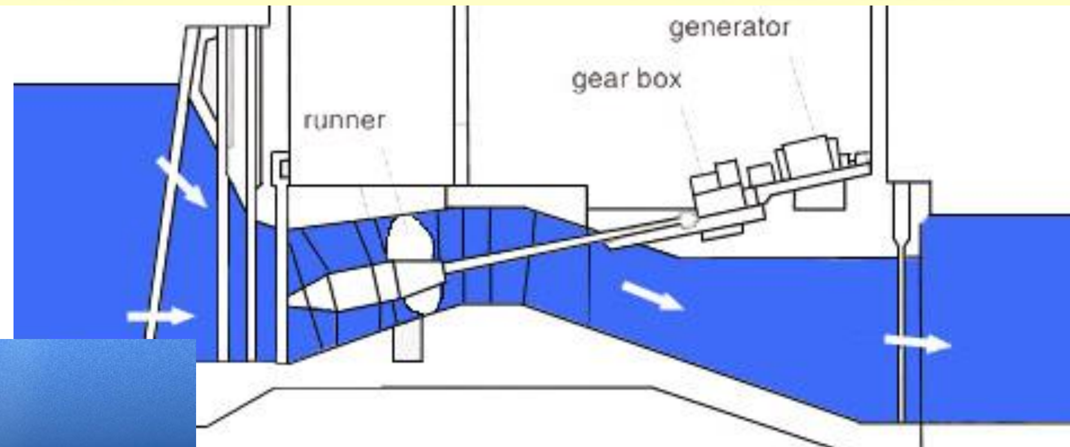
Two-basin

- <u>Two-basin system:</u> two-basin system consists of two basins. The high basin is filled at high tide, while low basin emptied during low tide. Turbine operates on head difference between two basins.



Turbines

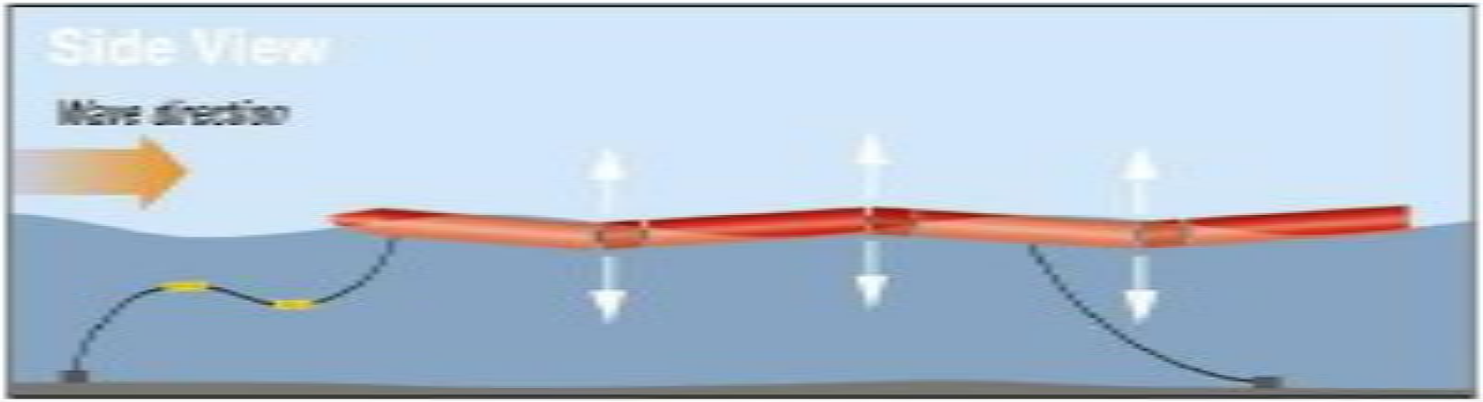

Sluice Gates
High Water Mark
Barrage
Basin
Sea
Turbine
Low Water Mark
Estuary Floor


generator
gear box
runner

Wave power

- Water waves generated from wind motion and its effect on the sea and ocean water surface. The wave motion is up and down.
- Wave height varies according to location and wind speed.

Wave power



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Geothermal energy

- Geothermal energy refers primarily to utilizing the stored heat in the earth’s crust.
- The earth core, which is hot molten material mostly iron, is 6900km in diameter. Rock mantle is a bout 2900km, thick, and the outer crust 15 – 50 km thick. Normally the temperature gradient is 29 ^{o}C /km.

Geothermal resources

- The geothermal resources may be classified as :
  - Hydrothermal resources, underground reservoirs of hot water and steam of temperature 360 ^{o} C under hydrostatic pressure.
  - Geopressured reservoirs hot saline fluids found at very high pressure in porous formation. There are believed to contain large a mounts of dissolved natural gas at temperature 150 – 200 ^{o} C.
  - Hot dry rock resources: typical at about 3 miles deep, with little or no fluid present, temperature 140 – 400 ^{o} C.

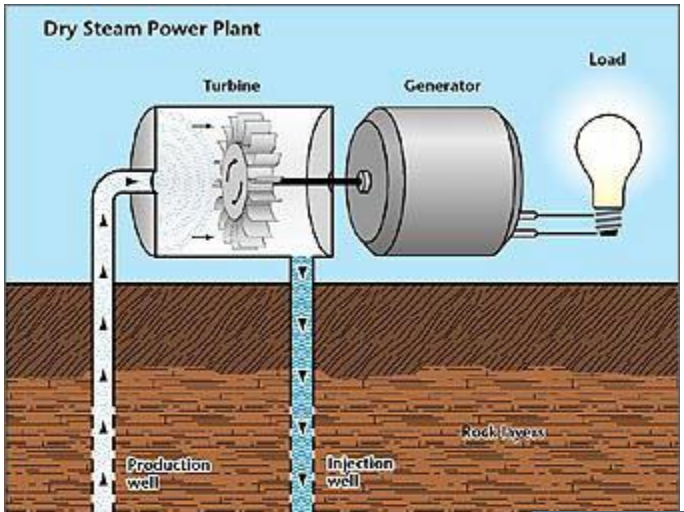
Classification of resources

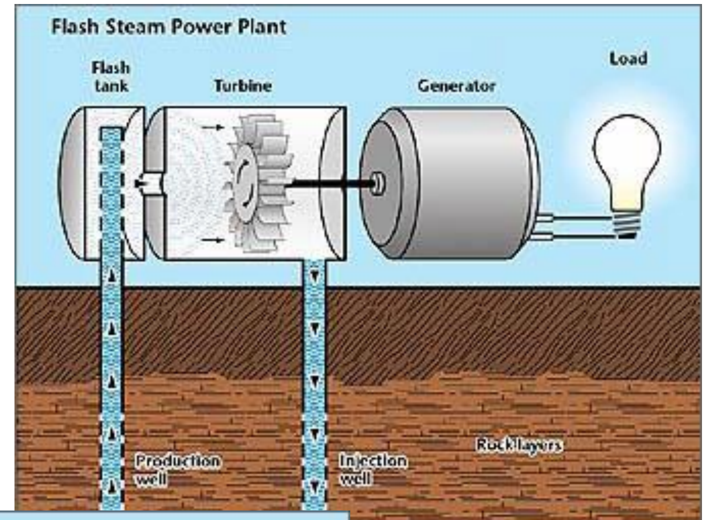
- Geothermal energy resources are generally classified to:
  - High-temperature for steam and electricity production
  - Medium-temperature for direct space heating and industrial processes.
  - Low-temperature for indirect use with heat pumps.

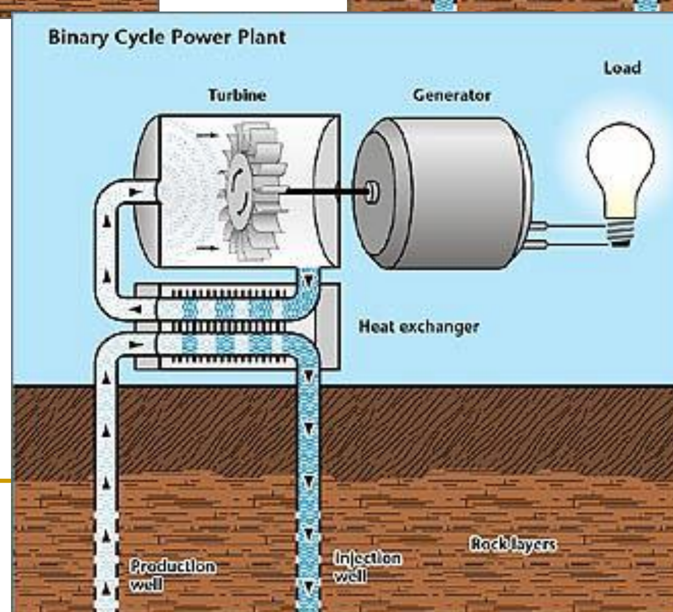
Geothermal energy applications

- Geothermal energy can be harnessed in three different ways:
  - Electricity production with the (hottest) hydrothermal resources.
  - Lower-temperature hydrothermal resources used directly for space and water heating.
  - Geothermal heat pumps (GHP) used for space heating and cooling.

Geothermal electricity



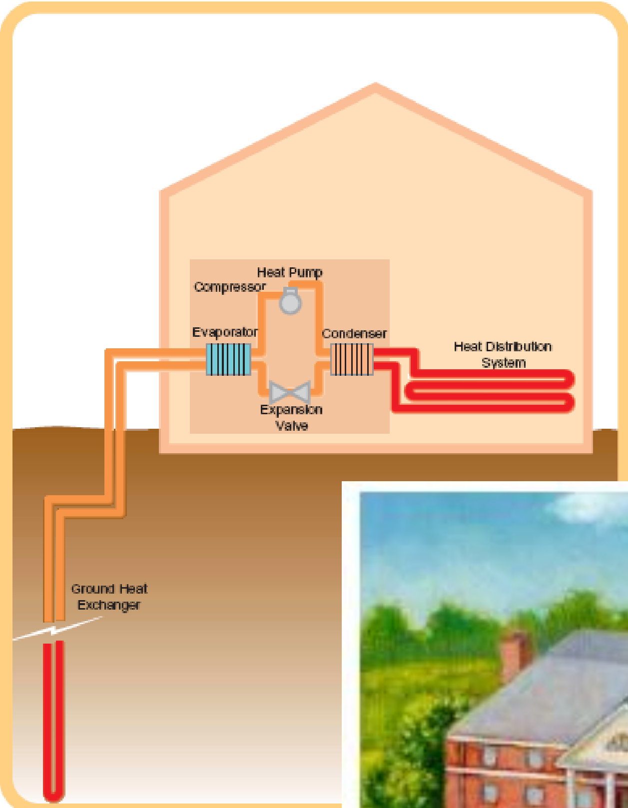


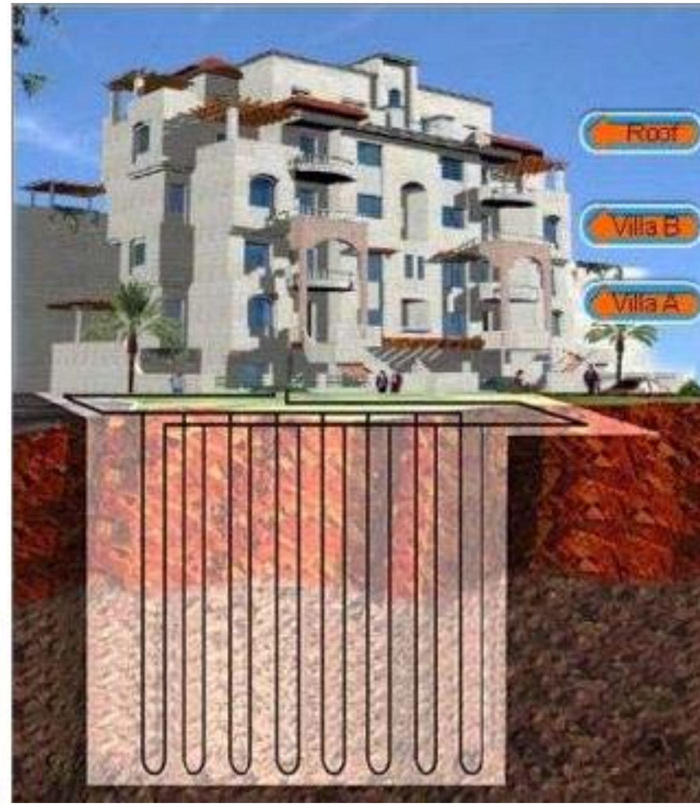


Geothermal Heat Pumps

- Below 10 m the ground temperature remains effectively constant at approximately the annual average air temperature.
- A GHP system consists of:
  - a ground heat exchanger,
  - water-to-water or water-to-air heat pump,
  - a heat distribution system.

Geothermal Heat Pumps





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Wind Power

- Early use of wind power was in windmill for grinding grains and for water pumping. With increase energy demand and the limited reserves of conventional fossil fuels research on alternative energy sources include wind energy has intensified.
- Historically, wind energy was used to propel ships, pump water and grind grains. Today it is more common to see large wind turbines being used for commercial electricity production.
- Pilot and prototypes for wind generation turbines was constructed in many parts of the world specially Europe and USA.

Wind turbines & mills

Wind power calculation

- For a horizontal axis wind turbine. Power associated with moving system equal to its kinetic energy.

$$W = mV^2/2 = 0.5\ (\rho AV)V^2$$

$$W = 0.5\ (\rho AV^3) = 0.5\ \rho \pi R^2 V^3$$

Where: ρ: air density

R: radius of rotating blade.

V: wind speed.

Wind power calculation

- Theoretical maximum power can be extracted from the wind is given as

  Wmax = (16/27) W = 0.593 W

  Wmax = (16/27) $\{0.5\ \rho \pi R^2 V^3\}$
- Constant (16/27) = 0.593 is known as Betz limit.
- Coefficient of performance

  Cp = (actual output power) / (available power in wind)
- Cp = Wactual / $0.5 \rho \pi R^2 V^3$

  and Cp = 0.593 ζ_0 ; ζ_0 overall efficiency.

Wind speed measurement

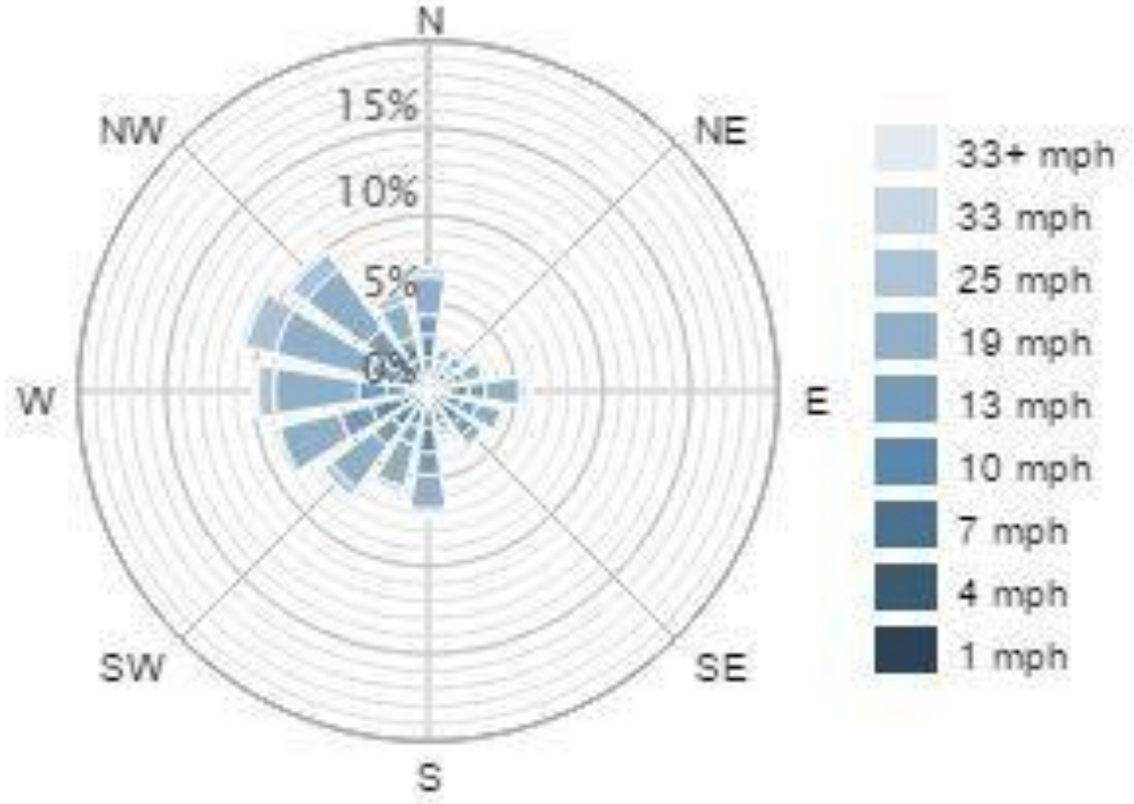
cup anemometer

turbine anemometer

ultrasound anemometer

Wind Rose

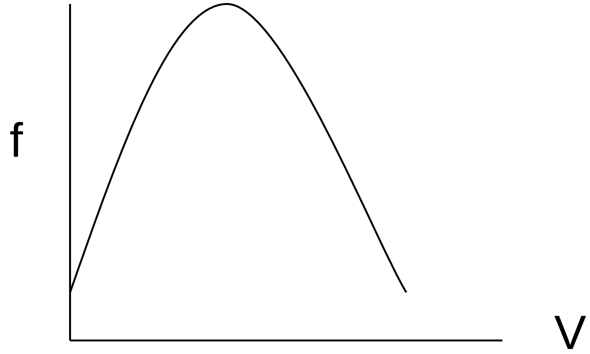
*Chart shows the **frequency** and **speed** of wind blowing **from** each direction.*



Speed frequency

- Velocity V(m/s)   0 1 2 3 4 5 6 7 8 - - - - - - - -
  Frequency of occurrence f 10 20 30 40 50 60 70 80 90 - - - - - - - -

- frequency of occurrence f versus V



Wind speed probability

- Probability could be calculated for each speed as frequency of occurrence for that speed divided by total frequency of occurrences over all speeds; $\Phi(V_i) = f_i / \sum f_i$
- In this case area under curve is normalized to one.
- Wind speed average can be calculated as: $V_{avg} = \sum f_i V_i / \sum f_i$ or $V_{avg} = \sum \Phi(V_i) V_i$
- Wind speed occurrence may be represented by a probability function.

Probability functions

- Rayleigh distribution (simple), one parameter Vm

  $\Phi(V) = \pi\ (V/2Vm^2)\ \exp(-\pi V^2/4\ Vm^2)$

  V: velocity, Vm : annual mean.

- Weibull; used in wind energy studies, two parameters:

  $\Phi\ (V) = (k/c)(V/c)^{(k-1)}\ \exp[-(V/c)^k]$

  Where k is the shape factor normally between 1.8 and 2.3 and c is a scale factor which is around the mean wind speed.

Velocity duration

Rayleigh probability:

$$\Phi(V) = \frac{\pi V}{2 V_m^2} \exp\left\{ \frac{-\pi V_x^2}{4 V_m^2} \right\}$$

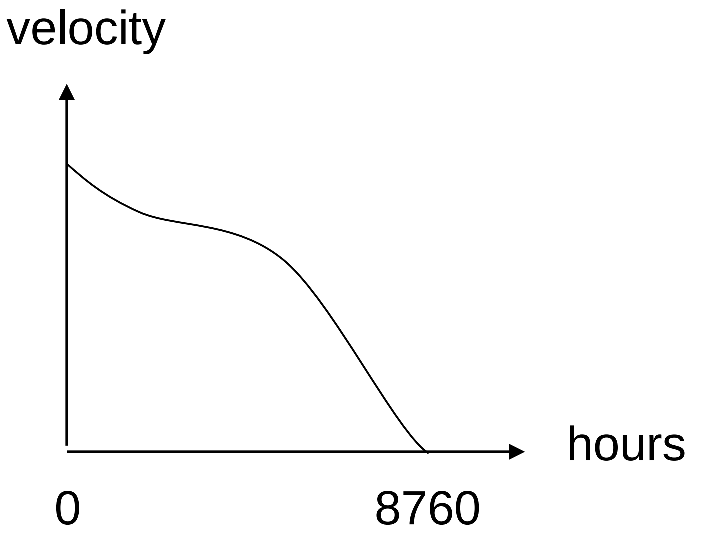
Then Rayleigh cumulative probability is;

$$\Phi(V \leq V_x) = \int_0^{v_x} \Phi(V) dv = 1 - \exp\left(\frac{-\pi V_x^2}{4V_m^2}\right)$$

$$\Phi(V \geq V) = 1 - \Phi(V \leq V) = \exp\left(\frac{-\pi V_x^2}{4V_m^2}\right)$$

Velocity duration

- Velocity duration curve: a plot of velocity, V versus time for which $V \geq Vx$;
- Time hours, $0 \leq T \leq 8760$ hr.



Generated wind energy

$$E_T = \int_0^{\infty} \Phi(v) * T * P_T(v) dv$$

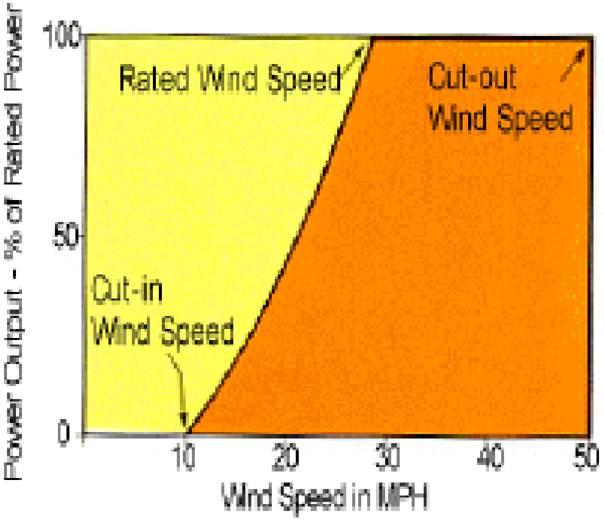
$$\Phi(V) = \frac{\pi V}{2 V_m^2} \exp\left\{ \frac{-\pi V_x^2}{V_m^2} \right\}$$

- T is the time period in hours
- $P_T(v)$ turbine output power function
- Integration limits between cut in and cut out velocities.

Turbine output power

- For an ideal turbine
- Turbine starts production at cut in velocity $V_{cut\ in}$
- Between cut in and rated speed, power is proportional to v^3
- Power at rated speed equals the rated power and remains constant until the cut out speed $V_{cut\ out}$.
- At cut out speed turbine stops and no power is generated.

$$P(v) = \begin{cases} 0 & V < V_{cutin} \\ CV^3 & V_{cutin} < V < V_r \\ w_r & V_r < V < V_{cutout} \\ 0 & V > V_{cutout} \end{cases}$$



Idealized Power Curve for a Wind Turbine

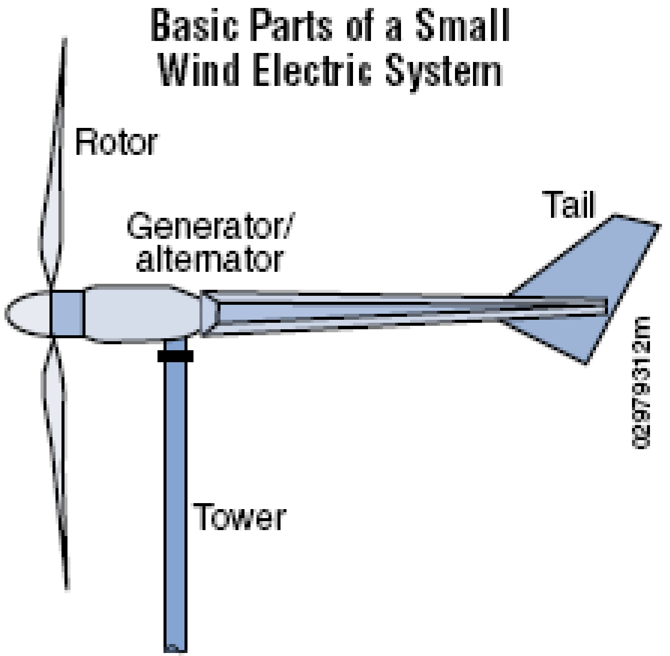
Generated energy

- "E" energy per unit time, then total generated energy is obtained by multiplying with total time period e.g 8760 hours per year.

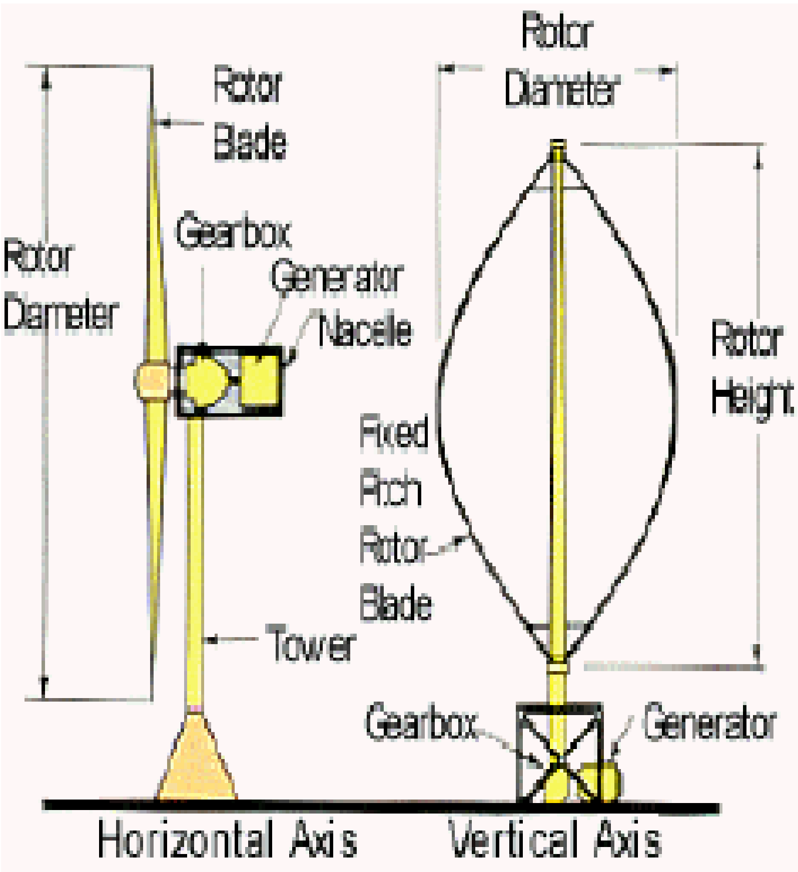
$$\text{Annual plant factor} = \frac{\text{actual energy output annually}}{(\text{Rated powering kW})(3600\text{s/hr})(8760\text{hr/yr})}$$

Wind turbine types

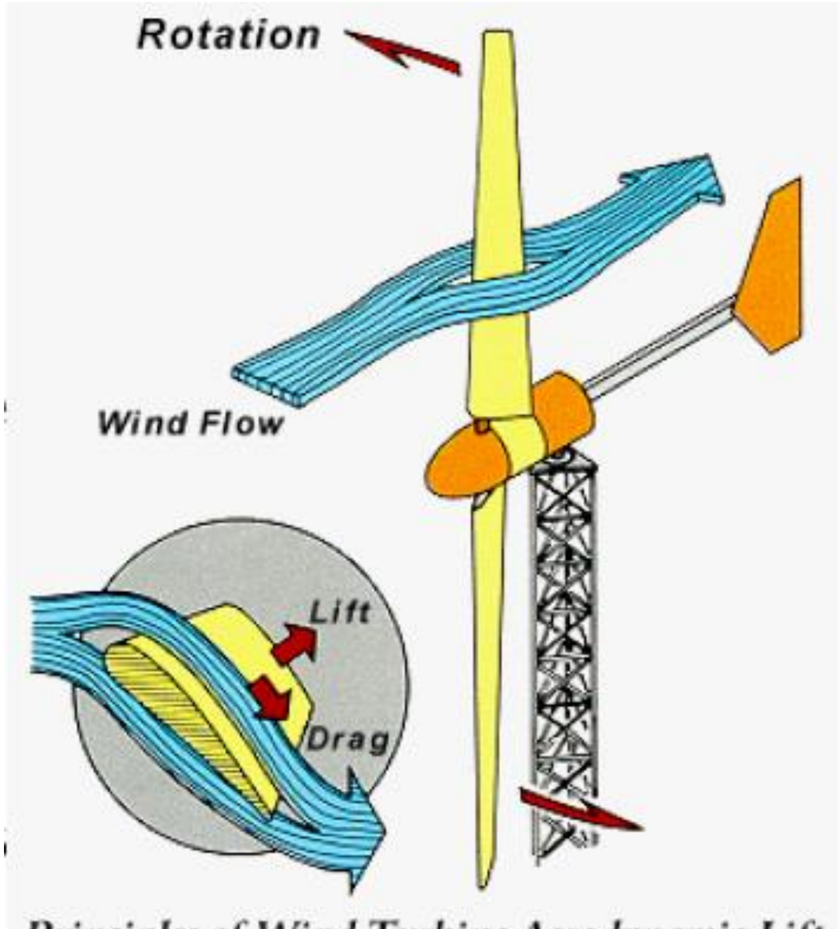
- Two main classis of wind turbine:
  - (a) horizontal axis; blades fixed on horizontal shaft,
  - (b) vertical axis; blades rotate in a plane normal to the wind velocity direction.



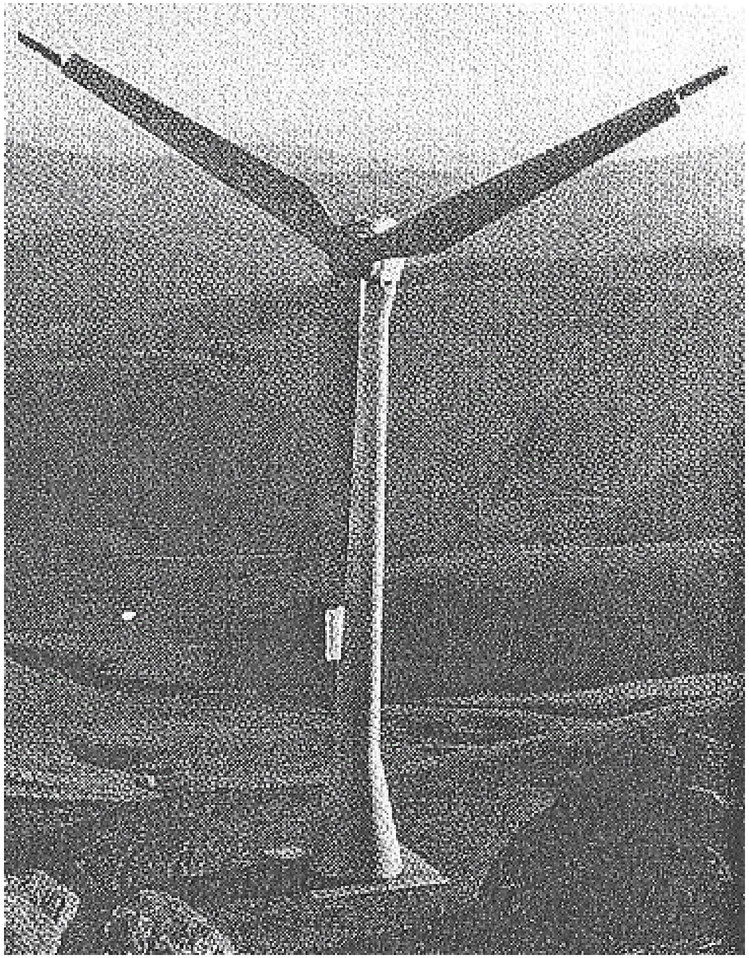
Vertical axis



Horizontal Axis Turbines



Principles of Wind Turbine Aerodynamic Lift



Turbine operation modes

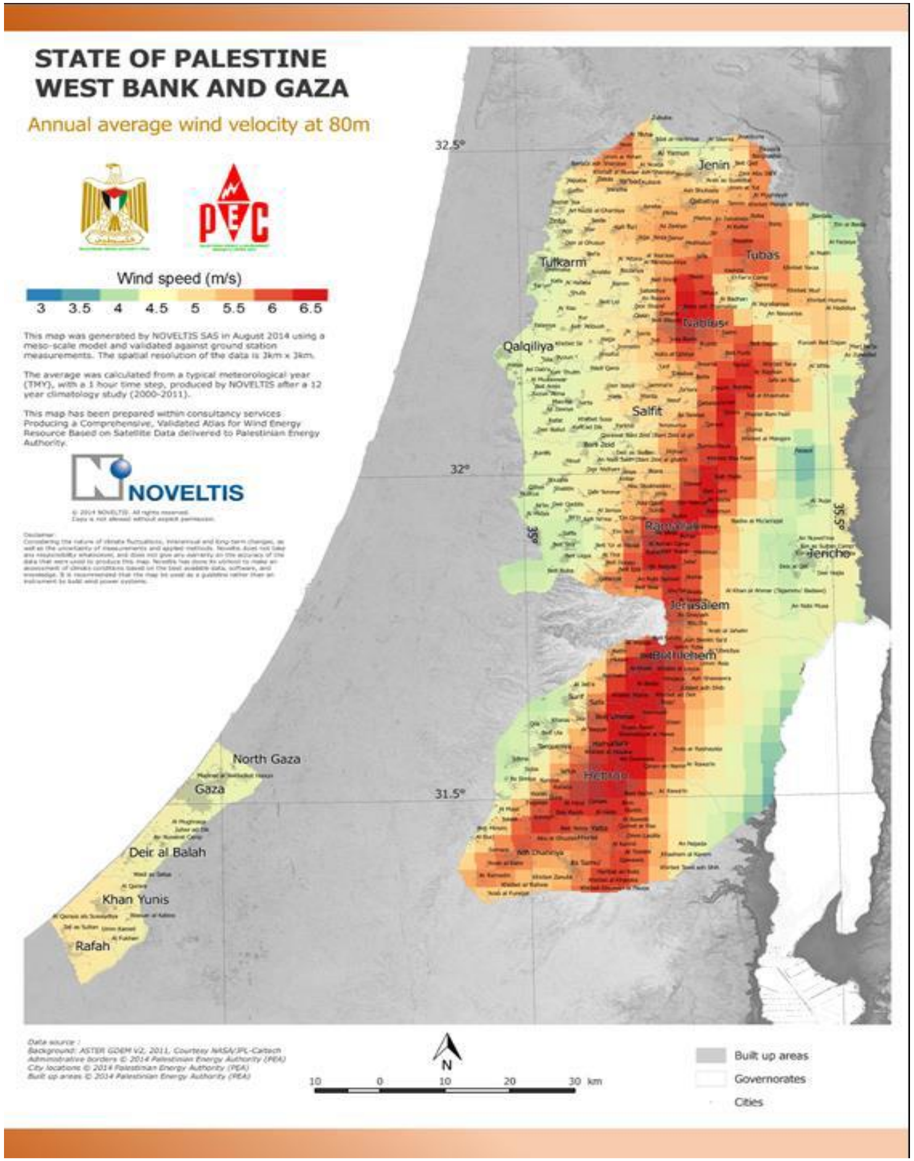
- Stand-Alone Systems
- Grid-Connected Systems
- Hybride: wind + Diesel/PV

- Also classified into;

  Small wind turbines: Size: 0.3 – 50 kW

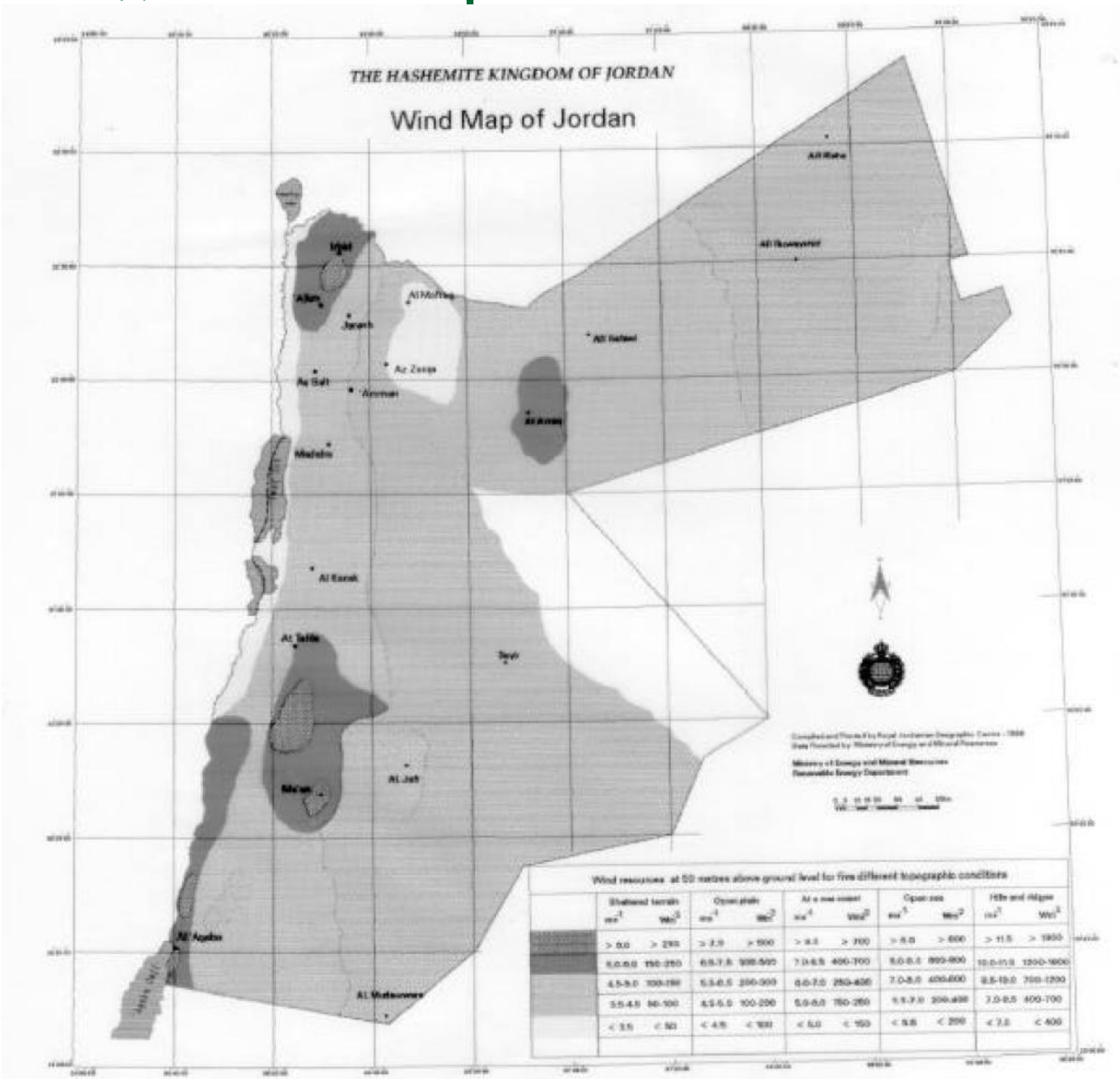
  - Intermediate turbines

  Large turbines: 500 kW to over 2 MW



STATE OF PALESTINE
WEST BANK AND GAZA
Annual average wind velocity at 80m
Wind speed (m/s)
3 3.5 4 4.5 5 5.5 6 6.5
This map was generated by NOVELTIS SAS in August 2014 using a meso-scale model and validated against ground station measurements. The spatial resolution of the data is 3km x 3km.
The average was calculated from a typical meteorological year (TMY), with a 1 hour time step, produced by NOVELTIS after a 12 year climatology study (2000-2011).
This map has been prepared within consultancy services Producing a Comprehensive, Validated Atlas for Wind Energy Resource Based on Satellite Data delivered to Palestinian Energy Authority.
NOVELTIS
32.5°
32°
31.5°
35°
35.5°
Jenin
Tubas
Tulkarm
Nablus
Qalqiliya
Salfit
Ramallah
Jericho
Jerusalem
Bethlehem
Hebron
North Gaza
Gaza
Deir al Balah
Khan Yunis
Rafah
N
10 0 10 20 30 km
Built up areas
Governorates
Cities

Jordan wind map



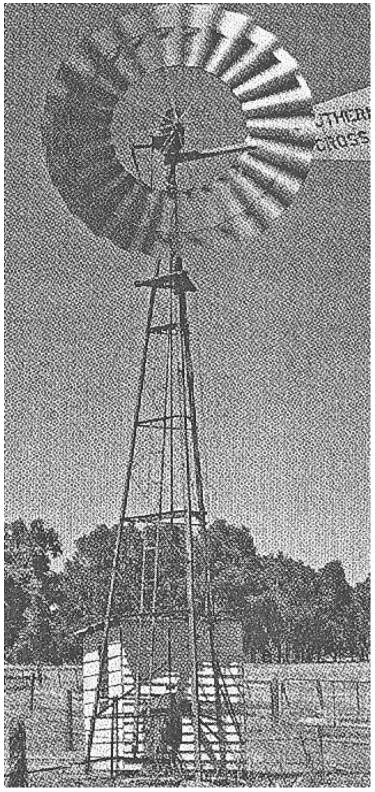
Tafila wind farm

Targeting a total installed capacity of 117MW. Total project costs are estimated at US$250m

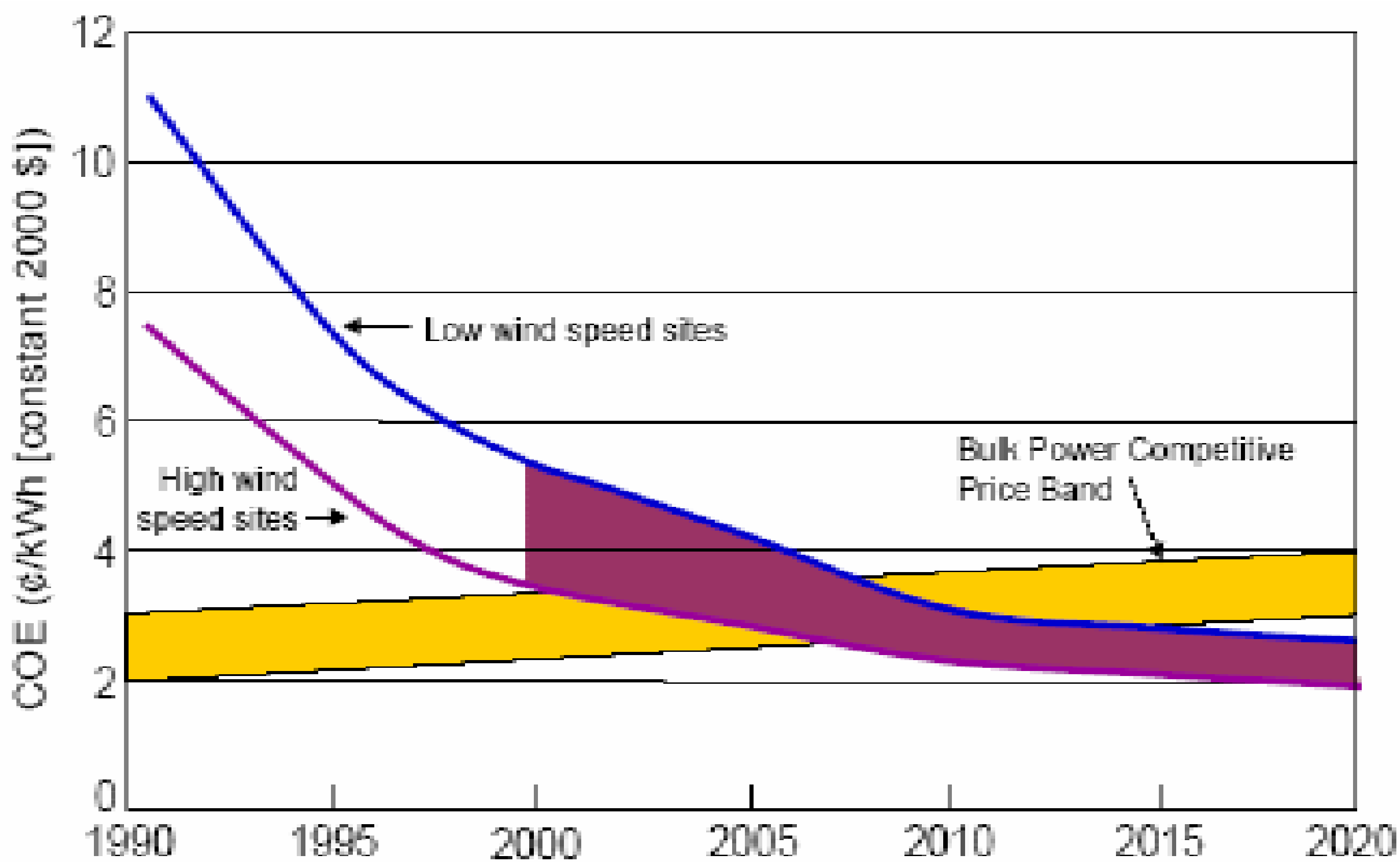
38 turbines at the Tafila Wind Farm has been erected. With a rated capacity of 3.075 MW, it is the largest wind turbine ever installed in the Middle East region

Wind water pumping

- High solidarity multi-blade turbines are suitable having high initial torque in light wind
- The traditional cylinder piston pump is simple and suitable for water wind pumping.



Wind Energy Cost Trend



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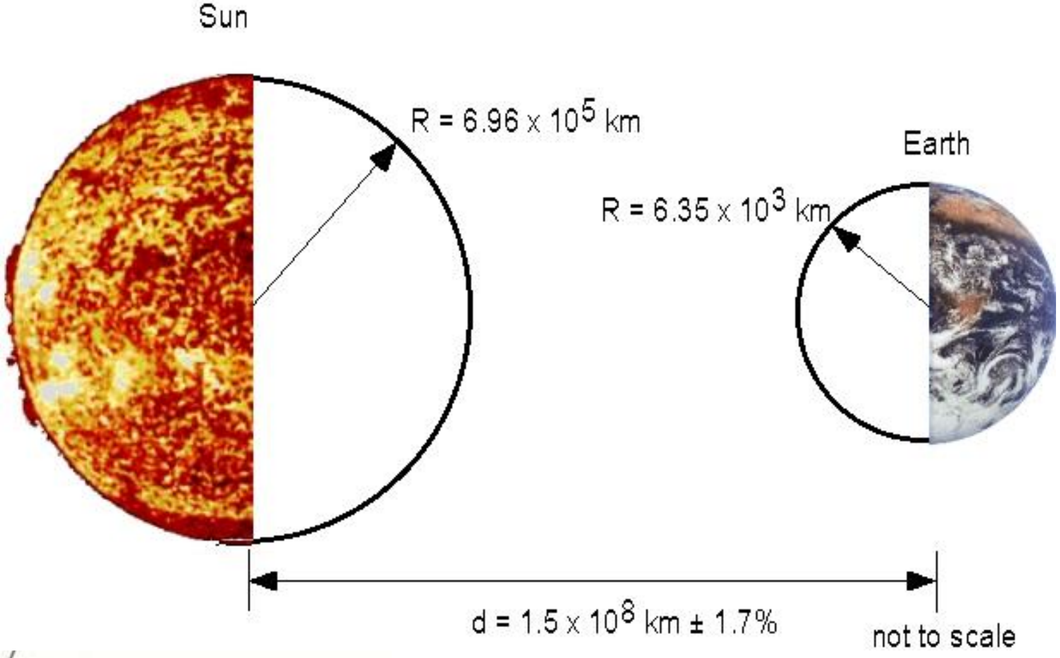
Solar Energy

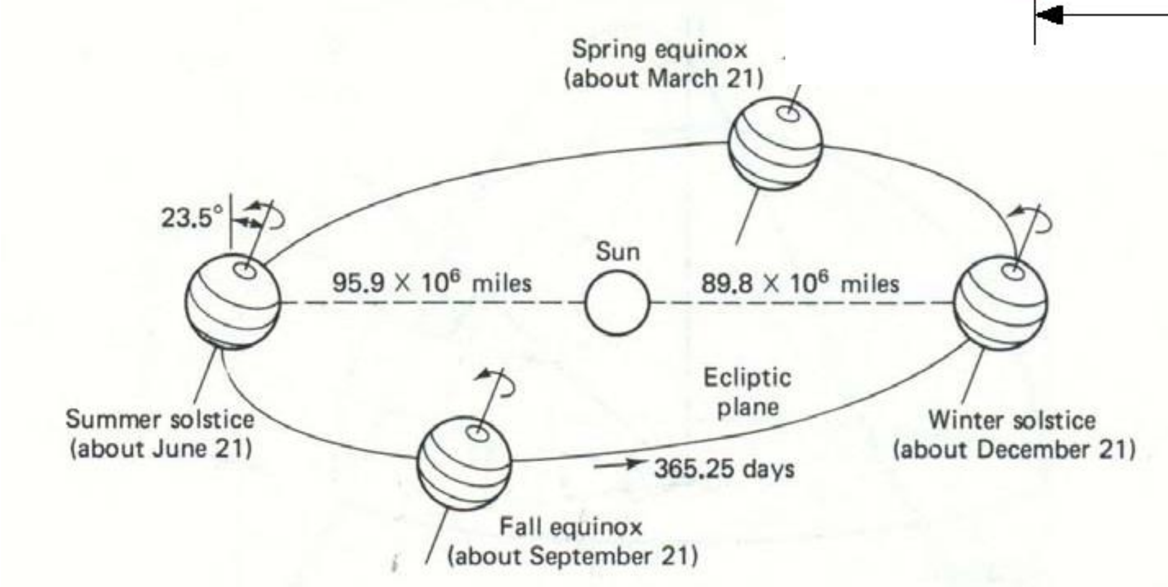
- The sun has a surface temperature of 6000 °C
- Continuous nuclear fusion reactions between hydrogen atoms within its interior.
- These nuclear reactions will gradually convert all of the hydrogen into heavier elements, but this is a relatively slow process and the sun should continue to supply power for another 5 billion years.

Extraterrestrial solar radiation

- The solar radiation received at earth mean distance from the sun (150 million km) is known as solar constant and it is not affected by the atmosphere.
- The solar constant Eo is taken as 1367 W/m^2.
- The actual power density varies slightly since the Earth-Sun distance changes as the Earth moves in its elliptical orbit around the sun
- The extraterrestrial solar radiation varies from 0.97 to 1.03 of the solar constant.

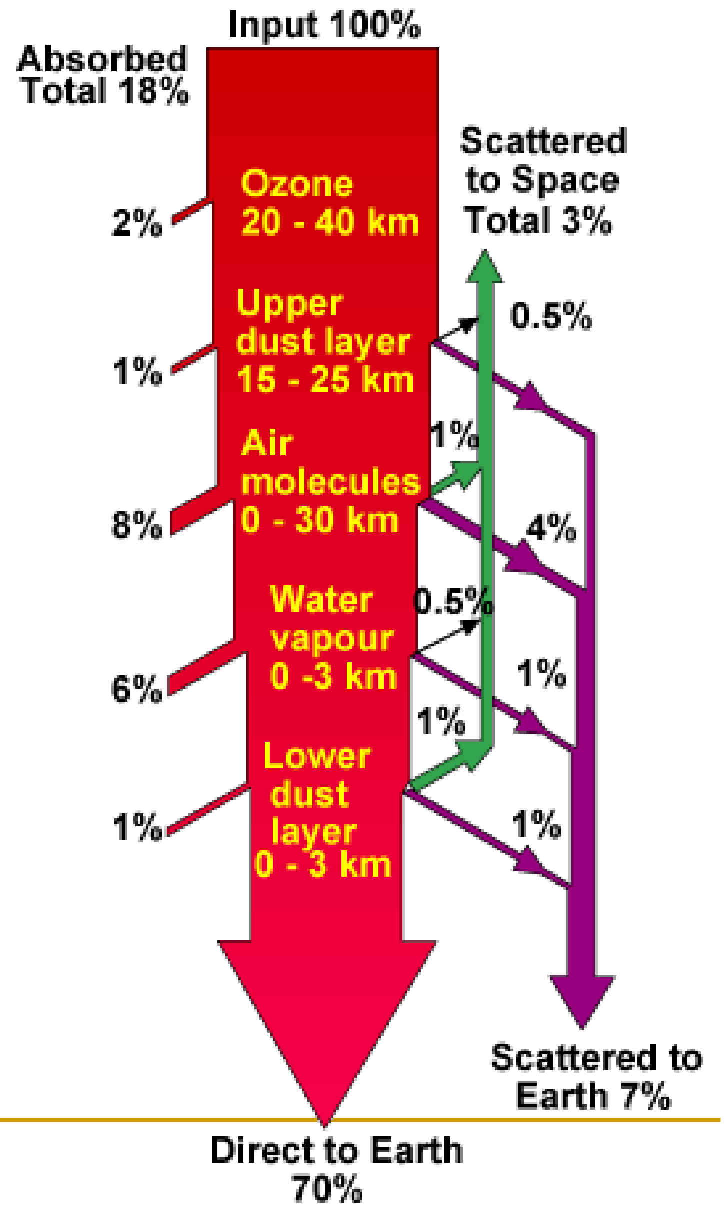
Earth & sun


Sun
R = 6.96 x 10^5 km
Earth
R = 6.35 x 10^3 km
d = 1.5 x 10^8 km ± 1.7%
not to scale


Spring equinox
(about March 21)
23.5°
Sun
95.9 X 10^6 miles
89.8 X 10^6 miles
Ecliptic
plane
Summer solstice
(about June 21)
Winter solstice
(about December 21)
365.25 days
Fall equinox
(about September 21)

Atmospheric effects

- The extraterrestrial solar radiation is attenuated as it passes through earth's atmosphere, about 150Km thick the a mount of radiation that reach's the earth surface at a given time depends upon many factors: air mass, angle, clouds and haze.

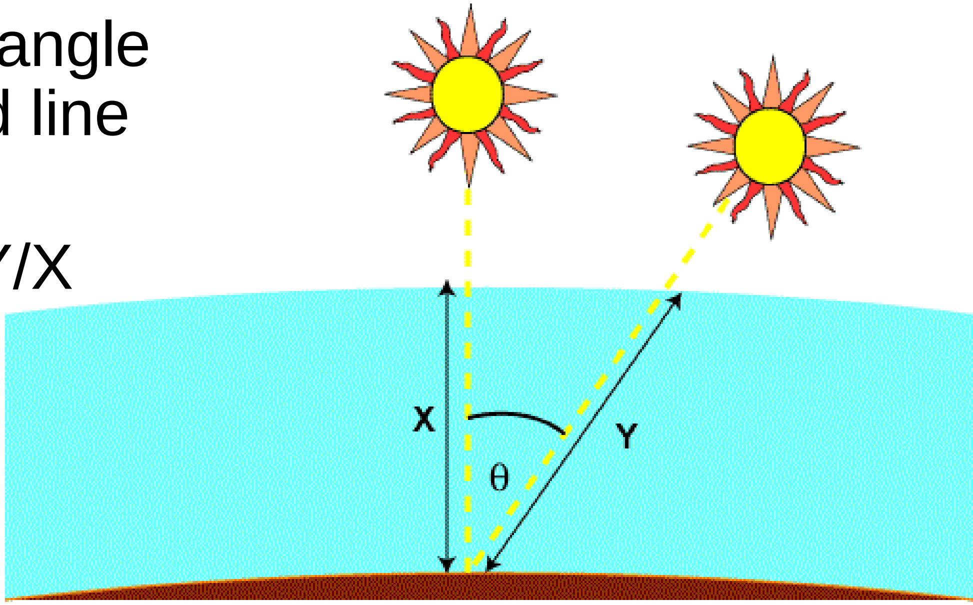


Atmospheric effects

- Short wave solar radiation passing through the atmosphere encounters many interactions including:
  - Absorption is the conversion of radiation to heat and subsequent re-emission as long wave radiation.
  - Scattering change of direction of the radiation with no absorption and the radiation continues at the same frequency.
  - Reflection waves are reflected outside atmosphere, on the average 30% is reflected back into space. Most of reflections occur from clouds little from earth surface such as ice and snow This reflectance is called the albedo.

Air mass factor

- The air mass factor, m, is the path length of radiation through the atmosphere, considering the vertical path at sea level as m=1, when the sun is at the zenith (directly over head).
- Let θz the zenith angle, the angle subtended by the zenith and line of sight of the sun, then:
- $m = \sec\theta z = 1/\cos\theta z = Y/X$



Normal direct beam radiation

- The direct radiation on surface oriented normal to the sun radiation at earth's surface En, then

  $En = Eo\ \tau^{m}$

  Where Eo: solar constant

  τ : transmission coefficient.

  m: air mass factor.

- Typically τ = 0.1 for a heavily overcast day, τ = 0.8 on a clear day.

Non-normal solar rays

- If the surface is inclined and not normal to the sun's rays;

  $E_i = E_n \cos\theta_i$

  Where

  θ_i : the incident angle, and measured between the sun's direction and the normal to the surface.

- For a horizontal surface the angle of incidence is equal to zenith angle, $\theta_i = \theta_z$ and,

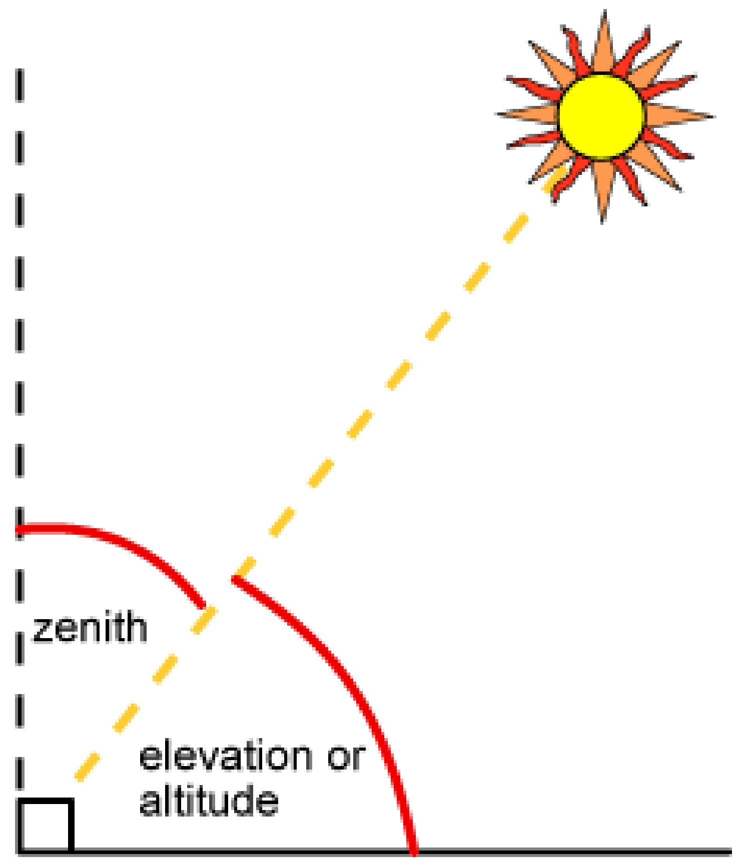
  $(E_i)_{horiz} = E_n (\cos\theta_i) = E_n (\cos\theta_z)$

Variation of solar radiation

- **The elevation angle α** is the angular height of the sun in the sky measured from the horizontal. The **zenith angle** θz is measured from the vertical rather than from the horizontal,

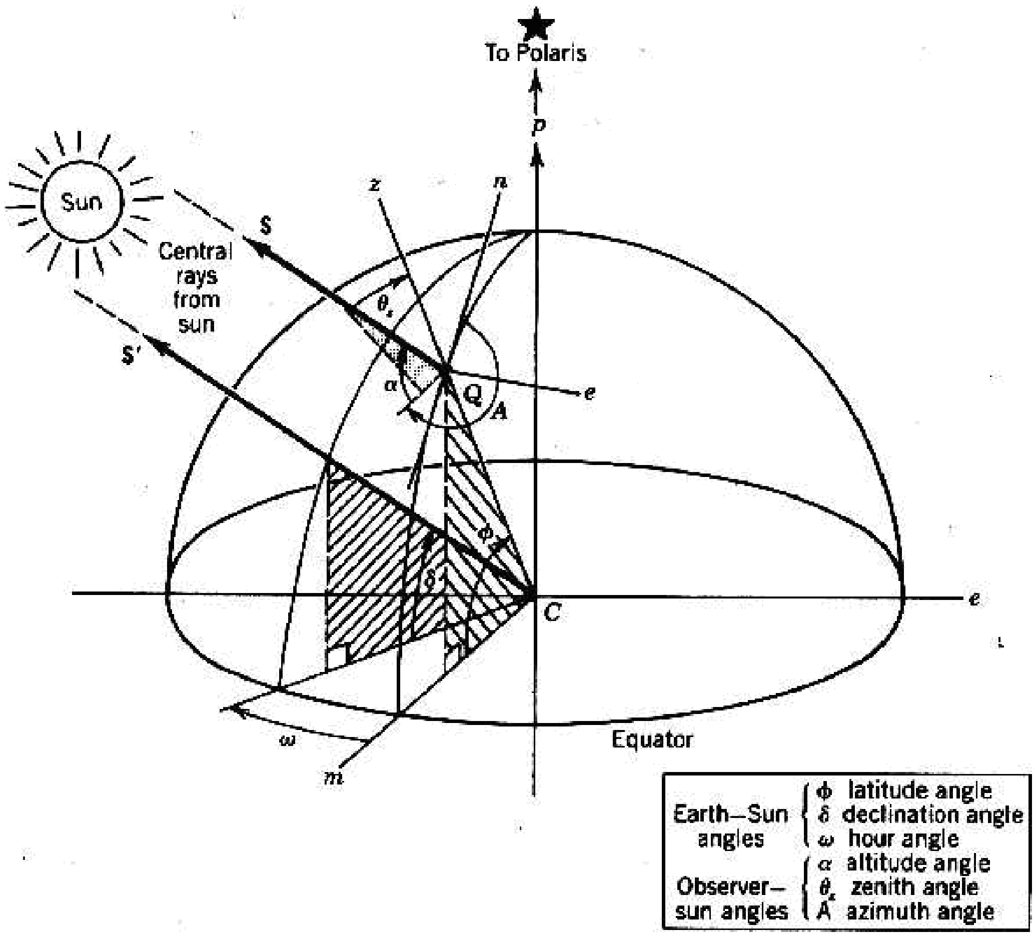
  zenith angle = 90° - elevation angle.

  $\theta z = 90 - \boldsymbol{\alpha}$



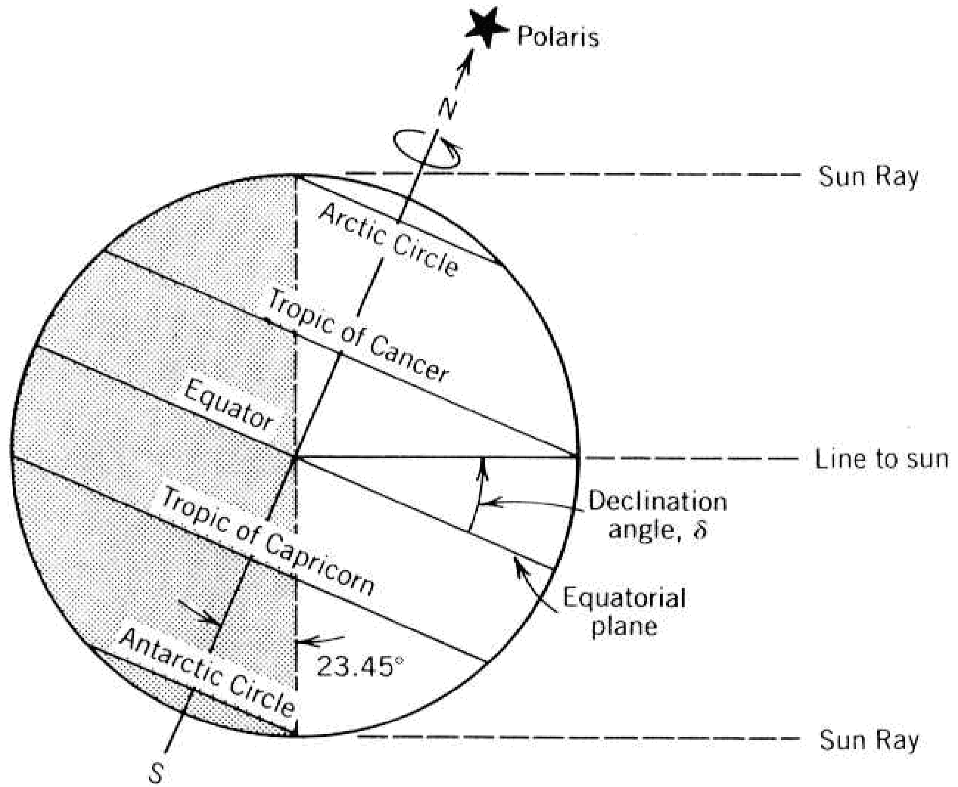
Latitude angle

- Φ : latitude, angle between equator and center of earth lines.
- Latitude, Φ : of a point P is the angular distance of the point north (or south) of equator, north latitude being positive. -90o ≤ Φ ≤ 90o).



Solar declination angle

- δ : solar declination, the angle between sun's projection on earth's surface and the equator.
- Solar declination angle varies seasonally due to the tilt of the Earth on its axis of rotation and the rotation of the Earth around the sun.

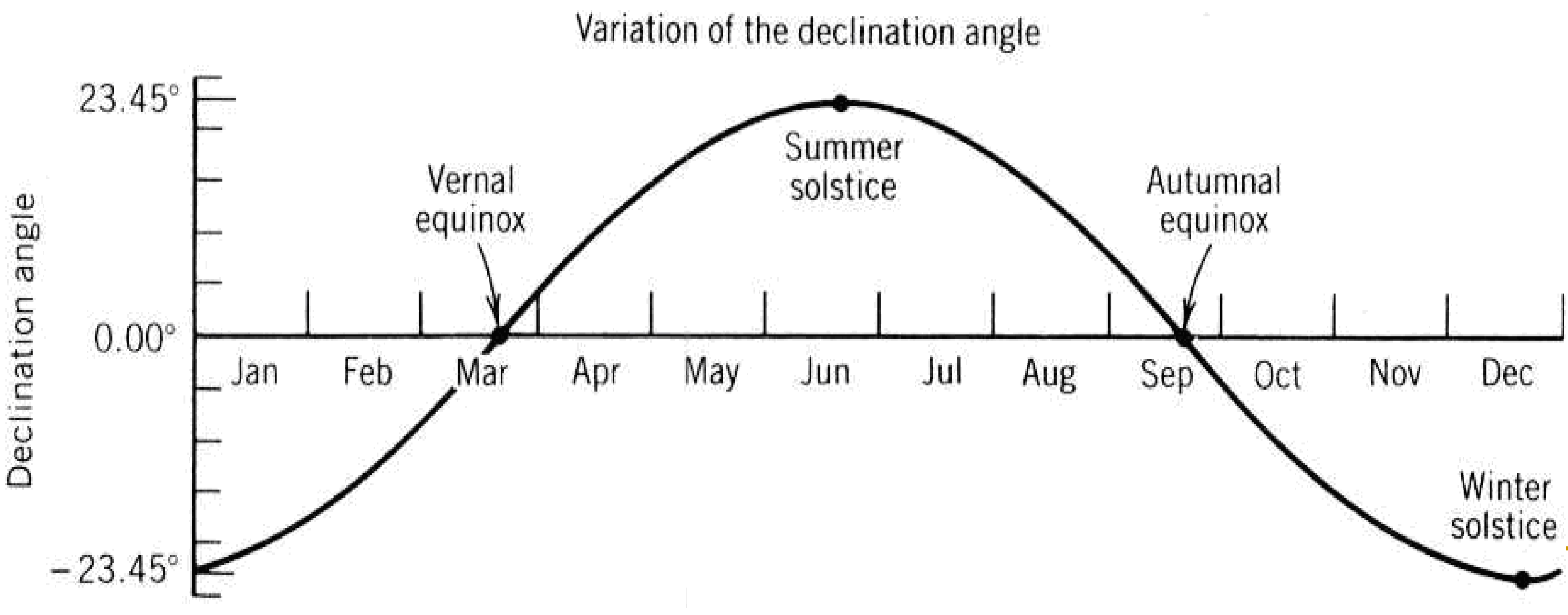


Solar declination angle

- δ is given by:

  $$\delta = 23.45 \sin\left[360 * \frac{(284 + n)}{365}\right]$$

  Where n is day of year e.g. Jan 1, n =1



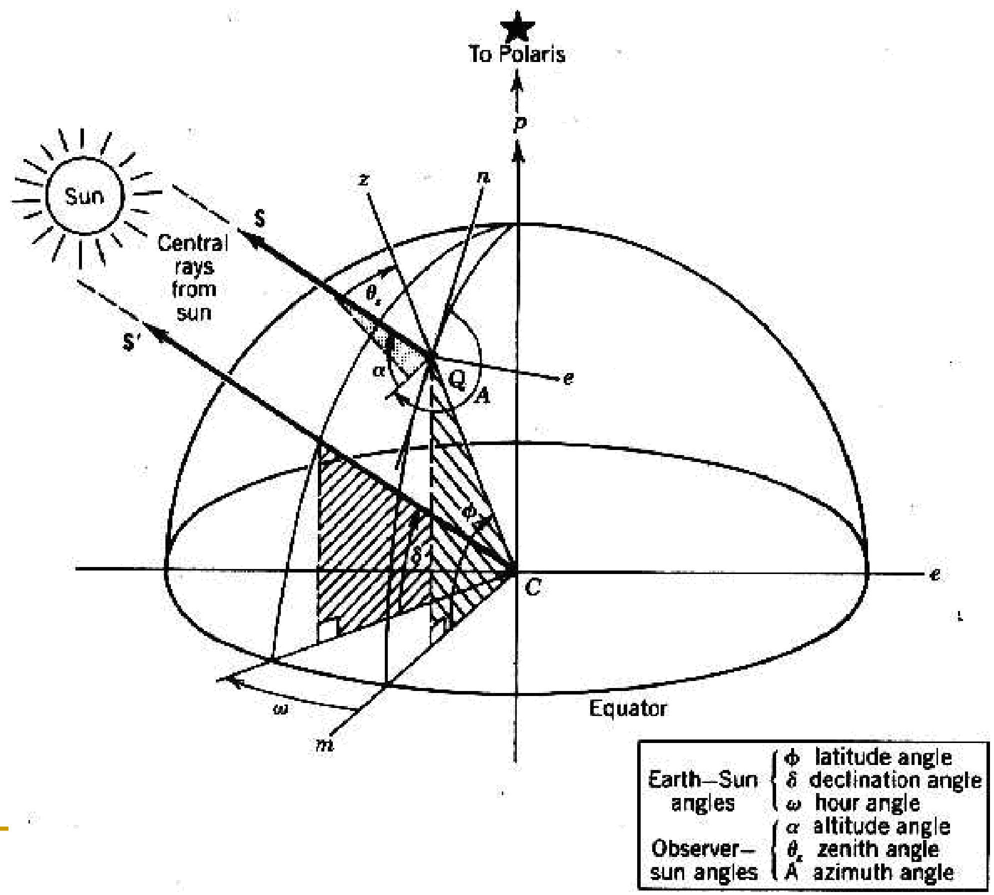
Hour angle of the sun

- Hour angle **ω** is the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15^o per hour.
- **ω** = 0 at solar noon
- **ω** > 0 after noon
- **ω** < 0 before noon
- **ω** = 15^o for each hour
- **ω** = –30^o for 10:00 AM
- **ω** = +30^o for 2:00 PM
- **ω** = ± ¼ (number of minutes from local solar noon)
- **ω** = 15 × (number of hours from local solar noon)

Calculating Zenith angle

- Using previous angles then:

  $\cos \theta_z = \sin\alpha = \sin\Phi \sin\delta + \cos\Phi \cos\delta \cos\omega$



Example:

- Find the solar altitude angle α or zenith angle θz at 11 am. Solar time of Feb. 23 at 30oN.
- *Solution:*
- $\omega = 15^o$ at 11am
- $\Phi = 30^o$
- $\delta = -10^o$ at Feb.23.
- Using the equation:

$\cos\theta z = \sin\Phi \sin\delta + \cos\Phi \cos\delta \cos\omega$

$= \sin30 \sin(-10) + \cos30 (\cos-10) \cos15.$

$= 0.758 = \sin\alpha$

- Then $\alpha = 47.5$, $\theta z = 42.5^o$

Or using the sun-path diagram:

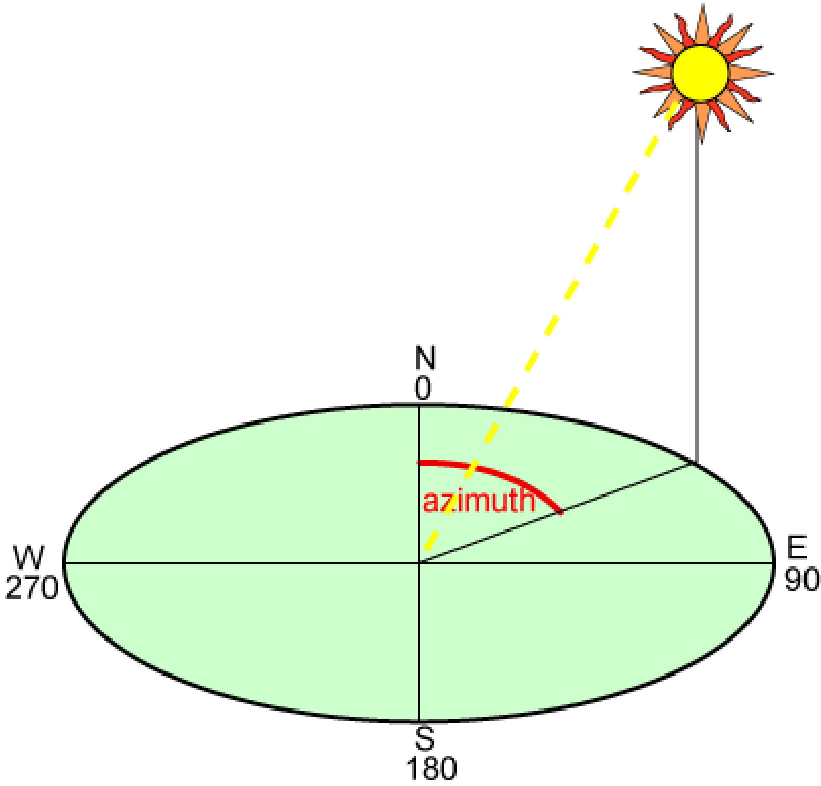
$40 < \alpha < 50 \rightarrow \alpha = 48^o$

And $20 < \alpha s < 30 \rightarrow \alpha s = 23^o$ E

Azimuth angle

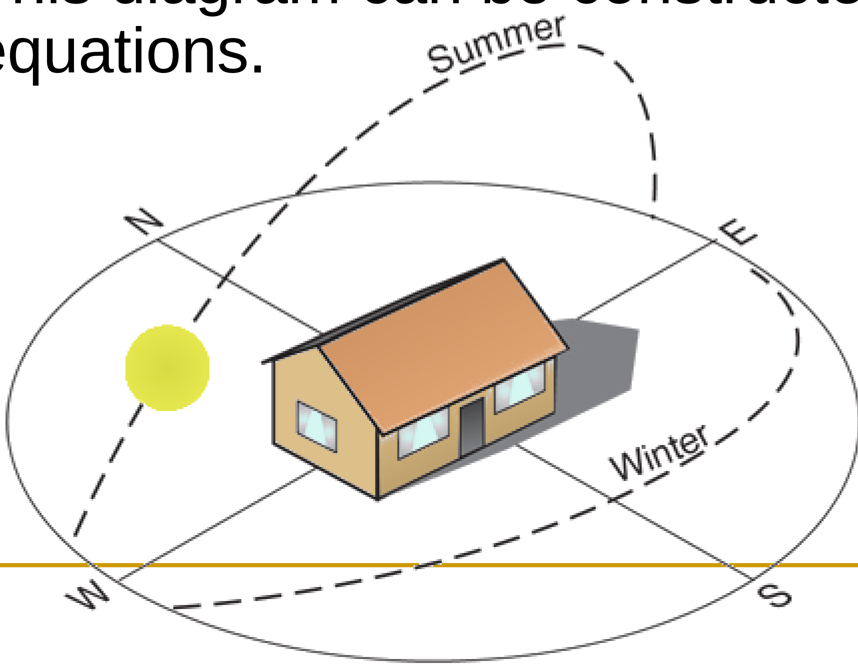
- Azimuth angle, α_s, is the angle between sun's direction and the north/south meridian

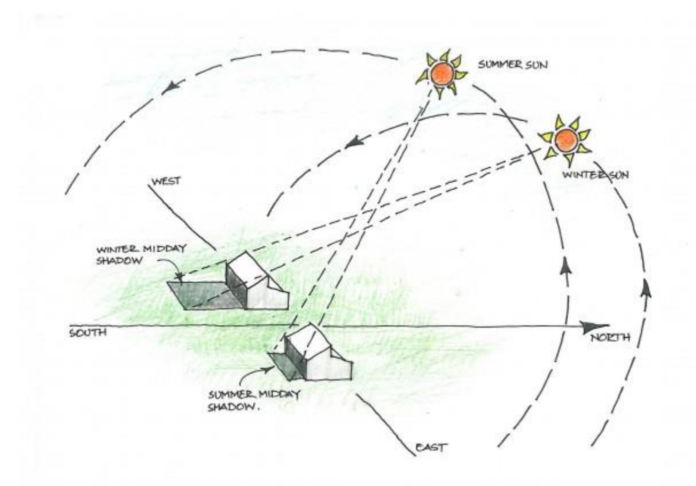
  measured on the horizontal plane).



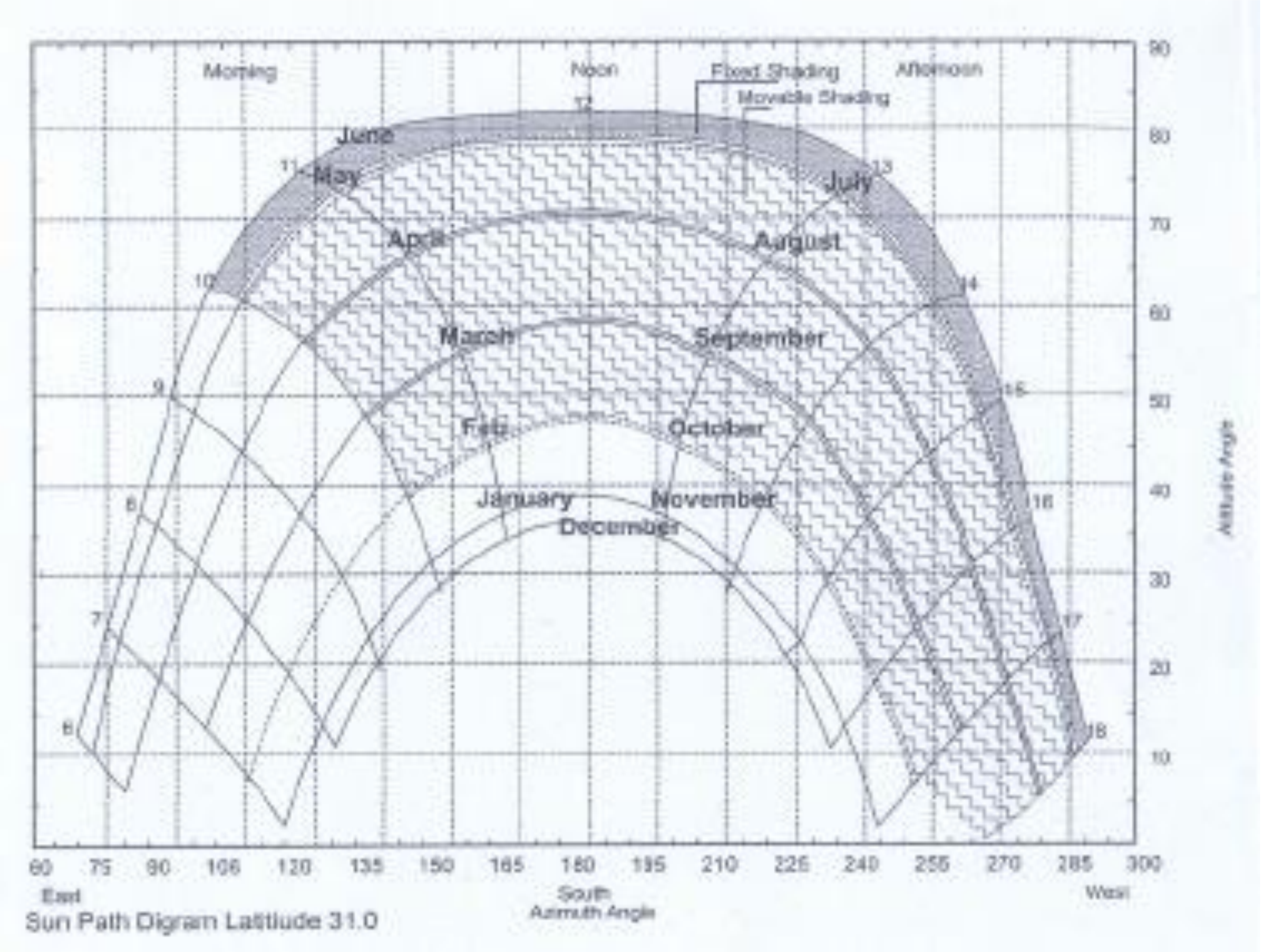
Sun path diagram

- It is a diagram that shows for a certain location (Φ latitude) the path of the sun at various days of the year from sun rise to sun set.
- Including the angle α, α**s** (The azimuth angle, α**s**, is the angle between sun’s direction and the south meridian measured on the horizontal plane).
- This diagram can be constructed using the above equations.





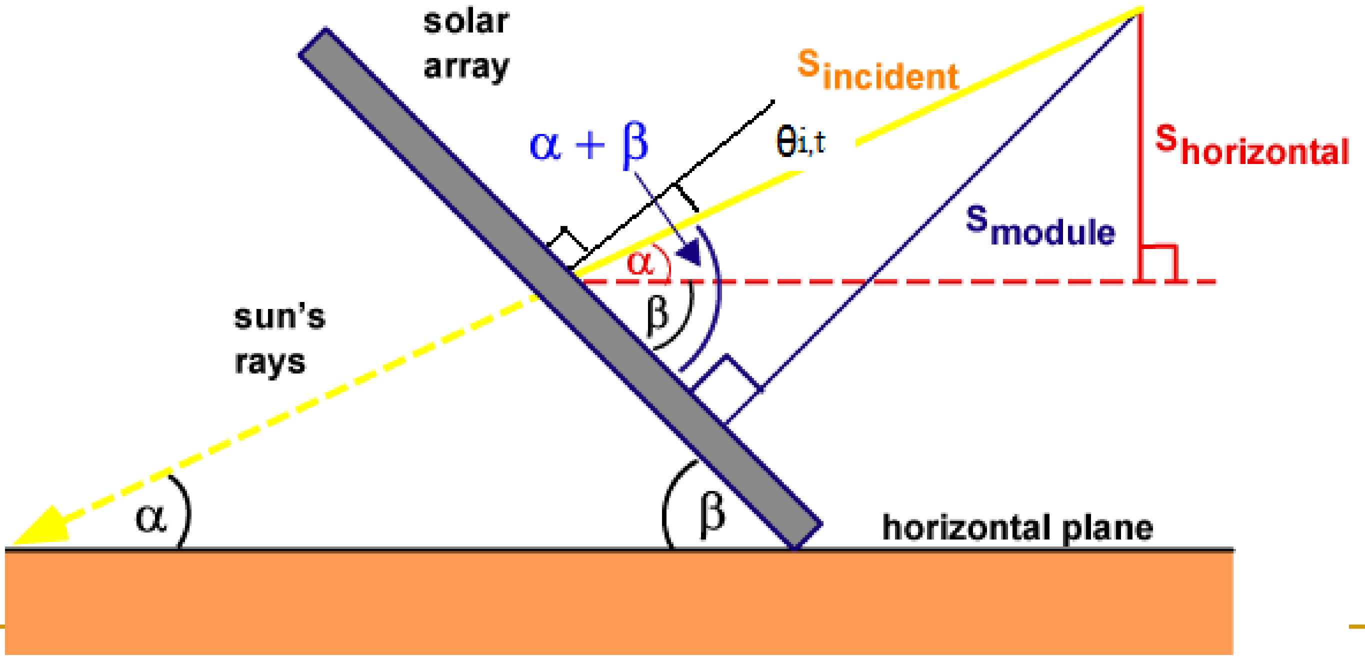
Sun path for Jerusalem



South- Facing Tilted Surface

- If the surface is aligned east west or south facing, and tilted angle β from horizontal.
- Incident angle on the titled surface θ**i,t** is given as,

  $\cos \theta_{i,t} = \sin(\Phi - \beta)\ \sin\delta + \cos(\Phi - \beta)\ \cos\delta\ \cos\omega$



Solar tracking- flat plate

- At solar noon and when sun is normal to the tilted surface $\theta_{\mathbf{i,t}} = 0$; $\omega = 0$.
- Then $\beta = \beta n$,and:

$$1 = \sin(\Phi - \beta n)\ \sin\delta + \cos(\Phi - \beta n)\cos\delta$$

$$1 = \cos(\Phi - \beta n - \delta)$$

Hence:

$$\Phi - \beta n - \delta = 0 \text{ and } \beta n = \Phi - \delta$$

Fixed surface tilt

- For a flat plate collector surface tilted to the south an adjustment of β at two week intervals is sufficient in compensation for solar declination.
- Solar collectors are usually installed in a fixed position where:

$$\beta n = \Phi - \delta$$

and δ is taken at time of winter Dec. 22. hence

$$\beta = 44o$$

Work e.g. 13.5 Sorenson p(467-468)

Example 13.4

A solar collector is located at latitude 47°N. On May 15, the solar declination is +19°, and the interval extending from sunrise to sunset is 14.90 hours. Determine the magnitude of β_n and, at solar noon, the zenith angle, altitude of the sun, and the value of $\cos \theta_{i,t}$ for $\beta = \beta_n$.

1 $\beta_n = \phi - \delta = 47° - 19° = 28°$

2 $\cos \theta_z = \sin \phi \sin \delta + \cos \phi \cos \delta$

$$= \sin 47° \sin 19° + \cos 47° \cos 19°$$

$$= 0.8830$$

$\theta_z = 28.0°$ at solar noon

3 $\alpha = 90° - \theta_z = 90° - 28.0° = 62.0°$

4 $\cos \theta_{i,t} = 1$ for $\beta = \beta_n = 28.0°$

Example 13.4

Now, determine the value of $\cos\theta_{i,t}$ at solar noon for $\beta_n - \beta = +10°$ and $-10°$.

1 For $\beta_n - \beta = +10°$, → $\beta = 18$

$$\beta = 18° \qquad \phi - \beta = 47° - 18° = 29°$$

$$\cos\theta_{i,t} = \sin(\phi - \beta)\sin\delta + \cos(\phi - \beta)\cos\delta$$

$$= \sin 29° \sin 19° + \cos 29° \cos 19° = 0.9848$$

2 For $\beta_n - \beta = -10°$, $\beta = 38$

$$\beta = 38° \qquad \phi - \beta = 47° - 38° = 9°$$

$$\cos\theta_{i,t} = 0.9848$$

Example 13.5

Determine for the surface described in Example 13.4 the magnitude of $\dot{E}_i$ at hourly intervals during the day. $\beta = \beta_n = 28°$, $\tau_a = 0.75$. The surface is fixed and faces south. The following relationships are used for obtaining the solution.

1 $\cos\theta_z = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega$

$$= \sin 47° \sin 19° + \cos 47° \cos 19° \cos\omega$$

$$= 0.2381 + 0.6448\cos\omega$$

2 $\dot{E}_n = \dot{E}_o\tau_a^m = 1361(0.75)^m\ \text{W/m}^2$

where $m = \text{secant}\ \theta_z$

3 $\dot{E}_i = \dot{E}_n\cos\theta_i = \dot{E}_n\cos\theta_{i,t}$

$\cos\theta_{i,t} = \sin(\phi - \beta)\sin\delta + \cos(\phi - \beta)\cos\delta\cos\omega$

$$= \sin 19° \sin 19° + \cos 19° \cos 19° \cos\omega$$

$$= 0.1060 + 0.8940\cos\omega$$

Time (hour)	$\cos\theta_z$	τ_a^m	$\dot{E}_n$ (W/m²)	$\cos\theta_{i,t}$	$\dot{E}_i$ (W/m²)
0	0.8829	0.7219	982.5	1.0000	982.5
1	0.8609	0.7159	974.4	0.9695	944.7
2	0.7965	0.6969	948.4	0.8802	834.8
3	0.6940	0.6607	899.2	0.7382	663.7
4	0.5605	0.5985	814.6	0.5530	450.5
5	0.4050	0.4915	668.9	0.3374	225.7
6	0.2381	0.2987	406.6	0.1060	43.1
7					—

Non-south Facing Tilted Surface

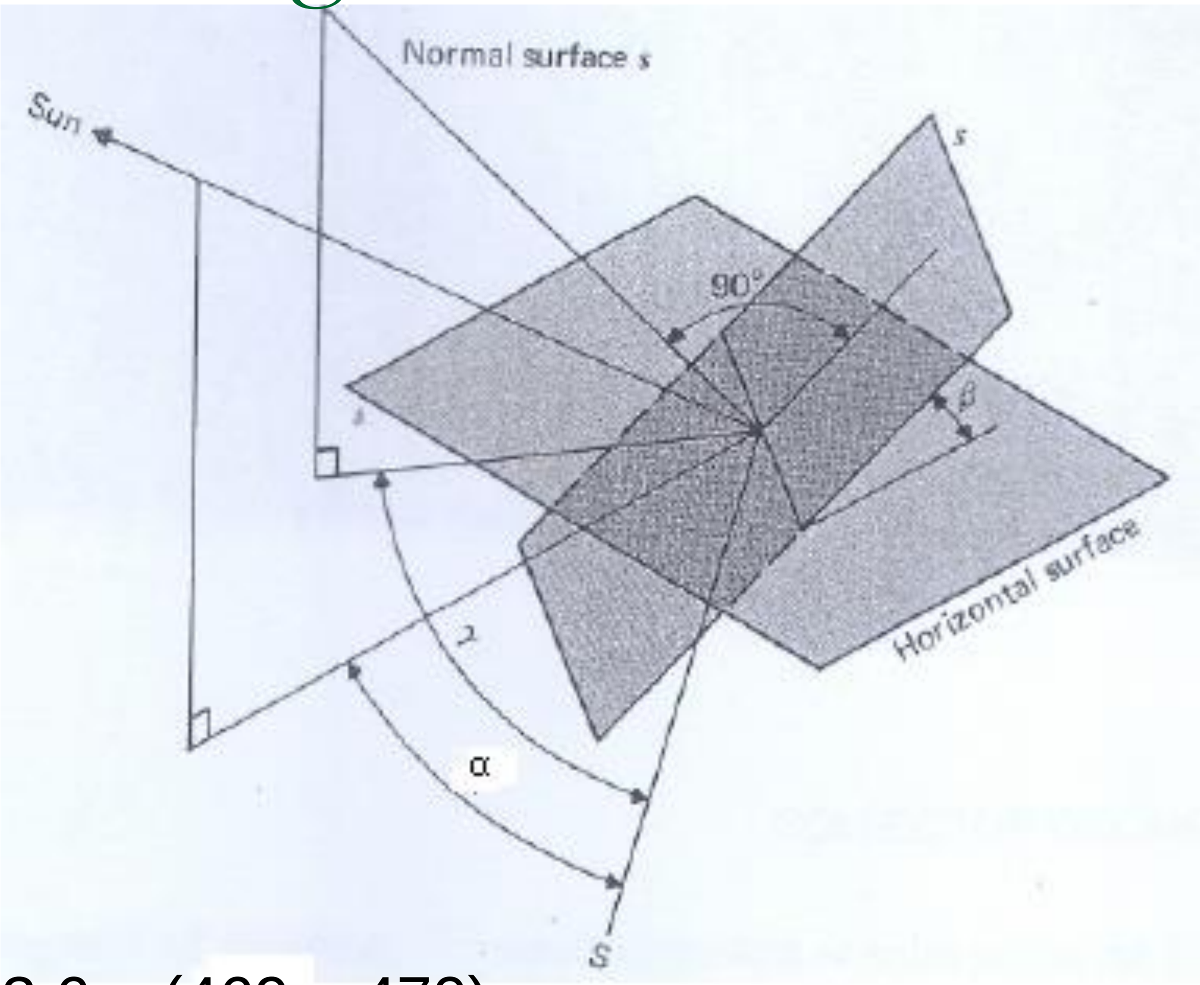
- Let β: tilted angle from horizontal.
- γ: angle between south meridian and normal to surface as measured on horizontal plane.
- α**s**: azimuth of the sun, angle between south meridian and sun direction measured on horizontal plane.
- Then:

$$\cos\theta_i = \sin\theta_z \sin\beta \cos(\alpha_s - \gamma) + \cos\theta_z \cos\beta$$

and:

$$\alpha_s = \sin^{-1}\left(\frac{\cos\delta \sin\omega}{\sin\theta_z} \right)$$

Non-south Facing Tilted Surface



Work example 13.6 p (469 – 470)

Example 13.6

A surface is exposed to the sun at 2:30 P.M. The inclination angle β is 38°. The solar declination is +15°, and the latitude is 42°N. The angle γ is 0° measured eastward from the south meridian. Calculate the incidence angle.

$$\cos\theta_z = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega$$

$$= \sin 42^\circ \sin 15^\circ$$

$$+ \cos 42^\circ \cos 15^\circ \cos 37.5^\circ$$

$$= 0.742671$$

$$\theta_z = 42.04^\circ$$

$\cos\theta_i = \sin\theta_z \sin\beta \cos(\alpha_s - \gamma) + \cos\theta_z \cos\beta$

$$\alpha_s = \sin^{-1}\left(\frac{\cos\delta \sin\omega}{\sin\theta_z}\right)$$

$\gamma = 10$

$$A = \sin^{-1}\frac{\cos\delta \sin\omega}{\sin\theta_z}$$

$$= \sin^{-1}\frac{\cos 15^\circ \sin 37.5^\circ}{\sin 42.04^\circ}$$

$$= 0.878099$$

$$A = 61.41^\circ$$

$$\cos\theta_i = \cos\theta_z \cos\beta + \sin\theta_z \sin\beta \cos(A - \gamma)$$

$$= \cos 42.04^\circ \cos 38^\circ + \sin 42.04^\circ \sin 38^\circ \cos(61.41^\circ + 10^\circ)$$

$$= 0.716669$$

$$\theta_i = 44.22^\circ$$

Example 13.7

The collector surface in Example 13.4 is arranged to track the sun continuously. Determine at hourly intervals the values of the tilt angle β and the angle γ. Values of $\beta = \theta_z$ are obtained from Example 13.5, and Eq. 13.10 is used to determine values of A and hence γ.

$$\phi = 47^\circ \qquad \delta = 19^\circ$$

Time (Hour)	β *(Degrees)*	γ = A *(Degrees)*
0	28.0	0
1	30.6	28.7
2	37.2	51.4
3	46.0	68.3
4	55.9	81.4
5	66.1	92.6
6	76.2	103.2
7	85.9	113.7

Solar tracking

- In order to track the sun, collector surface should be normal to sun's direction hence

  $\theta i = 0$ then $\cos\theta i = 1$
- The surface is rotated such that $\alpha \mathbf{s} - \gamma = 0 \rightarrow \alpha \mathbf{s} = \gamma$
- Last equation simplifies to:

  $1 = \sin\Phi z \sin\beta + \cos\Phi z \cos\beta$

  $1 = \cos(\theta z - \beta)$
- Thus $\theta z - \beta = 0 \quad \rightarrow \quad \beta = \theta z$
- so surface is rotated about a vertical axis holding $\gamma = \alpha s$, and the tilt angle, β is continuously adjusted to maintain $\beta = \theta z$

Diffuse radiation

- Diffuse radiation results from the scattering of sun rays by clouds and other atmosphere gases. Total energy reaching a collector surface is equal to the sum of the direct beam radiation and the diffuse radiation.
- On bright sunny day diffuse radiation is 10% of total radiation while on a partly cloudy day diffuse radiation is 50% of total. But on a completely overcast day diffuse radiation is 100%.
- The collecting surface will receive the same diffuse radiation for any orientation of the surface because the diffuse radiation is assumed to be uniformly over the sky.

Total radiation

- Total radiation on inclined surface equals to direct radiation plus diffuse solar radiation plus the reflected radiation, which is reflected from the ground.
- Hence

  $E_t = E_n \cos\theta_i + F_1 E_d + F_2 \rho (E_n \cos\theta_z + E_d)$

  Where:

$F1 = \dfrac{1 + \cos\beta}{2}$ sky to collecting surface

$F2 = \dfrac{1 - \cos\beta}{2}$ ground to surface, note $F1+F2 = 1.0$

ρ: ground reflectivity of radiation.

Work example 13.9 p(471) Sorenson.

Example 13.9

A solar panel faces south at an angle of 50° from the horizontal surface. The intensity of the solar normal beam radiation is 760 W/m², and the diffuse radiation from the sky is 190 W/m². The zenith angle is 25°, and $\cos\theta_i = 0.8088$. The

$$F_1 = \frac{1 + \cos\beta}{2}$$

$$= \frac{1 + \cos 50^\circ}{2} = 0.821$$

$$F_2 = 1 - F_1$$

$$= 1 - 0.821 = 0.179$$

$$\dot{E}_t = \dot{E}_n \cos\theta_i + F_1\dot{E}_d + F_2\rho(\dot{E}_n \cos\theta_z + \dot{E}_d)$$

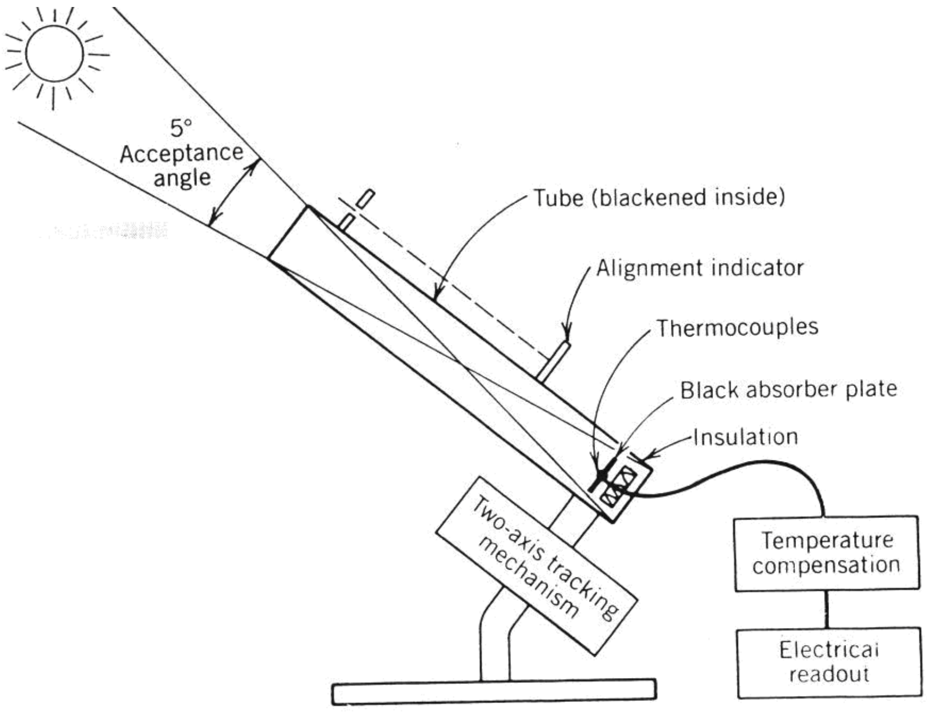
$$= (760 \times 0.8088) + (0.821 \times 190) + 0.179 \times 0.22[(760 \times 0.9063) + 190]$$

$$= 614.7 + 156.0 + 34.6 = 805.3\ \text{W/m}^2$$

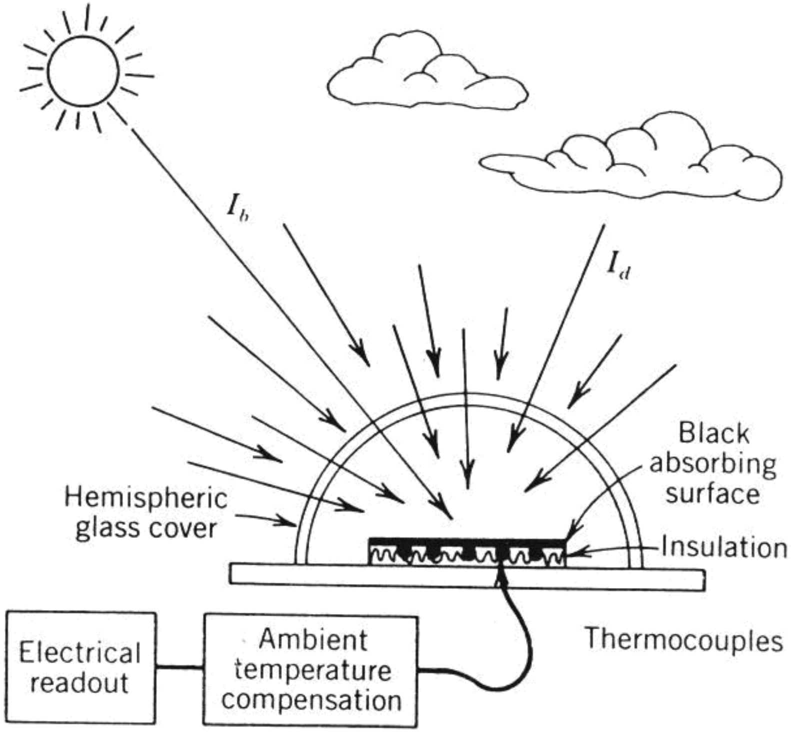
Measurement of solar radiation

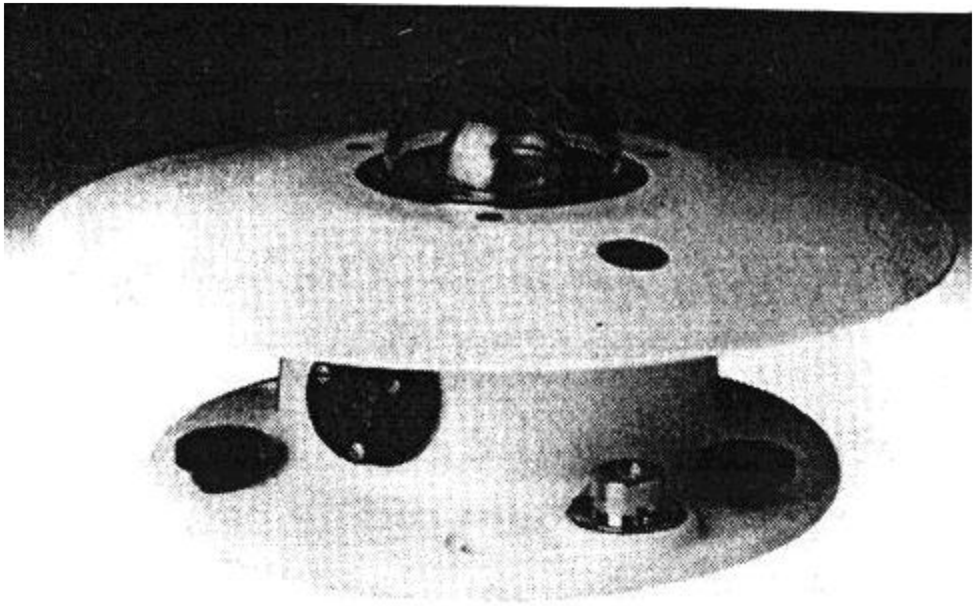
- There are two basic types of instruments used to measure solar radiation:
  - pyranometer and
  - pyheliometer.
- Pyranometer: has a hemispherical view of surroundings and is used to measure total, direct and diffuse solar radiation on a surface, also known as solar meter.
- Pyheliometer: has a restricted view, about 5o and is used to measure direct beam solar radiation it follows the sun with two axis tracking.
- Pyranometer is used also to measure diffuse radiation by using a shadow band to block the direct sun view.

Pyheliometer



Pyranometer





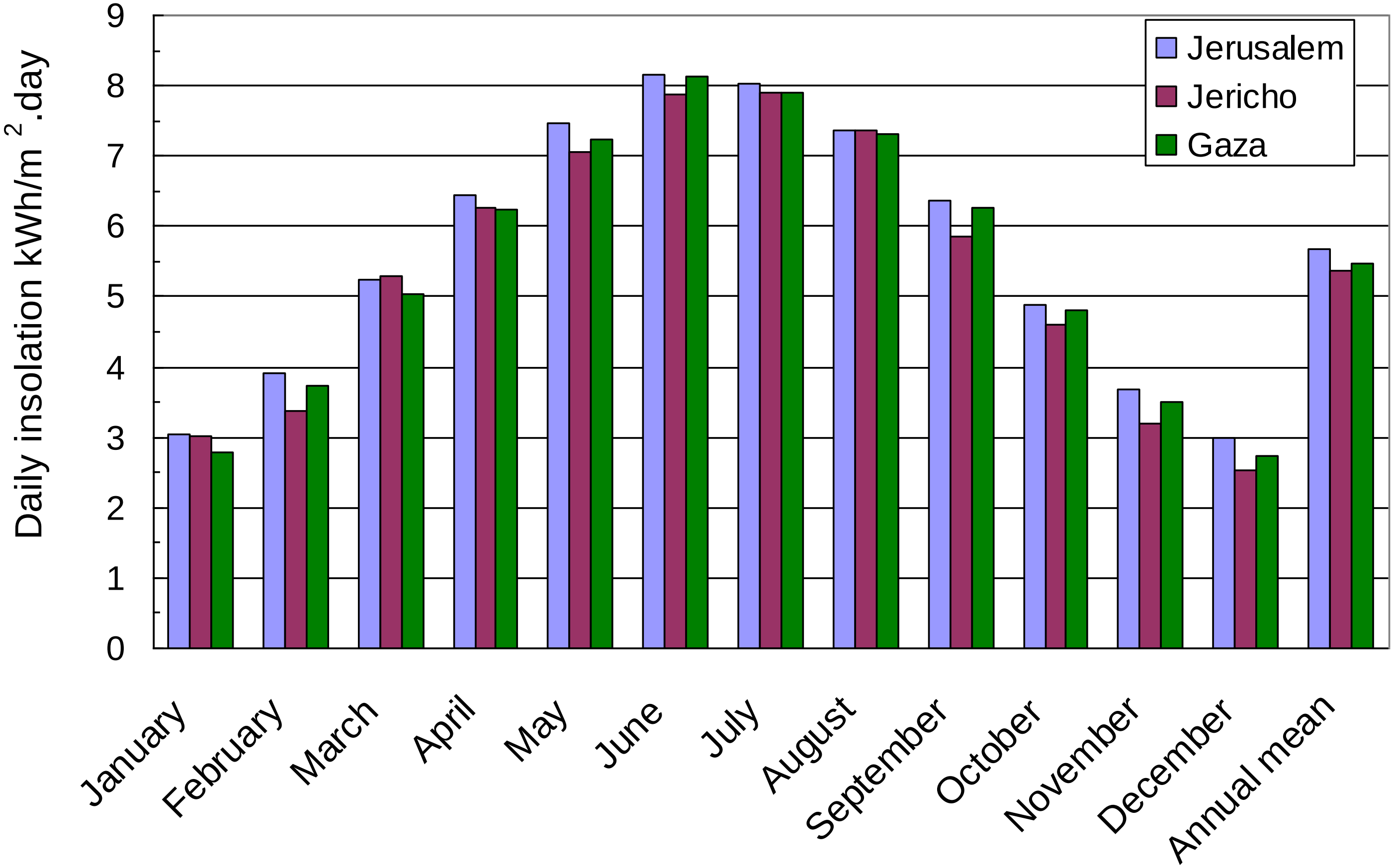
Sunshine duration

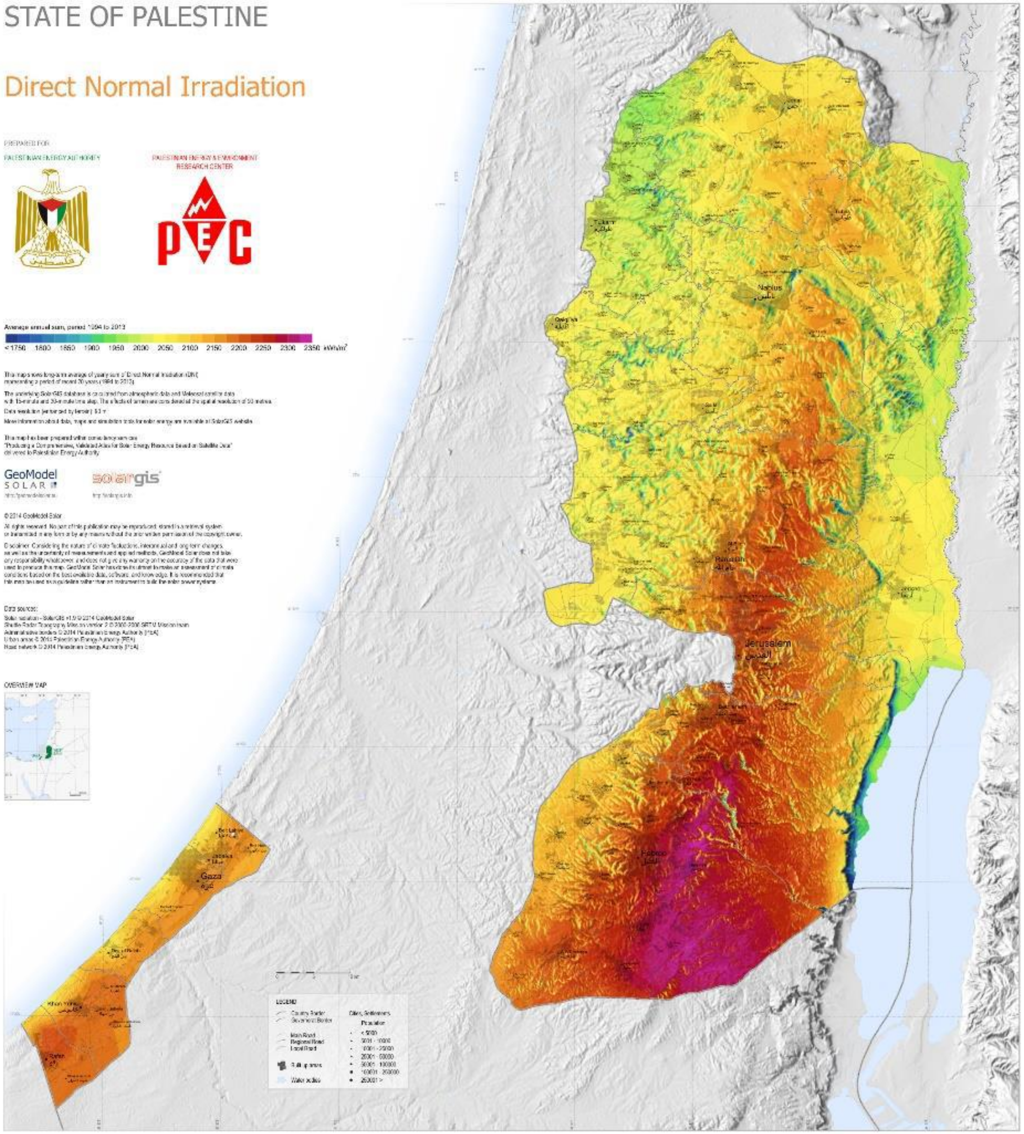
- Campbell-Stokes sunshine recorder is used to measure sunshine duration.
- It uses a solid clear glass sphere as a lens to concentrate the solar beam on the opposite side of the sphere.
- A strip of heated paper marked with time graduations is mounted on opposite side of sphere where the beam is concentrated, and it burns the paper, the length of the burned part of strip gives duration of bright sunshine.

Local solar radiation

- Palestine at 32º N is located in the solar sun belt which has a high solar radiation levels.
- Average daily solar insolation is: 5.45 kWh/m^2.day.

Local solar radiation




STATE OF PALESTINE
Direct Normal Irradiation
PREPARED FOR
PALESTINIAN ENERGY AUTHORITY
PALESTINIAN ENERGY & ENVIRONMENT RESEARCH CENTER
PEC
Average annual sum, period 1994 to 2013
<1750 1800 1850 1900 1950 2000 2050 2100 2150 2200 2250 2300 2350 kWh/m²
GeoModel SOLAR
solargis
Nablus
Jerusalem
Gaza

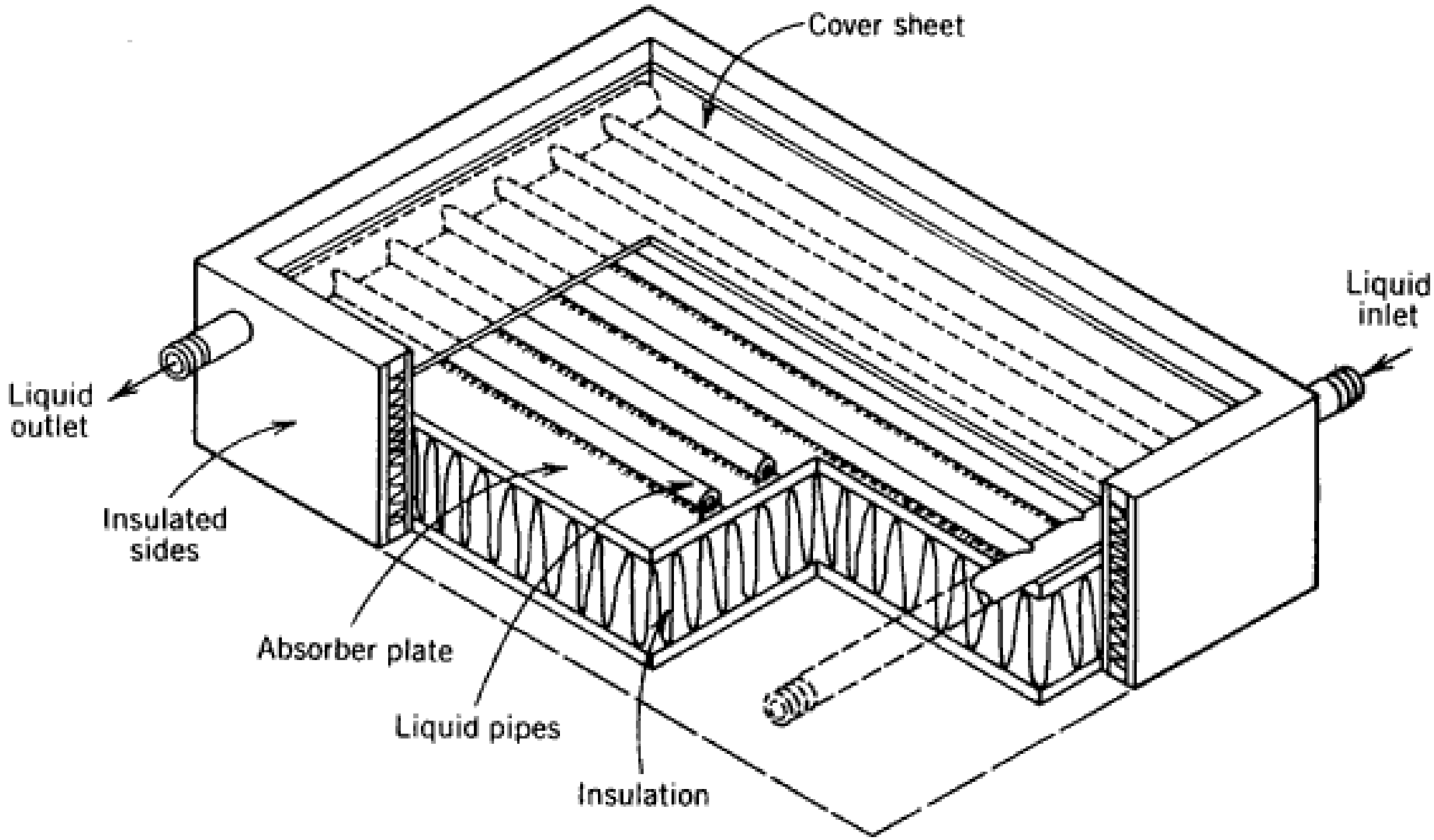
Solar collectors

- The function of solar collector is to converted solar radiation (electromagnetic waves) into thermal energy.
- The basic principle of solar thermal collection is that when solar radiation strikes a surface, part of it is absorbed, thus increasing the temperature of the surface this temperature is used to heat some fluid that carries this thermal energy to the intake application.
- Solar collectors can be classified into:
  - Flat plate collectors.
  - Concentrating collectors.

Flat Plate Collectors

- Flat Plate Collectors can be classified according to the employed heat transfer fluid, into:
  - Liquid based collectors.
  - Air based collectors.
- Flat plate collector makes use of all the sun radiation direct, diffuse and ground reflected radiation.
- Flat plate collectors are used for temperature requirement up to 75^{o}C, although higher temperature can be obtained from high efficiency collectors.
- The equilibrium (stagnation) temperature is the maximum collection temperature (when no useful heat is without from collector).

Liquid flat plate collectors



Structure of flat collectors

- The collector consists of:
  - Glazing: one , two or three covers of transparent material like glass.
  - Absorber:
  - Insulation: to minimize heat losses from back and side of collector
  - Container: box or casing.

Absorber

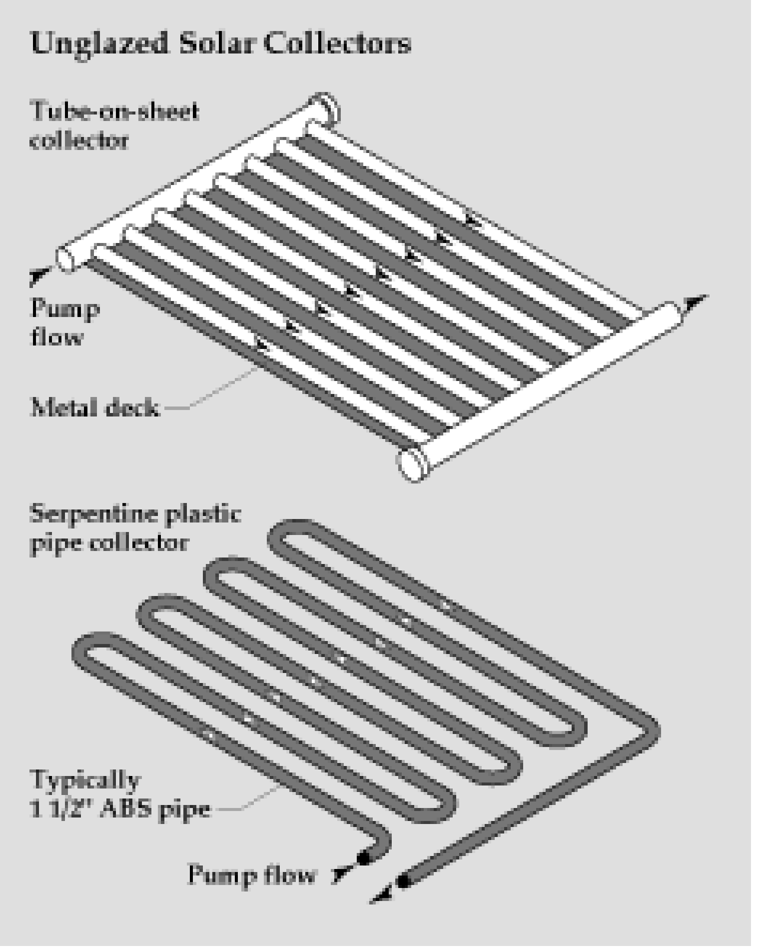
- perform three functions:
  - absorb the maximum possible amount of solar irradiance,
  - conduct this heat into the working fluid at a minimum temperature difference, and
  - lose a minimum amount of heat back to the surroundings.
- Absorber plate is usually painted black, or electro plated with a selective absorber.
- Selective surfaces consists of a very thin layer of reflective under surface of metal that has very little radiation, covered with thin layer of black absorbing paint.
- Nickel oxides exhibit selection absorption 0.90 absorptive, 0.2 emissivity of long wave radiation.

Fluid channels

- Absorbing plate can be any metal, plastic, and rubber. Unusually aluminum, copper or steel is used.
- Many forms of absorbing plates are available:

- Liquid collector absorber plates often consist of a flat sheet of metal with tubes spaced 10-25 cm (4-10 in.) apart and attached to it in some fashion (integral, brazed or press fitted).

Unglazed collectors



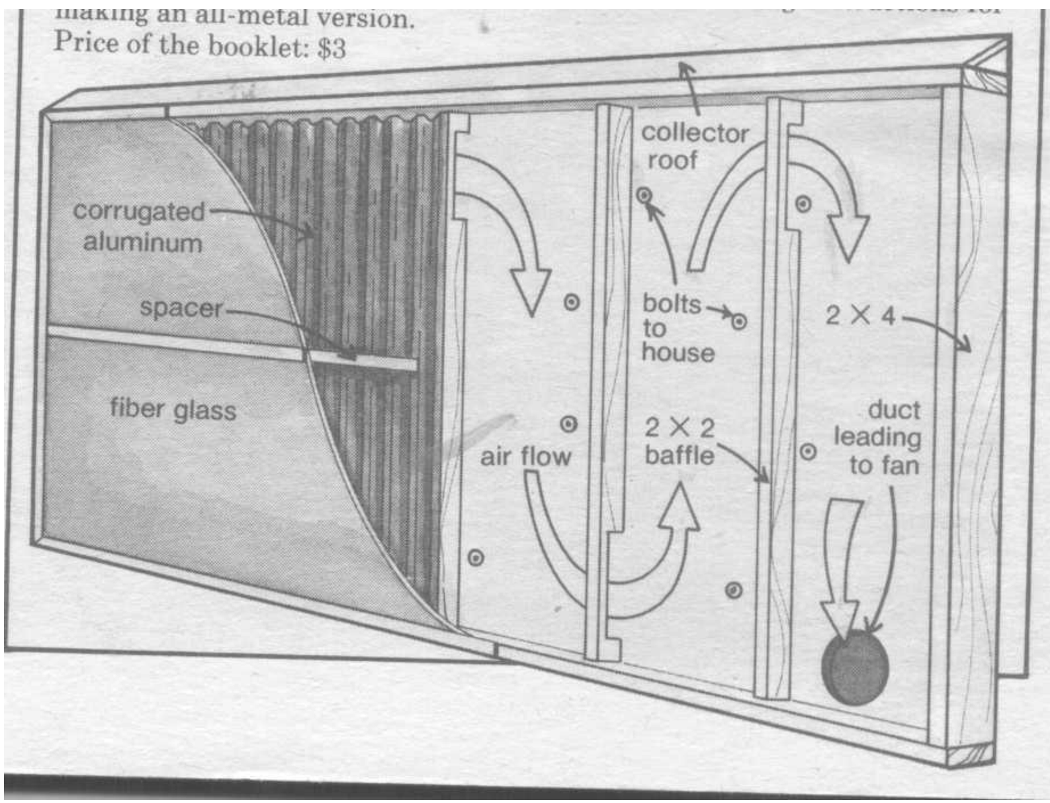
Air based collectors

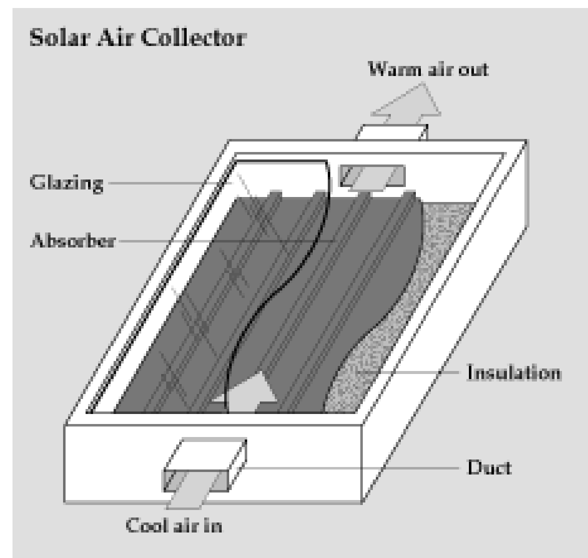
- Air collectors are more commonly used for agricultural drying and space heating applications.
- Because of low heat capacity of the air and the low convection heat transfer coefficient between absorber and the air, larger surface area and higher flow rates are used.
- Air collectors consist of:
  - glazing,
  - absorber plate,
  - insulation and a casing.

Air based collectors

- No need for a closed ducts or channels for the working fluid flow.
- Systems can operate with or without a fan. Without a fan the air is distributed by the action of a natural ventilation system.
- Fans could be used to enhance heat transfer to air.

Air based collectors





Power analysis

- Useful heat is the heat gained by the heat transfer fluid, qu
- qu = Solar gain – heat losses

- Collector efficiency is defined as useful heat divided by solar radiation,
  - $\eta = qu / AG$

Collector power analysis

- At steady conditions the heat lost from the plate is given by (Tp-Ta)/Rth , where

  Tp: plate temperature

  Ta: ambient air temperature

  Rth: total thermal resistant from plate to air.
- Net heat flow into plate is then,
  - $P_{net} = \alpha \tau A G - (T_p - T_a)/R_{th}$

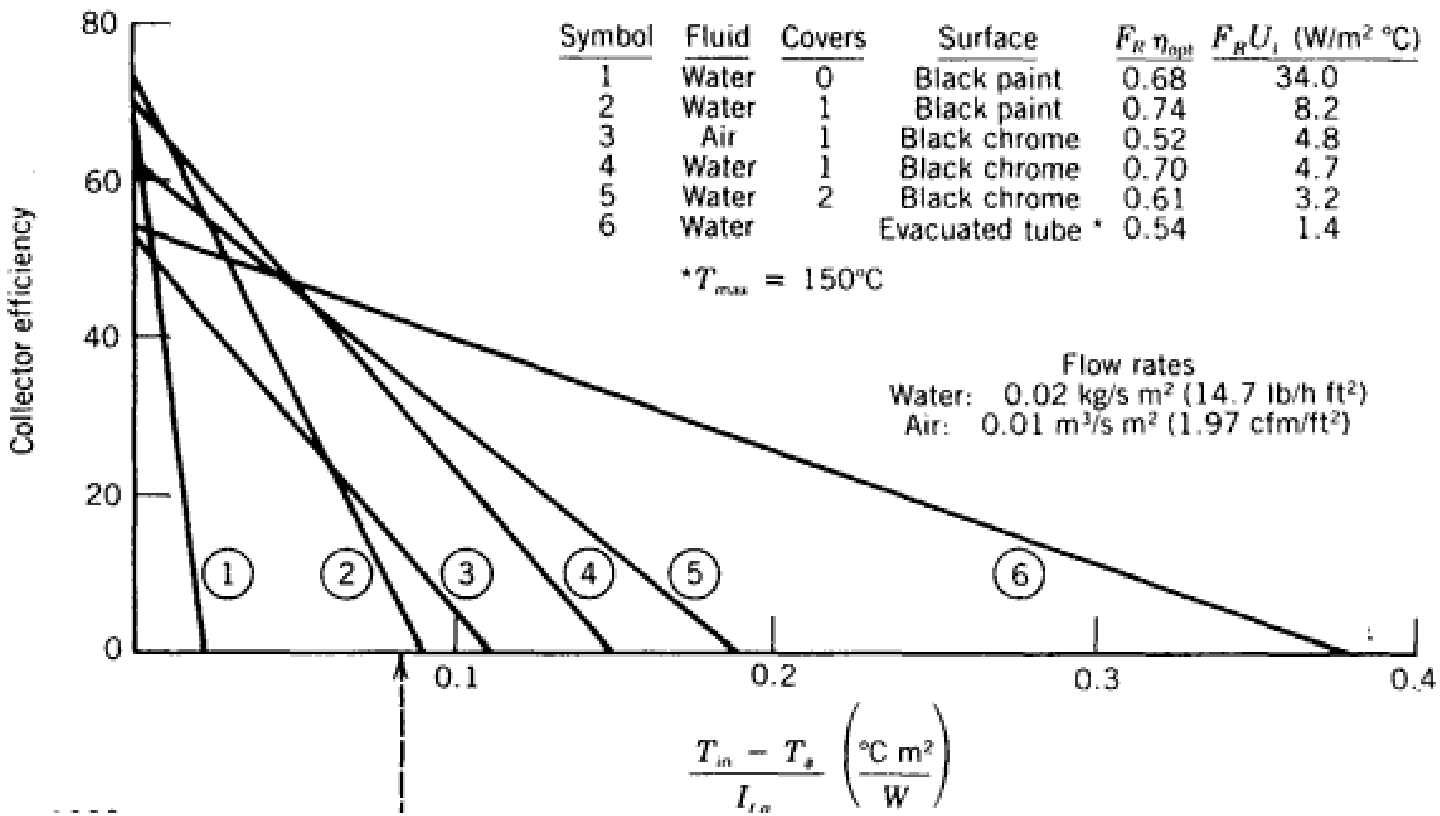
Collector efficiency

- however UA =1/ Rth then,
- $\eta = \alpha\,\tau - U(Tp-Ta)/G = \eta o - U(Tp-Ta)/G$

  where
  - U is the overall heat transfer coefficient, and Tp is the average plate temperature, ηo is the optical efficiency.
- In practice average plate temperature is difficult to measure and it is usual to express efficiency in terms of inlet fluid temperature Ti together with a correction factor F_R known as the heat removal factor.
- Then the efficiency is given as,
  - $\eta = F_R\,[\alpha\,\tau - U(Ti - Ta)/G]$

Collector efficiency

- Collector efficiency is plotted versus (Ti -Ta)/G leading to a straight line with slope U F_R and intercept of F_R α τ.



Concentrating collectors

- Concentrating of solar radiation is achieved by reflecting the incident flux on an aperture area Aa onto a smaller receive or absorber area Ar.
- Optical concentrating ratio CRo is defined as the ratio of the solar flux Ir on the receiver to the flux, Ia on the aperture or
- CRo = Ir / Ia.
- Geometric concentration ratio is based on area and is defined as:
- CR = Aa / Ar,

Efficiency

- The useful energy delivered by a collector qu is given as:

  $q_u = \eta_o I_c A_a – U (T_c – T_a) A_r$

  Where:

  η_o: is the optical efficiency ($\eta_o = \tau\alpha$)

  I_c: solar radiation on collector.

  A_r: receiver area.

- Dividing by Aa Ic which is the solar energy received by collector, to get the efficiency:

  $$\eta = q_u / A_a I_c = \eta_o – \frac{U_c (T_c - T_a)}{I_c * CR}$$

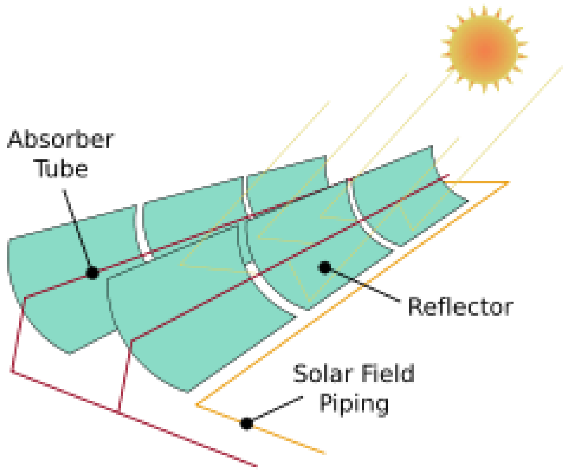
- For flat plate collector CR = 1.0, while for concentrating CR> 1, and the second term is smaller hence efficiency is larger.

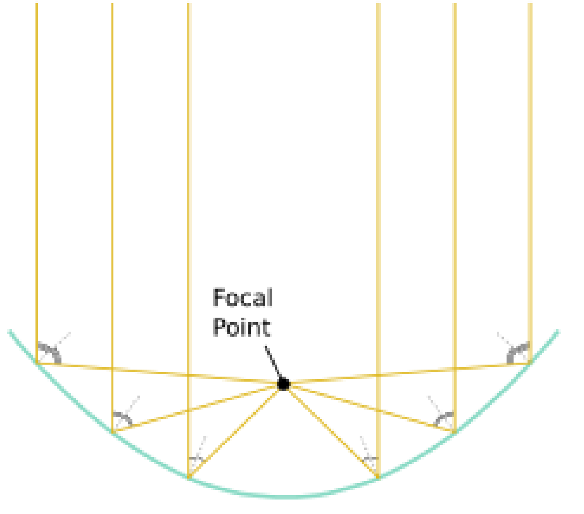
Types of concentrating collectors

- There are four basic types of concentrating collectors:
- Parabolic trough
- Parabolic/spherical dish
- Power tower/Central receiver collector
- Stationary concentrating collectors
  - For example CPC

Parabolic trough

- Parabolic troughs can focus the sun at 30 to 60 times its normal intensity on a receiver pipe located along the focal line of the trough.
- Synthetic oil captures this heat as the oil circulates through the pipe,
- reaching temperatures as high as 390°C (735ºF).





Parabolic trough

Normally it is installed east- west aligned with one degree of freedom for tracking, about its axis

Parabolic dish systems

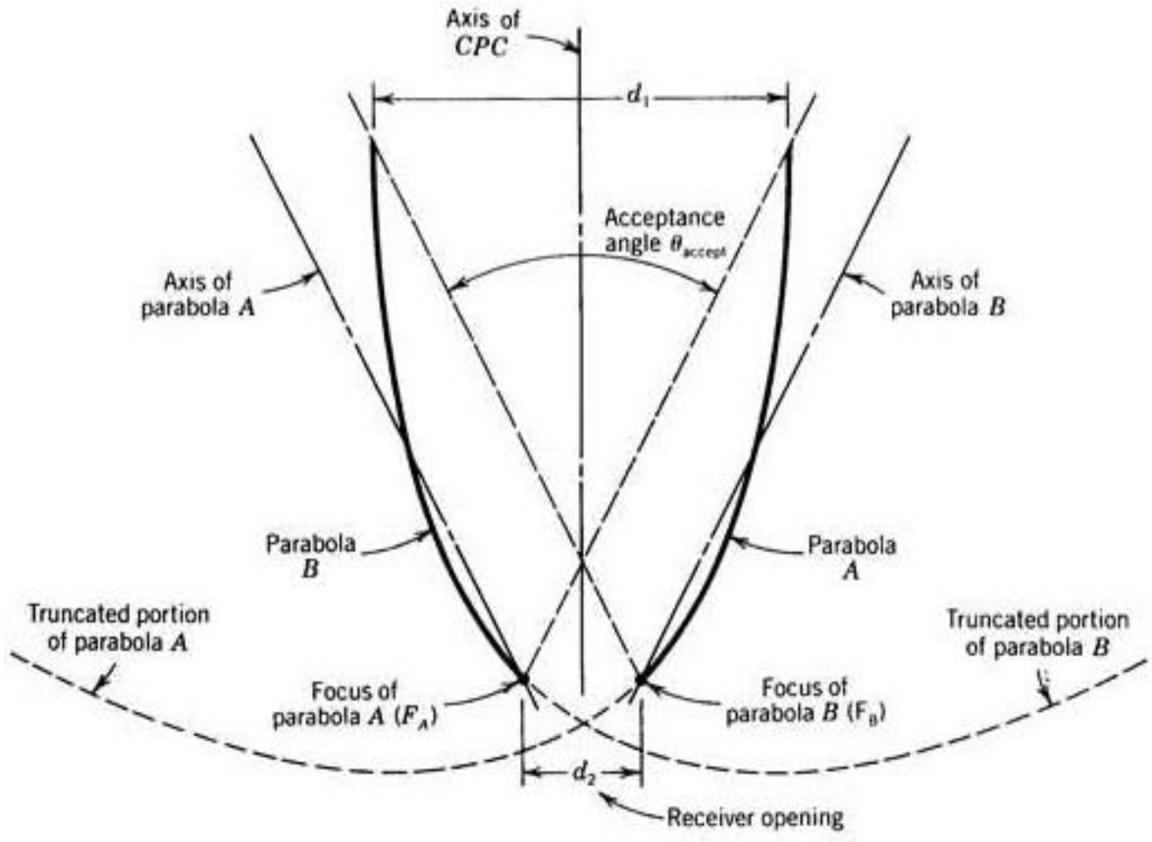
- The dish structure must track the sun continuously to reflect the beam into the thermal receiver.
- Parabolic dish systems can reach 1000 °C at the receiver.

Central tower collectors

- Solar central tower collectors use an array of flat, moveable mirrors (called heliostats) as reflector to focus the sun's rays upon a collector tower (the receiver).
- The heliostat mirrors will be continuously moved using computerized control mechanism such that it reflects the rays to the receiver (absorber).

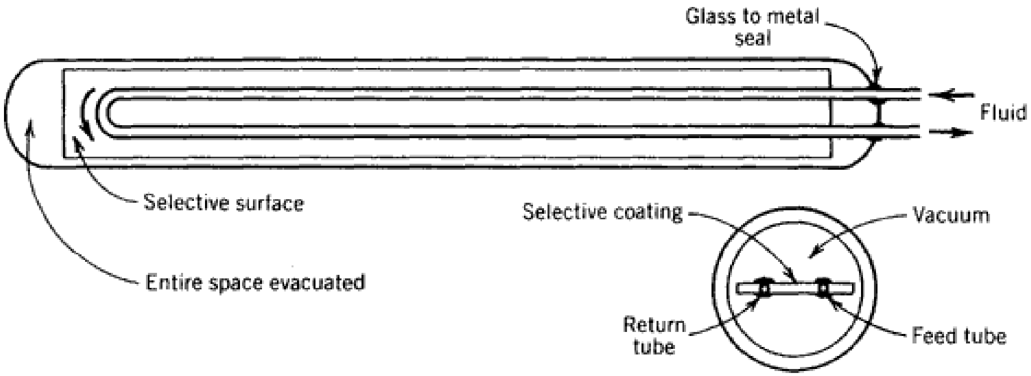
Compound parabolic concentrator (CPC)

- The name, compound parabolic concentrator, derives from the fact that the CPC is comprised of two parabolic mirror segments with different focal points as indicated.
- we have a concentrator that reflects (i.e. traps) all incoming rays to a region below the focal point.

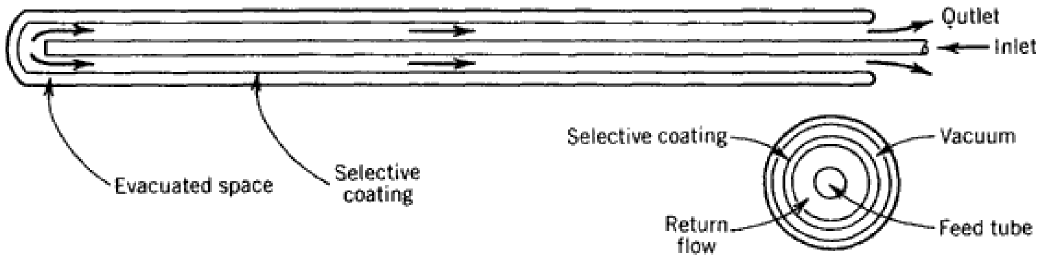


Evacuated-tube collectors

- Evacuated-tube collectors can achieve extremely high temperatures (170°F to 350°F),
- making them more appropriate for cooling applications and commercial and industrial application.
- However, evacuated-tube collectors are more expensive than flat-plate collectors, with unit area costs about twice that of flat-plate collectors.

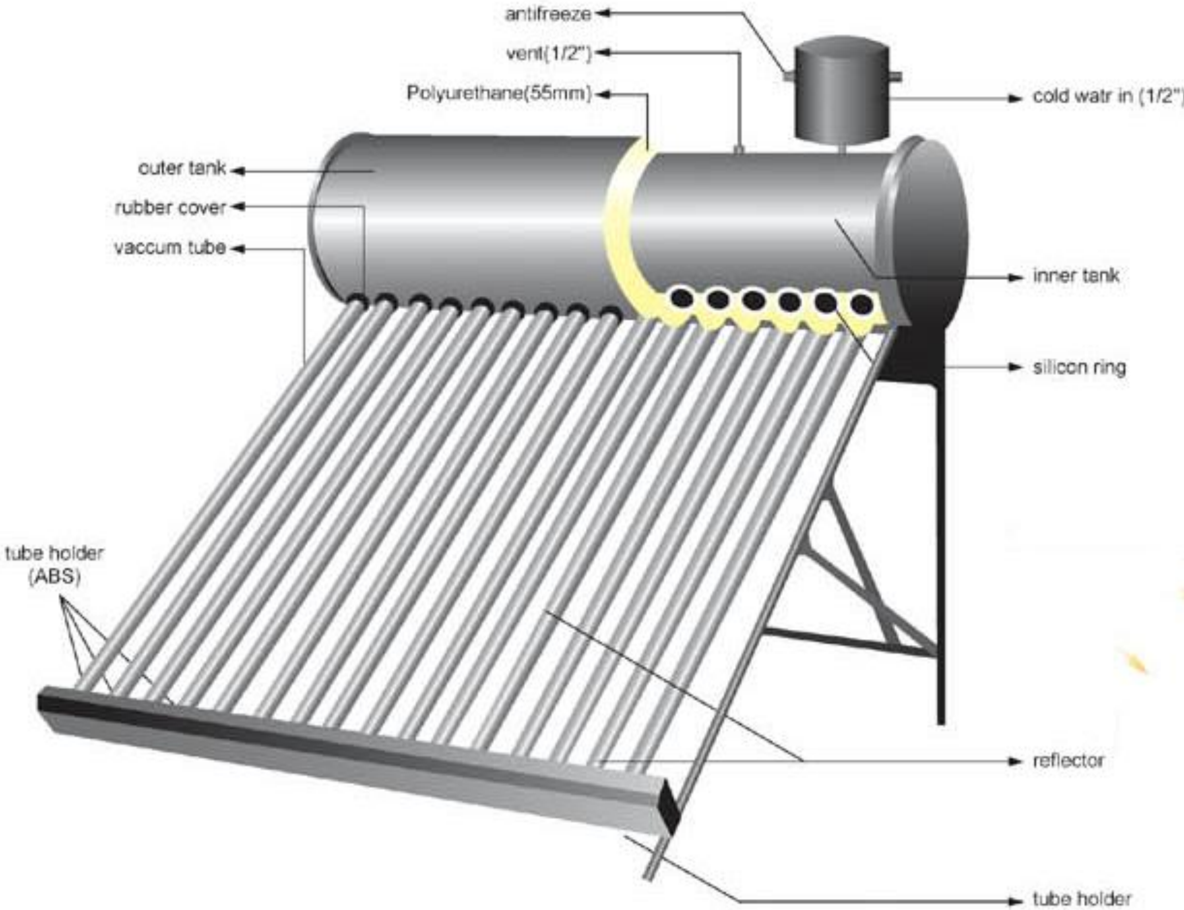


a) Corning Glass Company's evacuated tube



b) Owens Illinois Company's evacuated tube

Evacuated tube thermosyphon



Applications

Thermal solar applications include the following:

- Water heating
- Space heating, passive and active.
- Crop drying.
- Water distillation.
- Water disinfections and detoxification.
- Electricity generation.
- Cooling and refrigeration.
- Cooking.
- Swimming pool heating.

Solar water heating

- Basic elements of solar water system are flat plate collector, storage tank and connecting pipes and valves.
- Water circulation in the storage tank and collector can be either by natural circulation or by forced circulation where a pump is achieved by means of temperature differential collector.

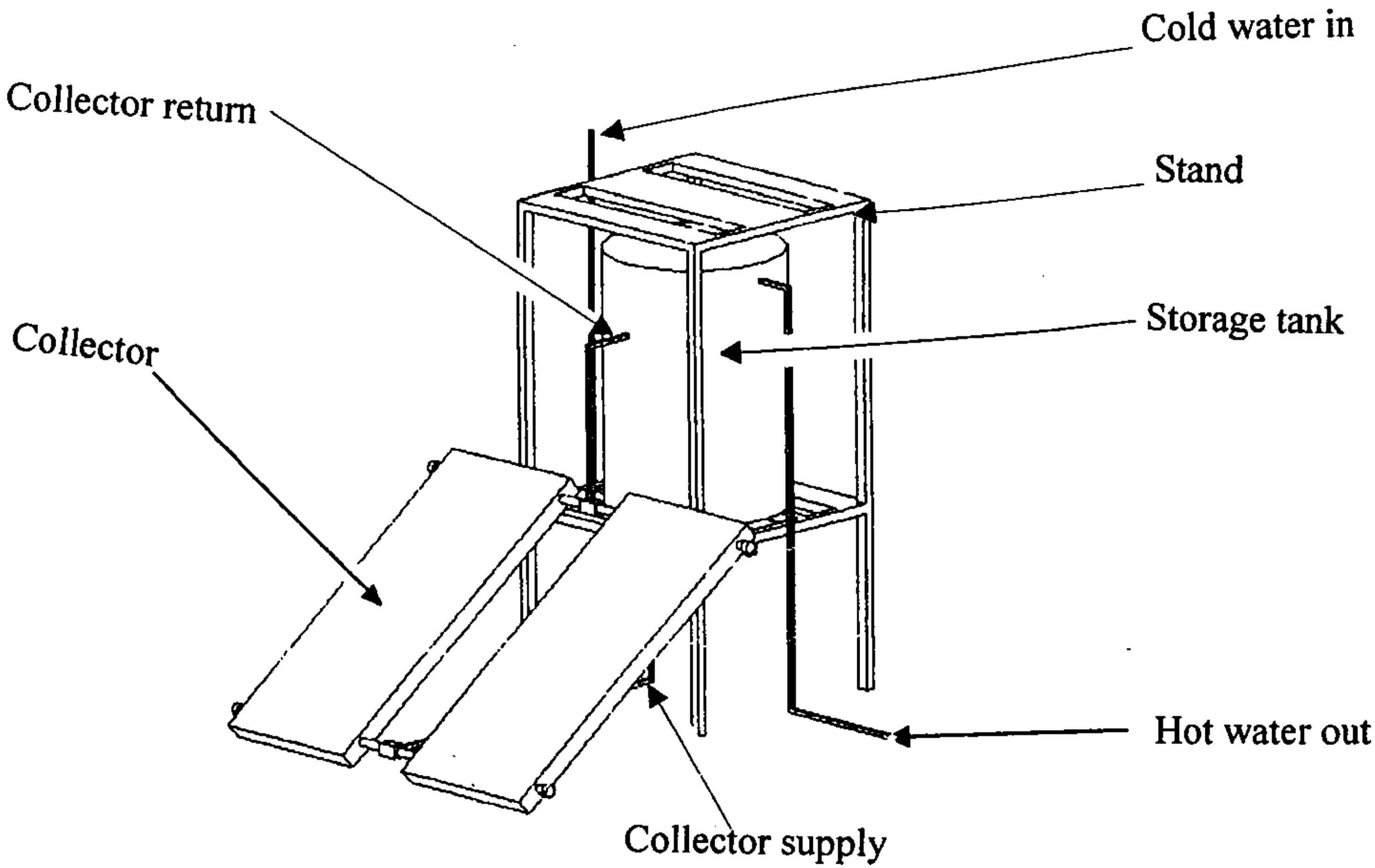
Classification

- Water heating systems can also classified as:
  - Direct circulation systems: where the drawn water is the same, which circulates through the collectors.
  - Indirect circulation systems: the fluid that removes heat from collector is different than with drawn water. a heat exchanger is added where the heat is exchanged (transferred) from the collector loop or fluid with the water withdrawn from the system.

Thermosyphon systems

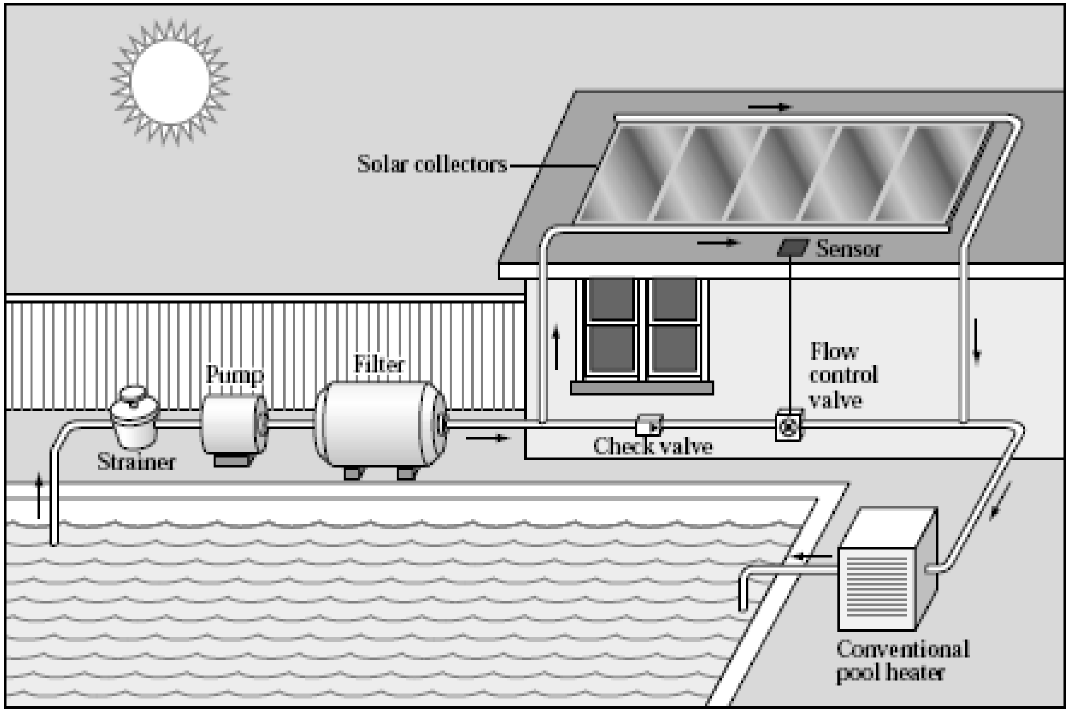
- Thermosyphon systems work on the principal of heat rising. it does not need additional power and it is the common used one in Palestine.
- In an open loop system (for nonfreezing climates only), the potable water enters the bottom of the collector and rises to the tank as it warms.
- In colder climates, an antifreeze solution, such as propylene glycol, is used in the closed solar loop, and freeze-tolerant piping, such as cross-linked polyethylene (PEX), is used for the potable water .

Local Thermosyphon



Swimming pool heating

- If a filter pump already exists, it can also be used for the solar circuit.
- In this case, the adequate dimensioning of the pump is very important.
- Plastic collectors are only operated during the summer months and have to be emptied before the first frost sets in.



A solar pool heating system.

Solar drying

- Solar drying was one of the early practices for conserving food used by mankind.
- For example crop drying for wheat, rice, similarly vegetable drying such as tomato, okra, mint, grape leaves, fruits as well grapes, apricots ..etc.
- Drying involves the reduction of moisture in the food or increasing the sugar concentration in order to prevent it from spoiling by insects or other organisms.

Solar building heating (space heating)

- Space heating could be either passive or active systems.
- Passive solar systems involve the use of windows, walls and other building elements for collecting solar energy.
- It also involves the orientation of building to receive larger amount of solar radiation in winter and minimum amount in summer. Such as using of external shading devices and over hangers.
- Use of south glass windows or veranda’s to collect and the use of of black walls to absorb and store thermal energy, such as the Trombe wall.

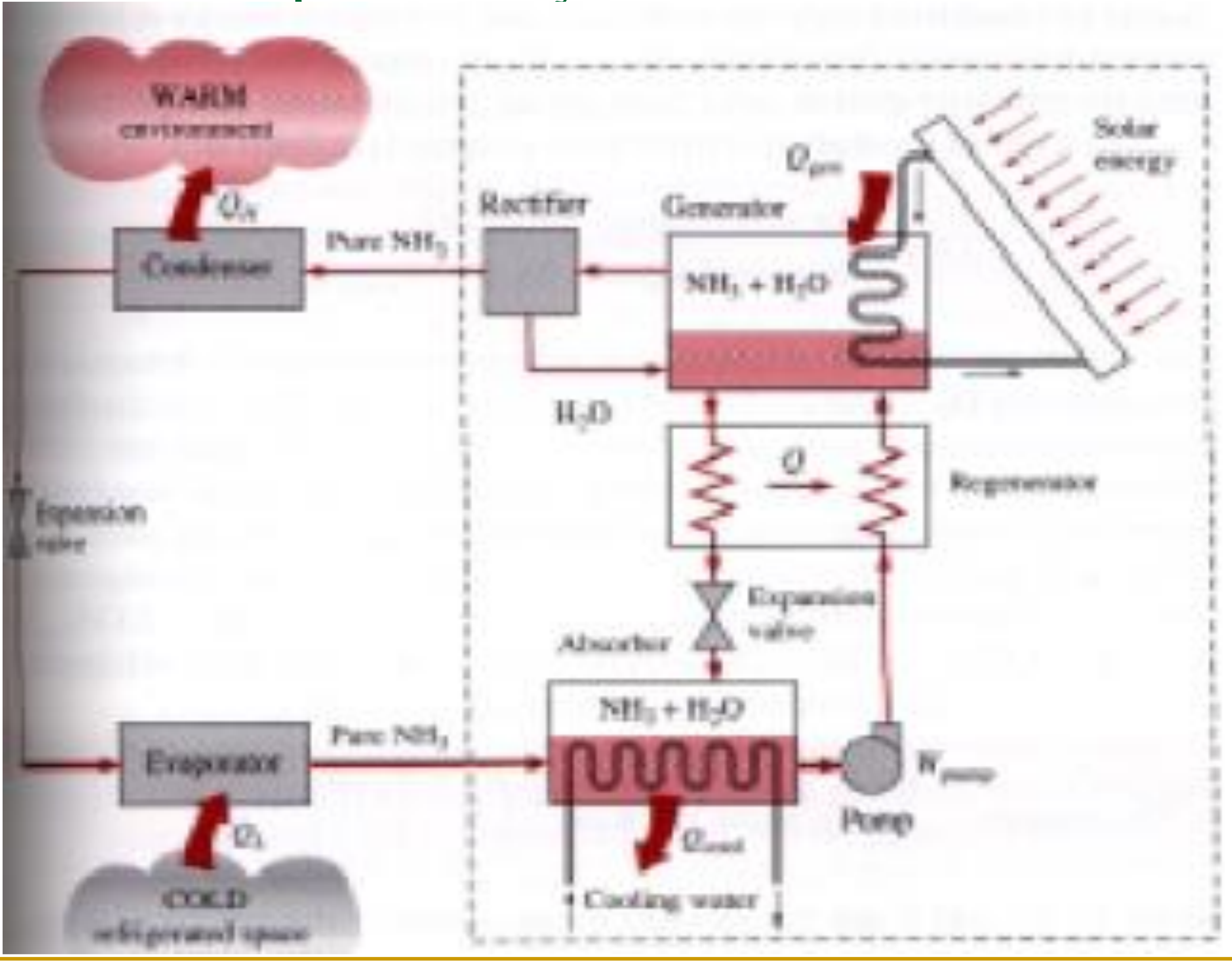
Active solar heating

- Active solar heating system consists of the basic element of solar energy collectors, storage of thermal energy, distribution system such as radiation, auxiliary heaters, and control and flow devices such as fans, pumps and dampers.
- Solar heating system might use as a working fluid either water or air. When using water as a working fluid flat plate collector might be used.

Solar thermal cooling

- Solar thermal cooling can be achieved via absorption refrigeration cycles, desiccant cycles and solar-mechanical processes.
- The absorption cycle solar cooling system works like a refrigerator in that it uses hot water to compress a gas that, once expanded, will absorb energy, which cools the air.
- The main problem currently is that the absorber machine works with liquid at 90 °C, a fairly high temperature to be reached with pumped solar panels with no auxiliary power supply.

Solar absorption cycle



Solar desalination

- A solar still uses solar energy to distill water.
- The main types are cone shaped, boxlike, and pit.
- In cone solar stills, impure water is inserted into the container, where it is evaporated by sunlight coming through clear plastic. Free of solids in suspension or solution, the water vapor condenses on top and drips down to the side, where it is collected and removed.

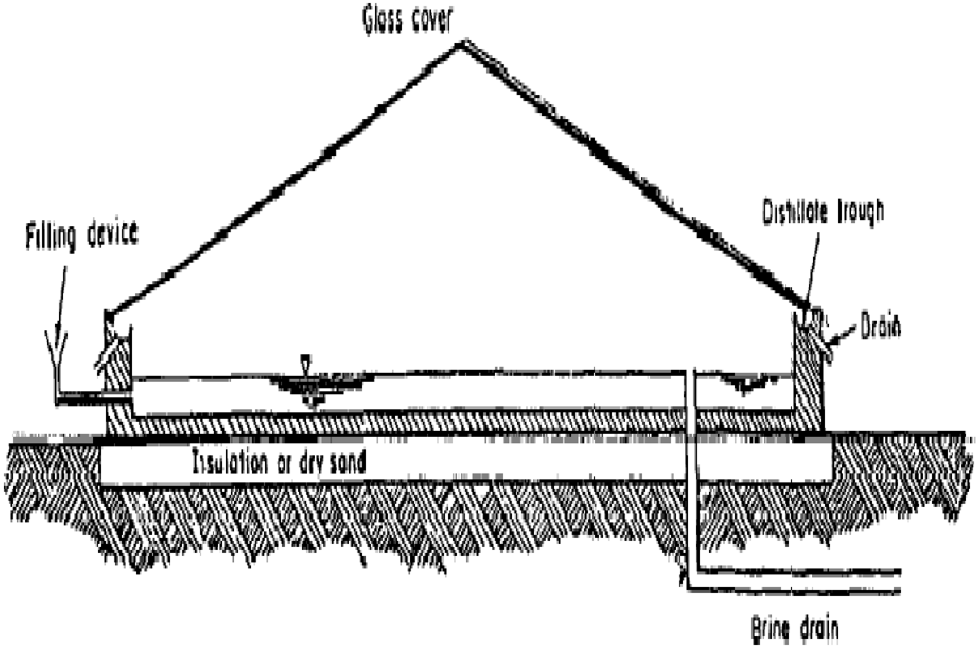
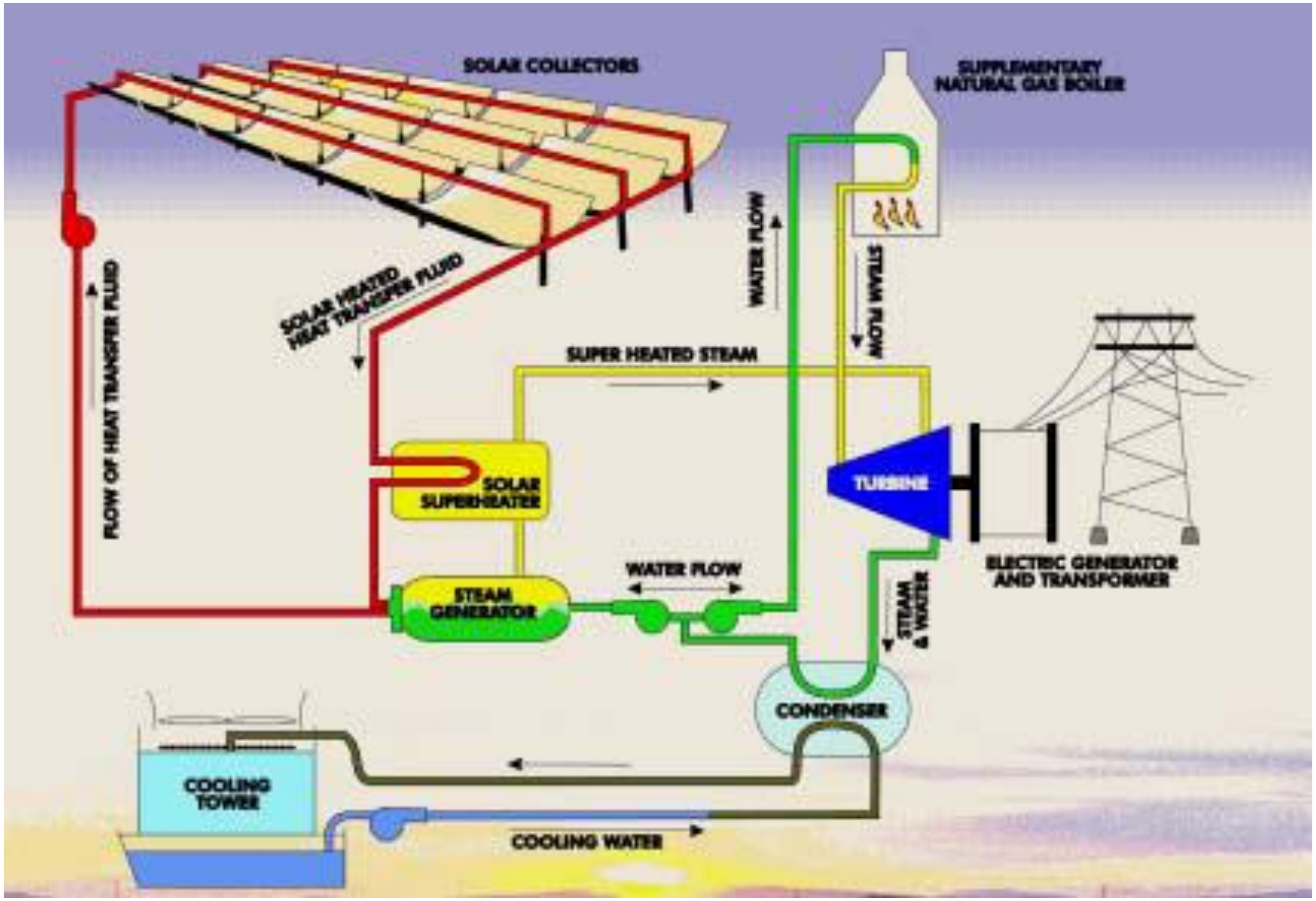


Figure: Basic solar still for seawater desalination.

Solar thermal electricity

- Concentrating solar power plants produce electric power by converting the sun's energy into high-temperature heat using various mirror configurations.
- The heat is then channeled through a conventional generator.
- The plants consist of two parts: one that collects solar energy and converts it to heat, and another that converts heat energy to electricity.
- Some systems use thermal storage during cloudy periods or at night. Others can be combined with natural gas and the resulting hybrid power plants.
- Concentrating solar power systems can be sized for village power (10 kilowatts) or grid-connected applications (up to 100 megawatts).

Trough CSP


SOLAR COLLECTORS
SUPPLEMENTARY NATURAL GAS BOILER
SOLAR HEATED HEAT TRANSFER FLUID
FLOW OF HEAT TRANSFER FLUID
WATER FLOW
STEAM FLOW
SUPER HEATED STEAM
SOLAR SUPERHEATER
TURBINE
STEAM GENERATOR
WATER FLOW
STEAM & WATER
ELECTRIC GENERATOR AND TRANSFORMER
CONDENSER
COOLING TOWER
COOLING WATER

Solar water disinfection

- Solar water disinfection, also known as SODIS, is a simple method of disinfecting water using only sunlight and plastic PET bottles.
- SODIS is a cheap and effective method for decentralized water treatment, usually applied at the household level and is recommended by the World Health Organization as a viable method for household water treatment and safe storage.

Solar cookers

- The simplest type of solar cooker is the box cooker.
- A basic box cooker consists of an insulated container with a transparent lid.
- These cookers can be used effectively with partially overcast skies and will typically reach temperatures of 50-100 °C.

End of non –reactive energy resources.