# MECH 1905 Buildings for Contemporary Living

# Renewable Energy for Buildings

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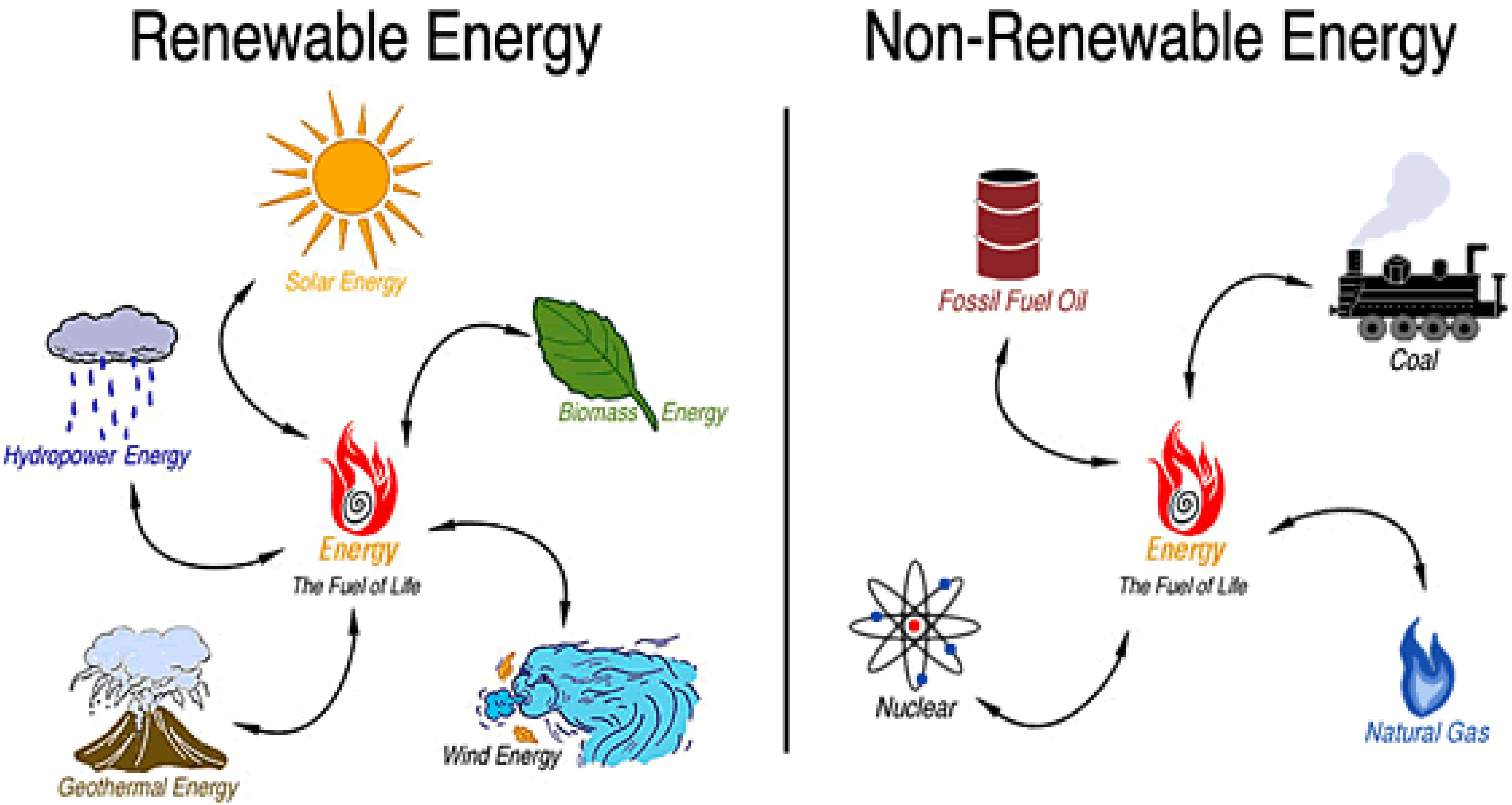
# Outline

- Introduction
- Energy from the Sun
- Solar Thermal Power
- Solar Photovoltaic Power
- Wind Energy Sources
- Wind Power Generators
- Geothermal Heat Pump
- Remarks

# Renewable Energy
# *vs.*
# Non-Renewable Energy



# Renewable Energy

- Renewable energy refers to energy resources that occur naturally and repeatedly in the environments and can be harnessed for human benefit.
- Examples of renewable energy systems include solar, wind, geothermal energy (getting energy from the heat in the earth), as well as biomass such as trees and plants, even garbage, along with other natural resources such as hydro power including rivers and dams, tides and waves, plus ocean thermal energy.
- Renewable energy encompasses many different types of technology at different stages of development and commercialization, from the burning of wood for heat in the residential sector (traditional and low-technology) to wind-generated electricity (widespread and technically proven) to processes such as biomass gasification for electricity generation (still under development although some plants are operating).
- Renewable energy is generally considered as environmentally friendly, thus earning its name as sustainable meaning not expected to be depleted in a timeframe relevant to the human race.

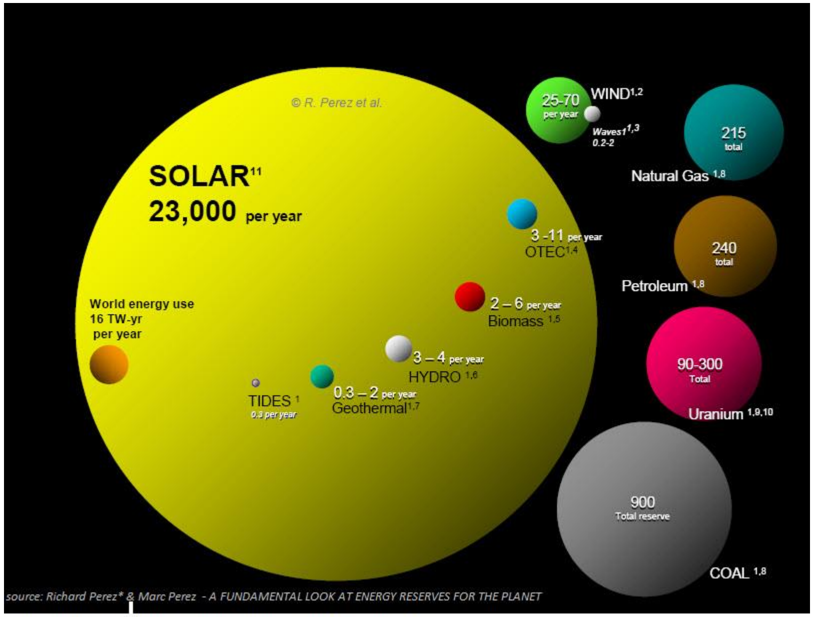
# Modern Sources of Renewable Energy

- Solar
  - *thermal **
  - *photovoltaic **
  - thermal power generation, solar updraft tower, etc.
- Wind
  - *electricity generation **
  - mechanical energy application
- Water
  - hydroelectric power
  - tidal power
  - wave energy
  - ocean thermal energy conversion (OTEC)
- Geothermal
  - electricity
  - *heating or cooling through long earth pipes or heat pipes **
- Biomass
  - solid fuels such as wood or solid waste
  - liquid biofuels such as alcohols from fermentation of vegetations
  - biogas
    - anaerobic digestion
    - direct gasification of biomass solids

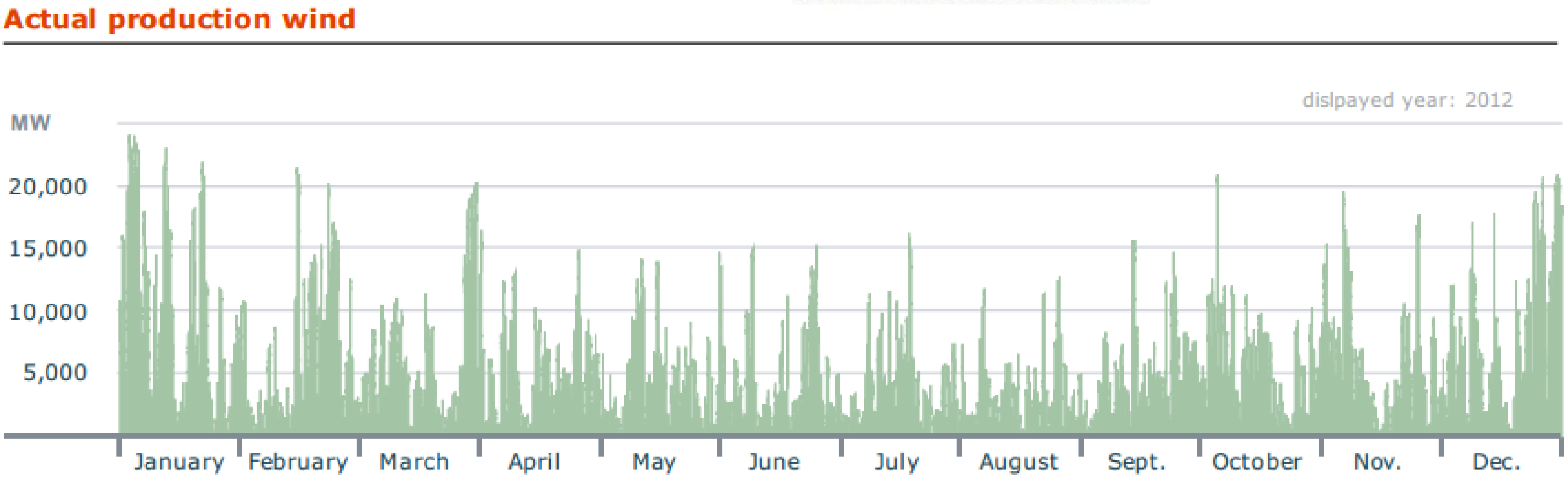
** suitable power sources for buildings*

# Limitation of Renewable Energy

- Low energy/power density
  - need large area to install
- Intermittent availability
  - no sunlight at night/cloud
  - no wind *vs.* typhoon
- Unreliable sources
  - climate change
- Expensive
- Technology intensive
- Supplementary system needed




Comparing finite and renewale planetary energy reserves )Terawatt-years).
Total recoverable reserves are shown for the finate resources.



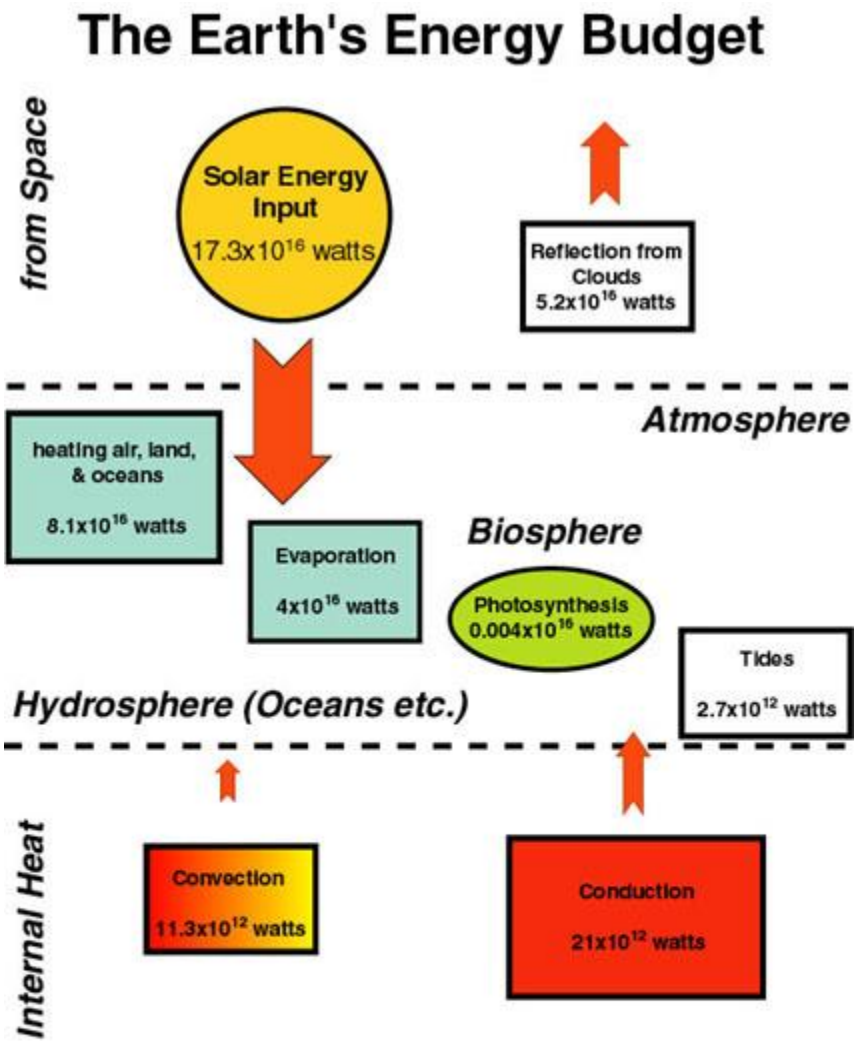
# Capacity Factor of Power Plants

- The net **capacity factor** of a power plant is the ratio of the actual output of a power plant over a period of time and its potential output if it had operated at full nameplate capacity the entire time.

$$\textit{Capacity Factor} = \frac{\textit{actual energy output of a power plant over a period of time}}{\textit{potential energy output operated at full nameplate capacity the entire time}}$$

- To calculate the capacity factor, take the total amount of energy the plant produced during a period of time and divide by the amount of energy the plant would have produced at full capacity.
- Capacity factors vary greatly depending on the type of fuel that is used and the design of the plant.
  - Wind farms 20-40%.
  - Photovoltaic solar in Massachusetts 12-15%.
  - Photovoltaic solar in Arizona 19%.
  - Hydroelectricity, worldwide average 44% (range of 20% - 75% depending on water availability).
  - Nuclear energy 91.2% (2010 average of USA's plants).

# Energy from the Sun




- **Gravitational Potential Energy** (falling rain gains kinetic energy from its gravitational potential, water flowing down from mountains)
- **Thermal Energy** (input from the sun, radioactive decay, molten rocks). Transmitted by conduction, convection, radiation
- **Kinetic Energy** (meteorite impact, movement of wind and water, ocean currents)
- **Chemical Energy** (holds together atoms in molecules, the energy of the chemical bond such as photosynthesis process in plants)

# Solar Energy

- Solar radiation reaches the Earth's upper atmosphere at a rate of 1,366 watts per square meter ($W/m^2$).
- While traveling through the atmosphere, 31 percent is reflected back to space by clouds, aerosols, the Earth’s surface and atmosphere, about 20 percent is absorbed by the atmosphere and 49 percent is absorbed by the Earth’s surface then transformed to infra-red radiation (heat) and re-radiated into the atmosphere resulting in a peak irradiance at the equator of 1,020 $W/m^2$.
- Average atmospheric conditions (clouds, dust, pollution) reduce insolation by 20% through reflection and 16% through absorption.
- In addition to affecting the quantity of insolation reaching the surface, atmospheric conditions also affect the quality of insolation reaching the surface by diffusing incoming light and altering its spectrum.

# Types of Solar Power Technology

- Solar design in architecture
  - passive solar buildings
  - active solar buildings
- Solar heating systems
  - active (with pumps)
  - passive (natural convection)
- Solar cooking, fruit canning and pasteurization
- Solar lighting (daylighting)
- Photovoltaic
  - solar cells in powering small electric appliances and power generators
- Power towers
- Concentrating collector with steam engine
- Concentrating collector with Stirling engine
- Solar updraft tower
- Solar pond
  - three layers of different salt concentration to prevent heat loss from natural convection
- Solar chemical such as photoelectrolysis
- Biofuels
  - oil in plant seeds
  - alcohols from fermentation

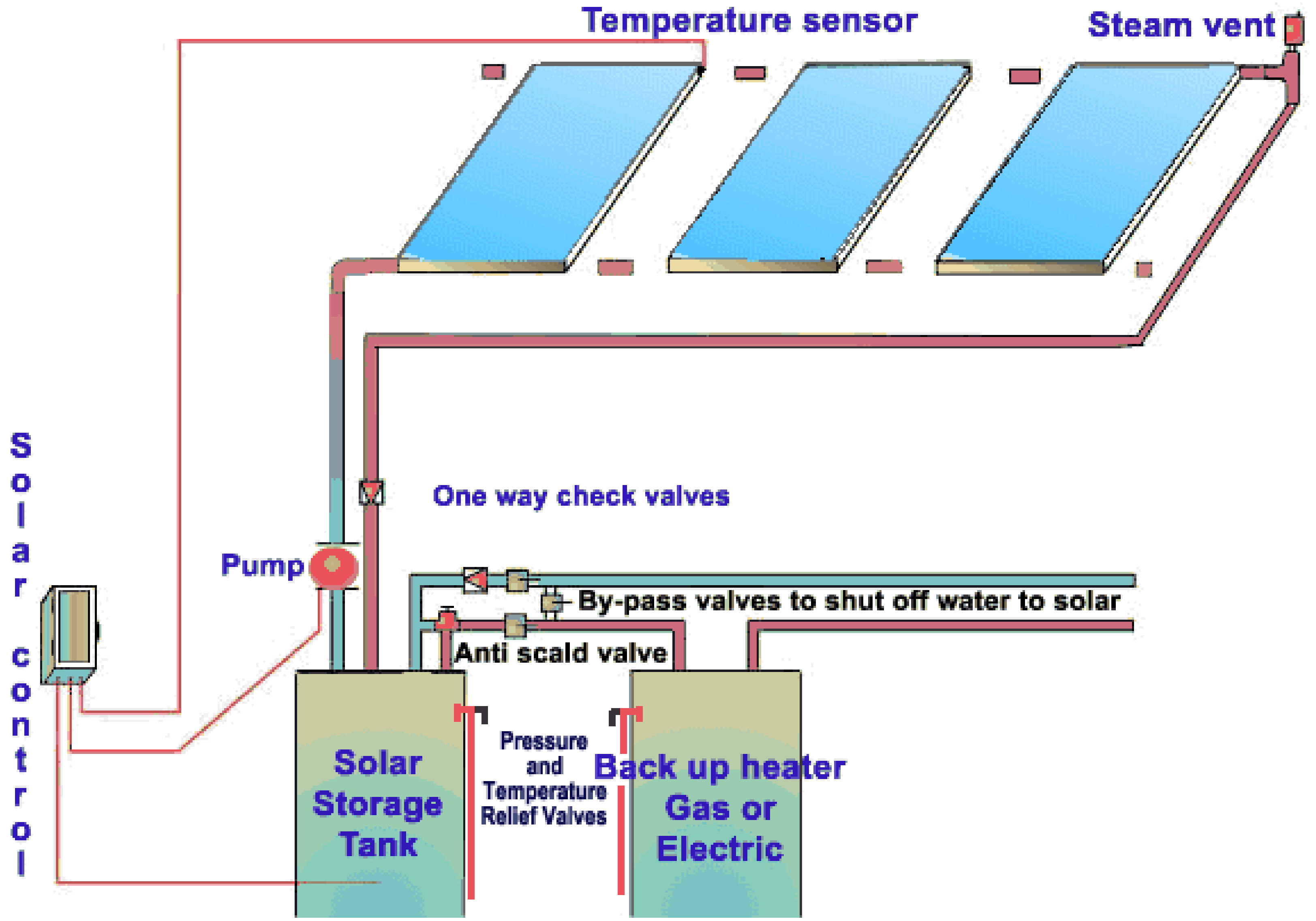
# Solar Heating Systems

- Solar heating systems are generally composed of solar thermal collectors, a fluid system to move the heat from the collector to its point of usage, and a reservoir to stock the heat for subsequent use.
- The systems may be used to heat domestic hot water or a swimming pool, or to provide heat for a heating circuit.
- The heat can also be used for industrial applications or as an energy input for other uses such as cooling equipment.
- In many climates, a solar heating system can provide a very high percentage (50 to 75%) of domestic hot water energy. In many northern European countries, combined hot water and space heating systems are used to provide 15 to 25% of home heating energy.
- Residential solar thermal installations can be subdivided in two kind of systems: compact and pumped systems. Both typically include an auxiliary energy source (electric heating element or connection to a gas or fuel oil central heating system) that is activated when the water in the tank falls below a minimum temperature setting such as 50 °C. Hence, hot water is always available.

# Solar Thermal Conversion Applications

- solar water heater
  - drinking water supply, shower/bath, dishwasher
- solar air heater
  - space heating
- greenhouse
  - temperature and humidity control
- evaporator
  - fruit juice concentration, seawater desalination
- solar cooking
  - food preparation
- stove
  - solar heater
- solar thermal cooling
  - heat source for chemical adsorption chillers
- desiccation
  - food preservation and detoxification
- thermal engine
  - liquid evaporation for mechanical work
- thermal power plant
  - electric power generation

# Solar Water Heating for Homes

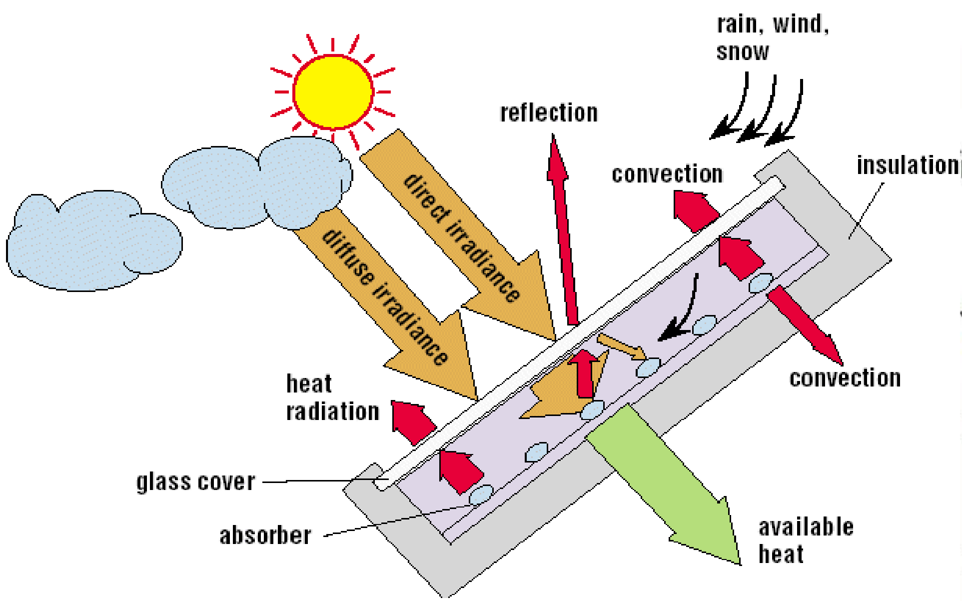


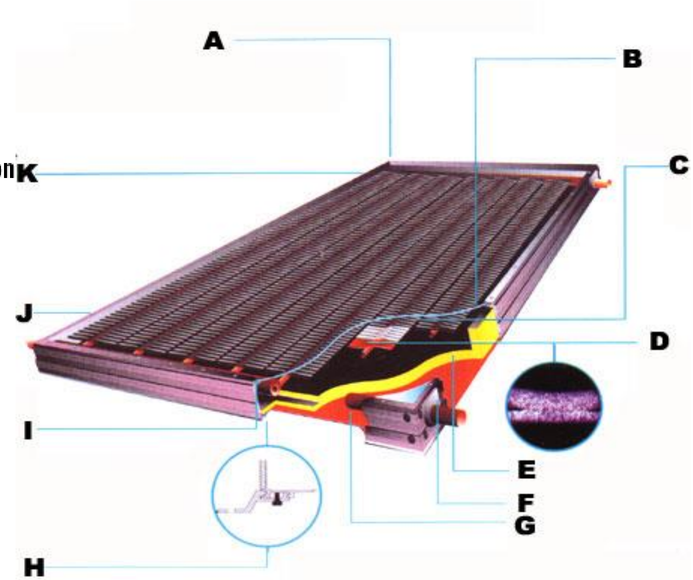
# Solar Hot Water Panel

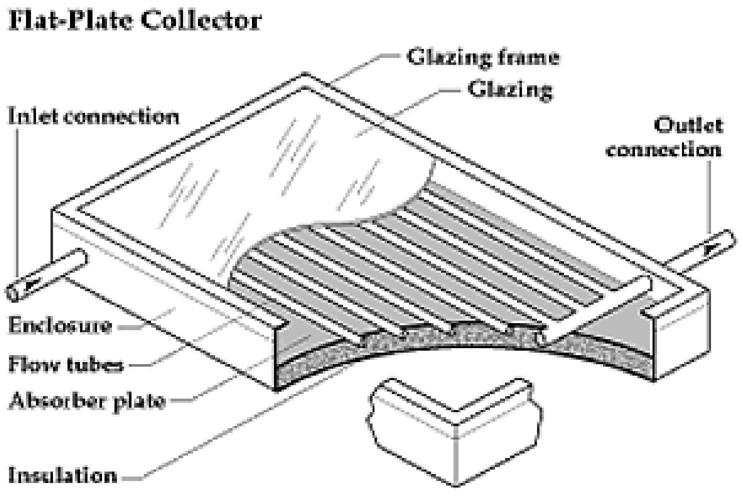

# Solar Thermal Collector

- *Flat plate collectors* are typically used in domestic and light industry applications.
- An insulated box containing a black metal sheet with built in pipes is placed in sun with an over head water tank.
- Solar energy heats up water in the pipes and it circulates through the tank automatically by convection.
- These panels generally consist of
  - a flat-plate absorber, which intercepts and absorbs the solar energy,
  - a transparent covers that allows solar energy to pass through but reduces heat loss from the absorber,
  - a heat-transport fluid (air or water) flowing through tubes to remove heat from the absorber, and
  - a heat insulating backing.

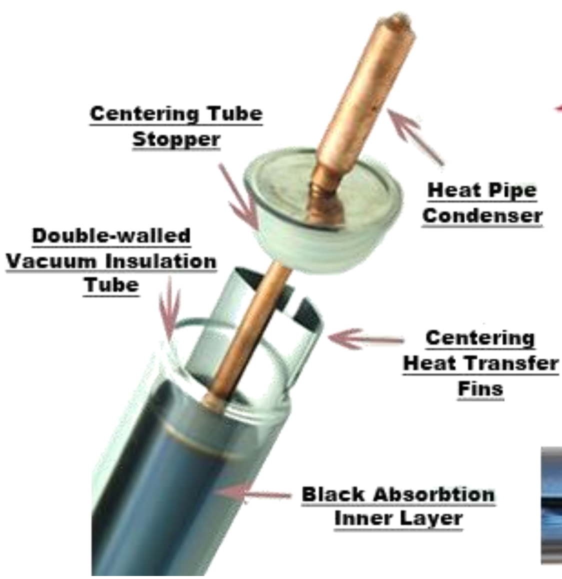
# Flat Plate Collectors

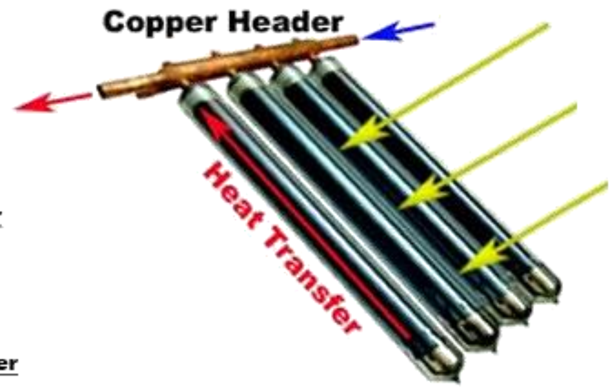


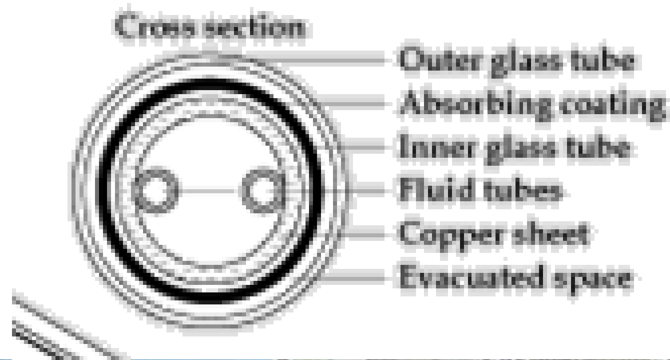



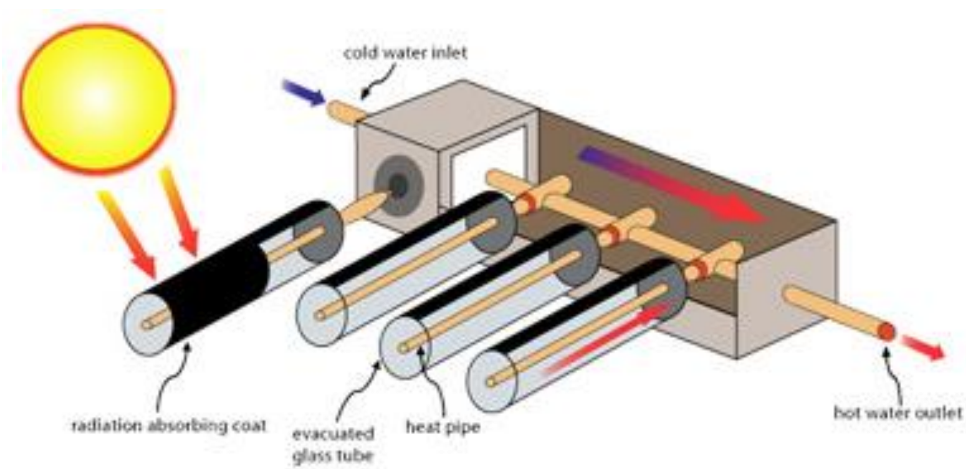

# Evacuated Tube Collectors



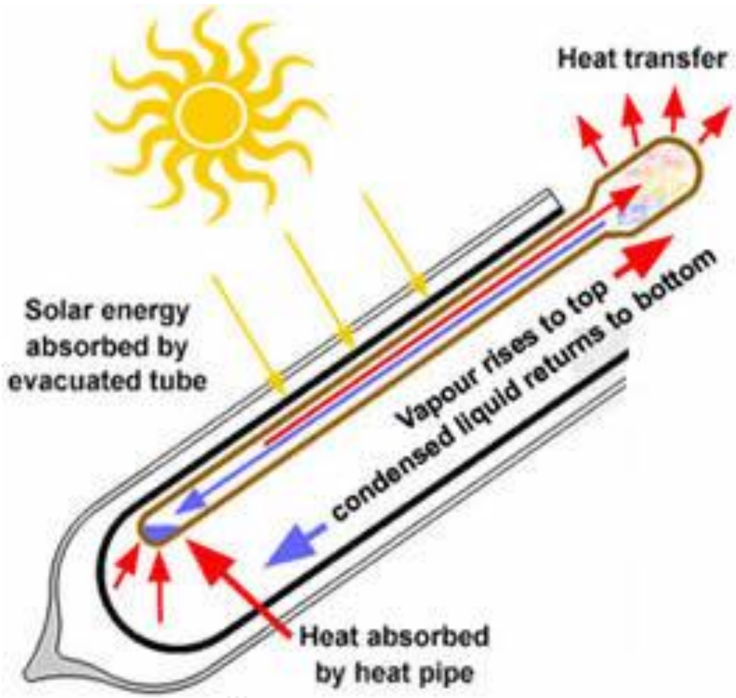



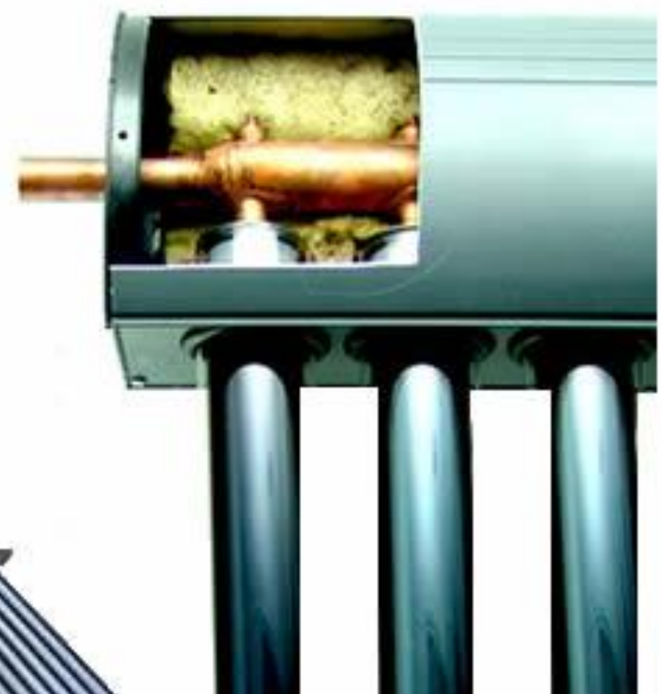





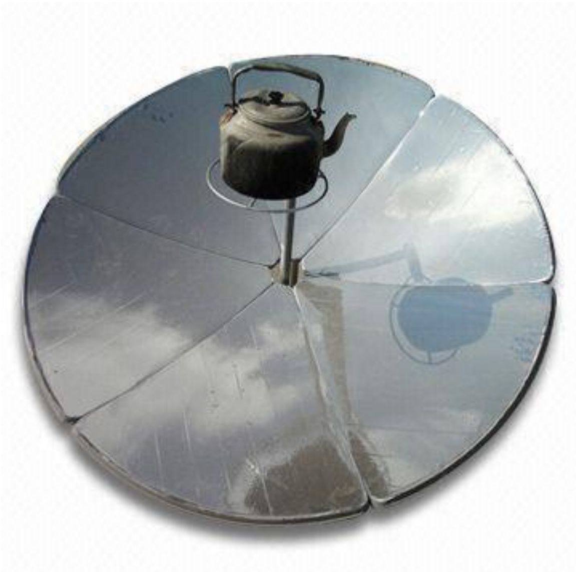


- *Evacuated tube collectors* are made of a series of modular tubes, mounted in parallel, whose number can be added to or reduced as hot water delivery needs change.



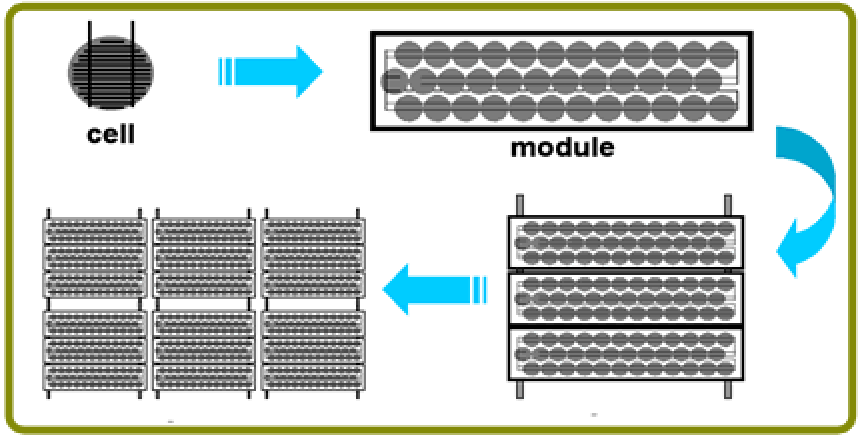
# Solar Cooker

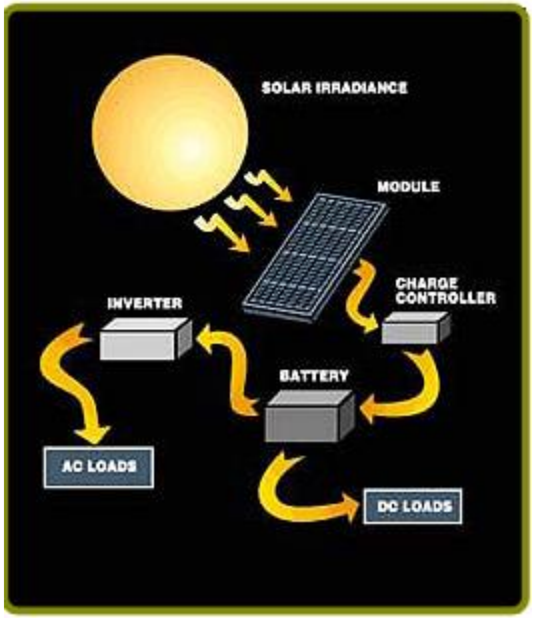


# Solar Food Dryer

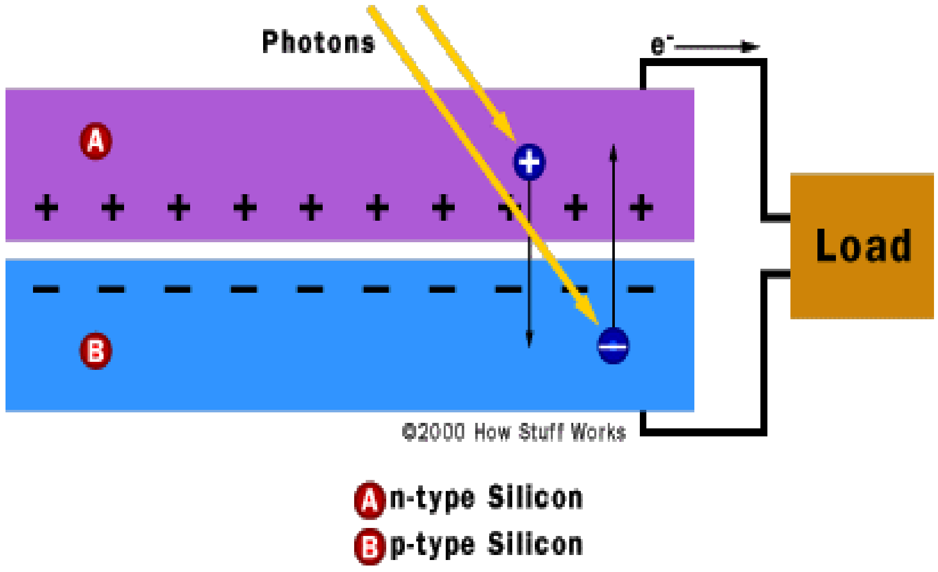
# Overview of Photovoltaic Principles

1. Photons in sunlight hit the solar panel and are absorbed by semi-conducting materials, such as silicon.
2. Electrons (negatively charged) are knocked loose from their atoms, allowing them to flow through the material to produce electricity. The complementary positive charges that are also created (like bubbles) are called holes and flow in the direction opposite of the electrons in a silicon solar panel.
3. An array of solar panels converts solar energy into a usable amount of direct current (DC) electricity.

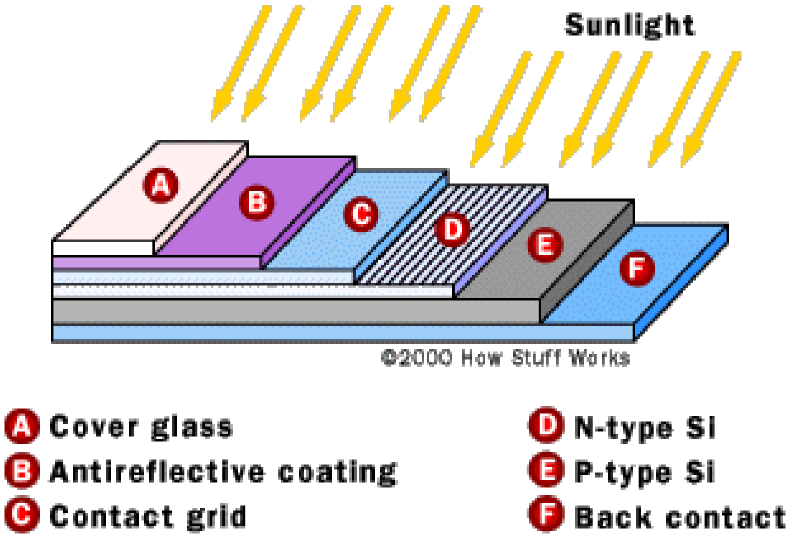


# Schematic of Power Generation by p-n Junction of Solar Cells




**Operation of a PV cell**

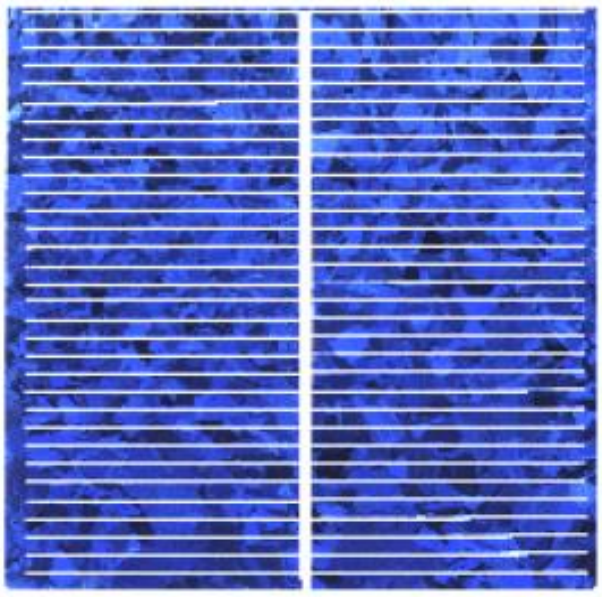



**Basic structure of a generic silicon PV cell**

# Types of PV Cells

- Single crystal silicon is one of the material used in PV cells.
- Polycrystalline silicon is also used in an attempt to cut manufacturing costs, although resulting cells are not as efficient as single crystal silicon.
- Amorphous silicon, which has no crystalline structure, is also used, again in an attempt to reduce production costs.
- Other materials used include gallium arsenide, copper indium diselenide and cadmium telluride.
- Since different materials have different band gaps, they seem to be "tuned" to different wavelengths, or photons of different energies.
- One way **efficiency** has been improved is to use two or more layers of different materials with different band gaps. The higher band gap material is on the surface, absorbing high-energy photons while allowing lower-energy photons to be absorbed by the lower band gap material beneath.
- This technique can result in much higher efficiencies. Such cells, called **multi-junction cells**, can have more than one electric field.

Mono-crystalline



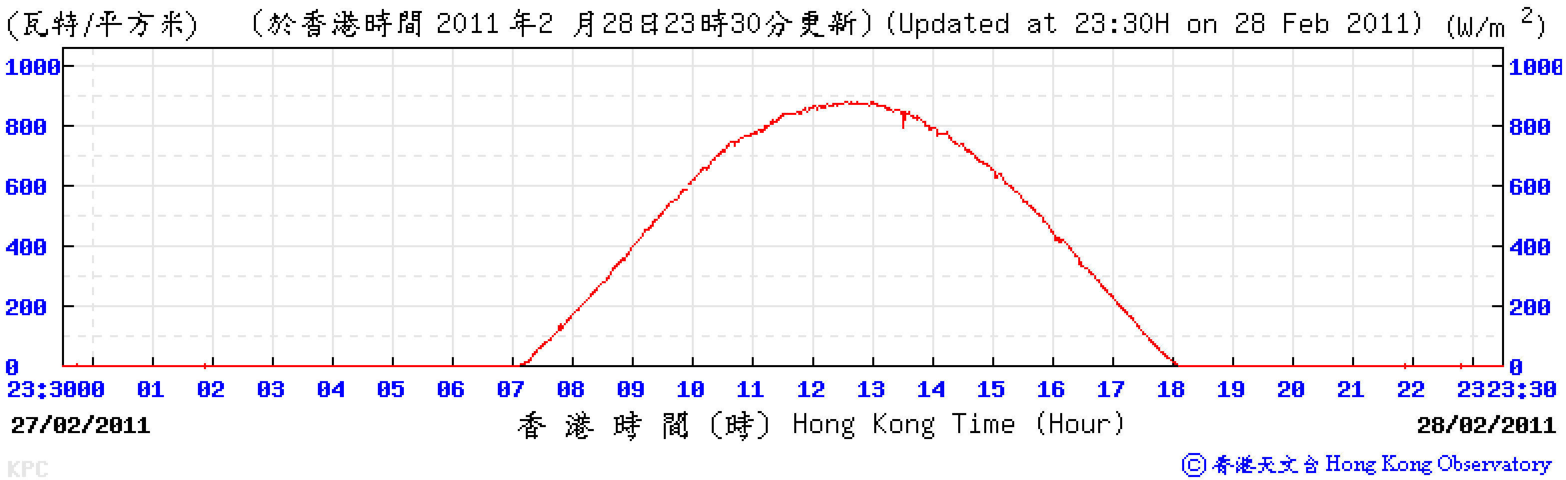
Poly-crystalline

Amorphous silicon

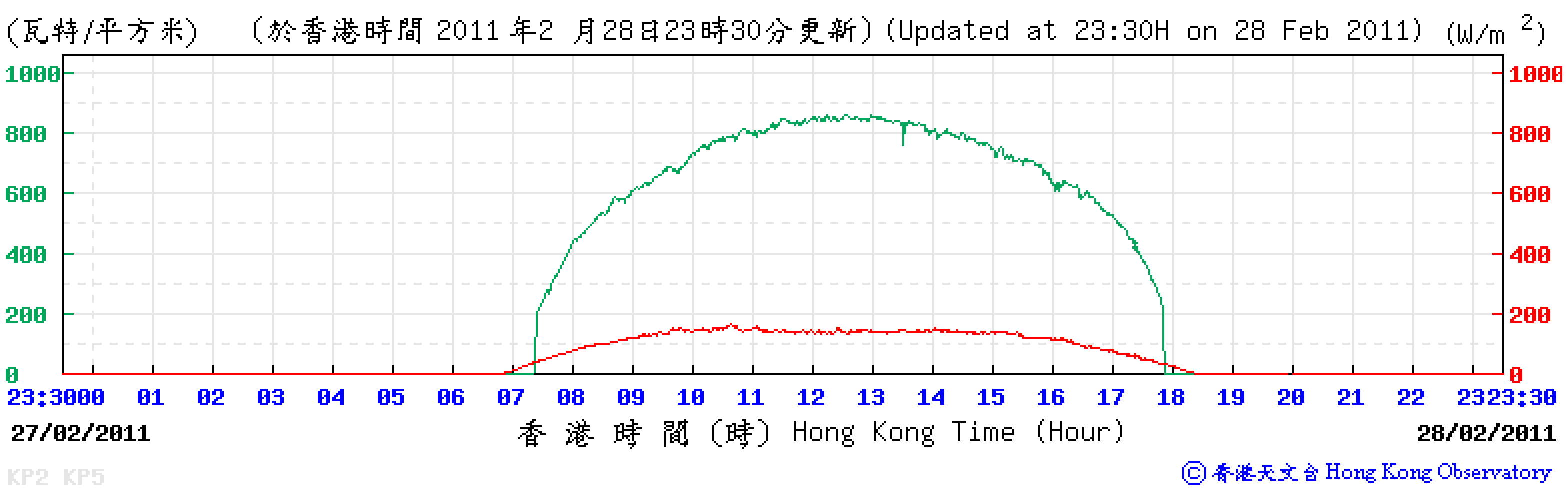
CIS copper indium selenide (**C**u**I**n**S**e2)

# Solar Radiation in a Clear Sunny Day in Hong Kong

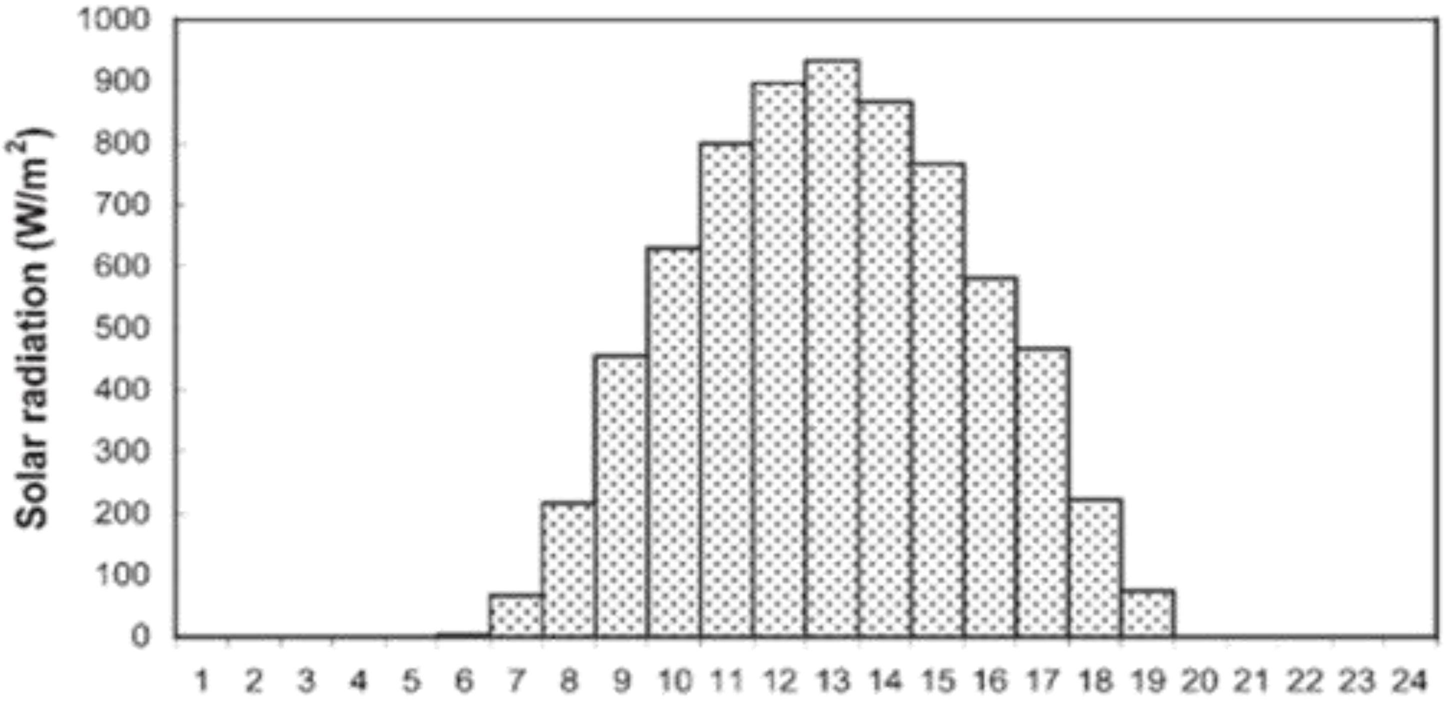
Global Solar Radiation




Direct and Diffuse Solar Radiation



# Typical Meteorological Data




Typical diurnal irradiation distribution in a sunny day in Hong Kong

# Example

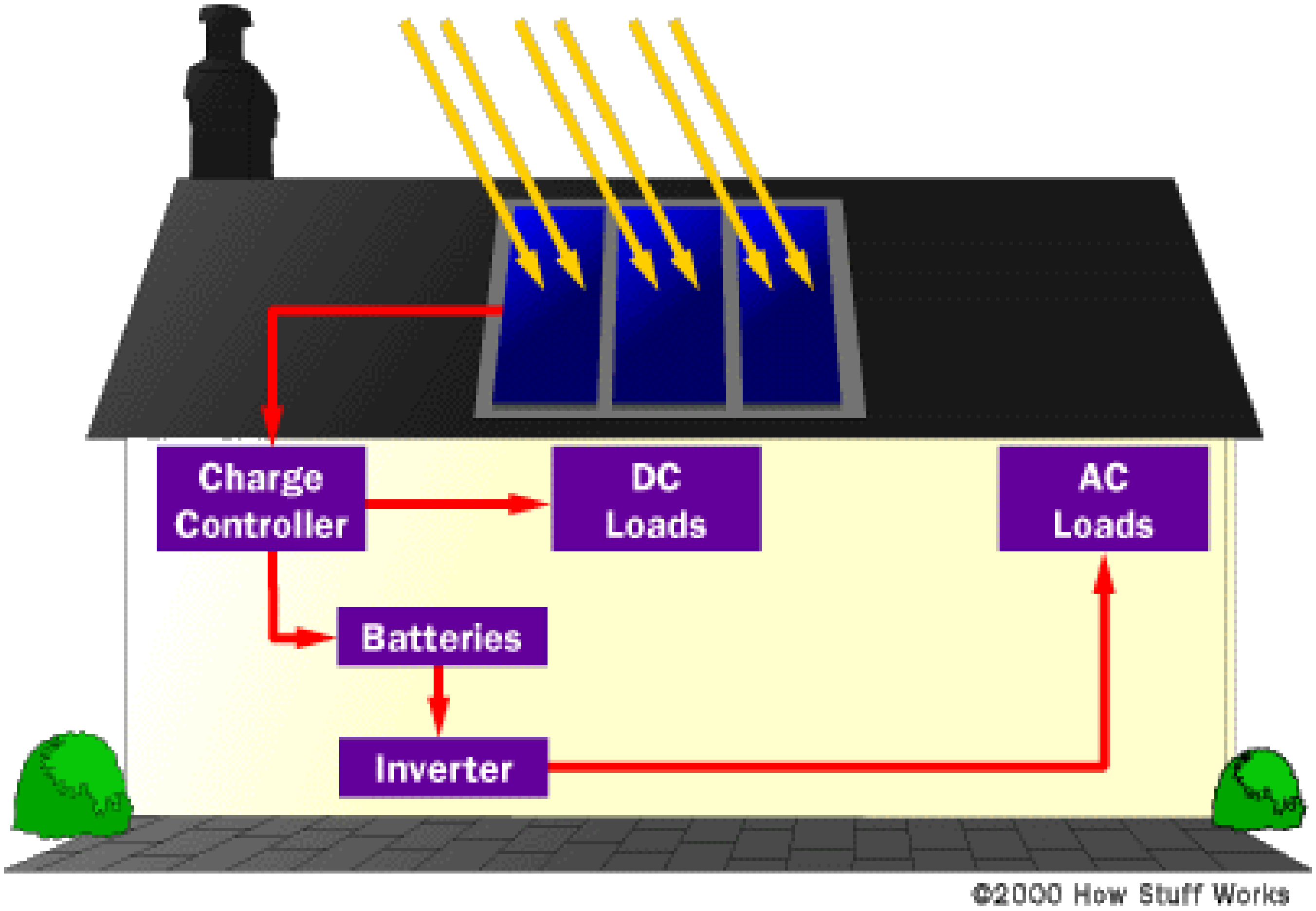
A solar panel of rated capacity of 1.0 kW (power generated under the STC radiation of 1,000 W/m$^2$) is installed in a place with a typical meteorological yearly data shown in the previous slide. Assuming the power generated by the PV panel is proportional to the solar radiation, calculate the capacity factor of this installation.

# Answer

| Time of the day | Solar Radiation W/m$^2$ | PV Power Generated Watts | PV Energy Generated kWh |
|---|---|---|---|
| 6:30 – 7:30 | 50 | 50 | 0.05 |
| 7:30 – 8:30 | 200 | 200 | 0.2 |
| 8:30 – 9:30 | 460 | 460 | 0.46 |
| 9:30 – 10:30 | 630 | 630 | 0.63 |
| 10:30 – 11:30 | 800 | 800 | 0.8 |
| 11:30 – 12:30 | 900 | 900 | 0.9 |
| 12:30 – 13:30 | 925 | 925 | 0.925 |
| 13:30 – 14:30 | 860 | 860 | 0.86 |
| 14:30 – 15:30 | 780 | 780 | 0.78 |
| 15:30 – 16:30 | 590 | 590 | 0.59 |
| 16:30 – 17:30 | 470 | 470 | 0.47 |
| 17:30 – 18:30 | 210 | 210 | 0.21 |
| 18:30 – 19:30 | 80 | 80 | 0.08 |

- The total quantity of electricity generated is 6.955 kWh in a period of 24 hours.
- For the same period of 24 hours, the potential output operated at full nameplate capacity is 1 kW x 24 hours = 24 kWh
- Hence, the capacity factor of this installation is 6.955 kWh/24 kWh = 28.98 %

# Powering a House by Photovoltaic Energy




**General schematic of a residential PV system with battery storage**

# Building Integrated PV (BiPV)

THE CHURCH OF CHRIST IN CHINA KEI WAI PRIMARY SCHOOL (MA WAN)

# Solar Cells and Energy Payback

- There is a common myth that solar cells never produce more energy than it takes to make them.
- While the expected working lifetime is around 40 years, the energy payback time of a solar panel is anywhere from 1 to 30 years (usually under five) depending on the type and where it is used.
- This means solar cells can be net energy producers and can "reproduce" themselves (from just over once to more than 30 times) over their lifetime.

# Wind Sources

- An estimated 1 to 3% of energy from the Sun that hits the earth is converted into wind energy. This is about 50 to 100 times more energy than is converted into biomass by all the plants on earth through photosynthesis.
- Most of this wind energy can be found at high altitudes where continuous wind speeds of over 160 km/h (100 mph) occur.
- Eventually, the wind energy is converted through friction into diffuse heat all through the earth's surface and atmosphere.
- The earth is unevenly heated by the sun resulting in the poles receiving less energy from the sun than the equator does, and the dry land heats up (and cools down) more quickly than the seas do.
- The differential heating powers a global atmospheric convection system reaching from the earth's surface to the stratosphere which acts as a virtual ceiling.

# Power in the Wind

- The amount of energy in the wind is a function of its speed and mass in the form of kinetic energy
- Kinetic energy (K.E.) = $\frac{1}{2} mv^2$
- The air mass can be derived from the product of its density ($\rho$) and its volume.  Because the air is constantly in motion, the volume must be found by multiplying the wind's speed (v) by the area (A) through which it passes during a given period of time (t)
- Hence, the wind energy = $\frac{1}{2} \rho Avtv^2 = \frac{1}{2} \rho Atv^3$
- Since power is the rate at which energy passes through an area per unit of time
- Therefore, power $P = \frac{1}{2} \rho Av^3$ meaning the power in the wind is proportional to cubic power of wind velocity

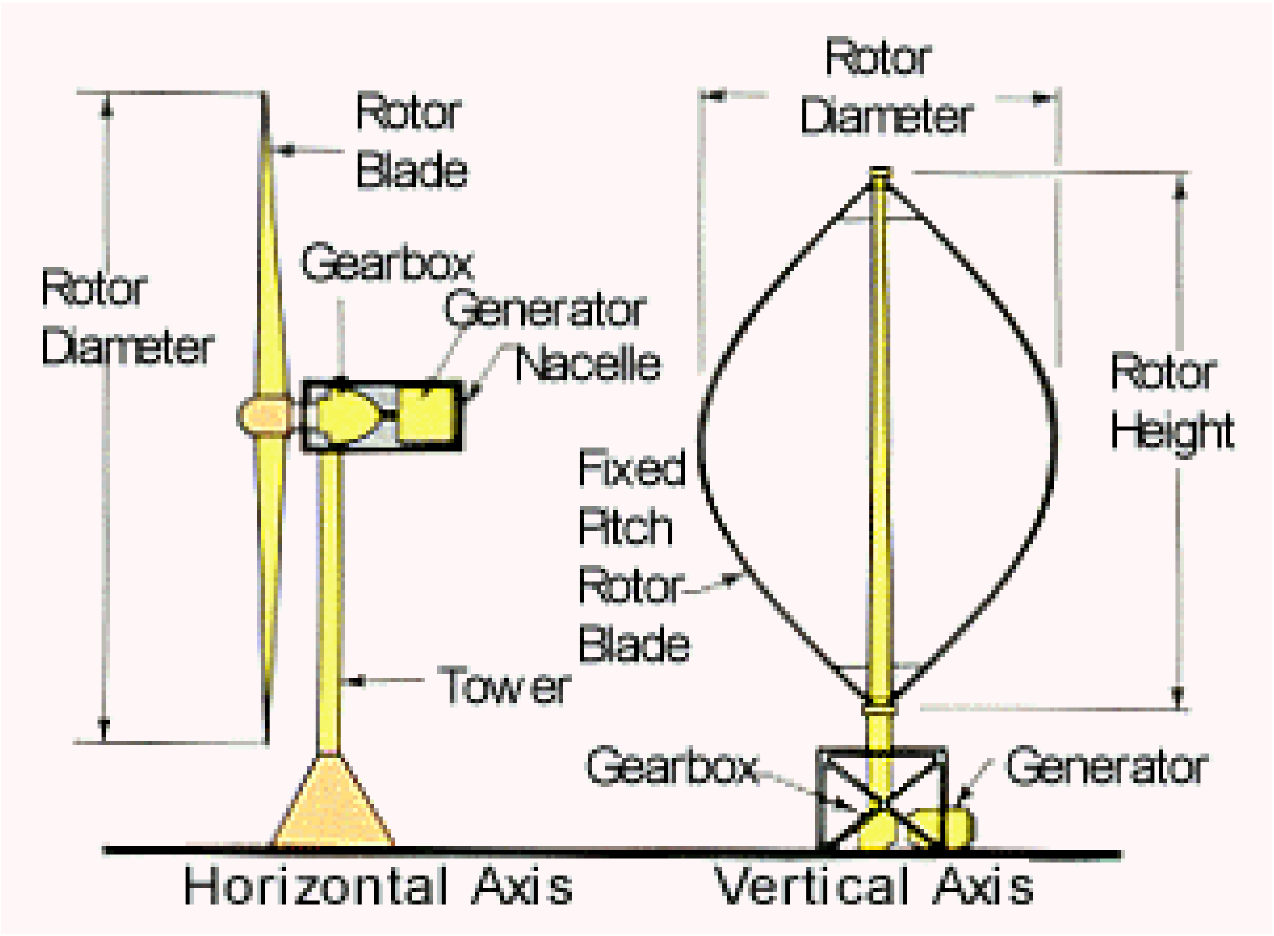
# Wind Turbines

- A wind turbine is a machine for converting the kinetic energy in wind into mechanical energy.
- If the mechanical energy is used directly by machinery, such as a pump or grinding stones, the machine is usually called a windmill.
- If the mechanical energy is then converted to electricity, the machine is called a wind generator.
- Wind turbines can be divided into two general types based on the axis about which the turbine rotates. Turbines that rotate around a horizontal axis are more common than the vertical axis turbines.
- Wind turbines may also be used in conjunction with a solar collector to extract the energy due to air heated by the Sun and rising through a large vertical Solar updraft tower.

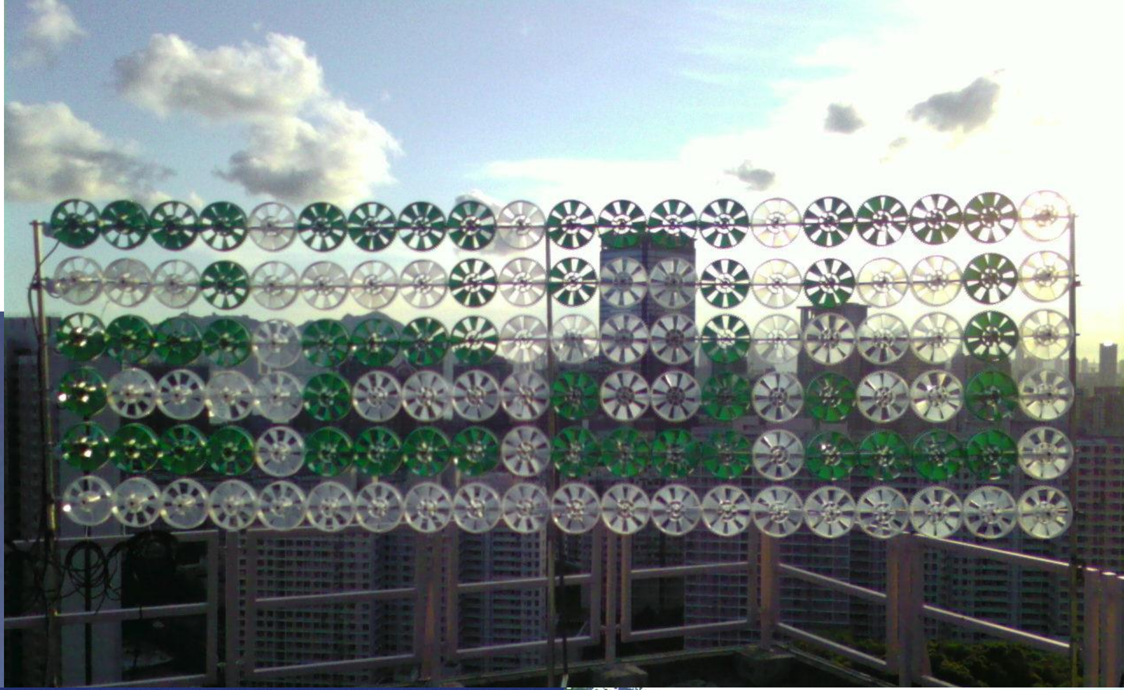
# Small Scaled Wind Power Generators

- Wind turbines have been used for household electricity generation in conjunction with battery storage over many decades in remote areas.
- To compensate for the varying power output, grid-connected wind turbines may utilize some sort of grid energy storage. Off-grid systems either adapt to intermittent power or use photovoltaic or diesel systems to supplement the wind turbine.
- In urban locations, where it is difficult to obtain large amounts of wind energy, smaller systems may still be used to run low power equipment.
- Distributed power from rooftop mounted wind turbines can also alleviate power distribution problems, as well as provide resilience to power failures.
- Equipment such as parking meters or wireless internet gateways may be powered by a wind turbine that charges a small battery, replacing the need for a connection to the power grid and/or maintaining service despite possible power grid failures.

# Configurations of Wind Turbines



# Horizontal Axis Wind Turbine



# Vertical Axis Wind Turbine


# Power from Wind Turbine

- For a wind turbine with diameter D

$$A = \frac{\pi D^2}{4}$$

- Kinetic energy

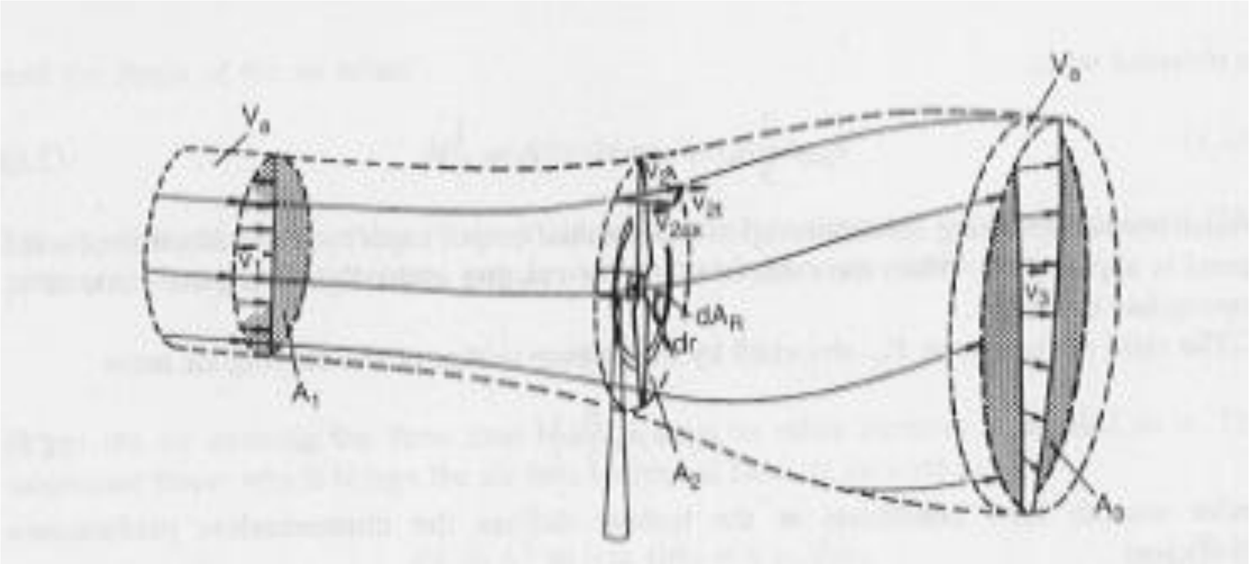
$$K.E. = \frac{1}{2} \rho \frac{\pi D^2}{4} t v^3 = \frac{\rho \pi D^2 t v^3}{8}$$

- Power

$$P_w = \frac{\rho \pi D^2 v^3}{8}$$

- Hence, both power and energy are proportional to the square of the diameter of the wind turbine and the cube of wind velocity blowing on it.

# Maximum Power of Wind Turbine




- Assumptions :
  1. no friction loss during blade operations
  2. complete air flow pattern separating air streams between the turbines and outer layer
  3. static pressure in upstream and downstream of the wind turbine not affected, equals to pressure far away ($P_2 = P_\infty$)
  4. even distribution of wind force on the blades
  5. no swirls in the air flow of the wind turbine

- Momentum balance between the front and back of turbine

$$F = \dot{m}\,(v_\infty - v_2) = \rho A\,U\,(v_\infty - v_2)$$

- This force comes from the pressure difference between the front and back of the turbine :

$$F = A(P^+ - P^-)$$

- Applying Bernoulli equation on the upstream of the turbine

$$\frac{1}{2}\rho v_\infty^2 + P_\infty = \frac{1}{2}\rho\,U^2 + P^+$$

- Similarly on the downstream of the turbine

$$\frac{1}{2}\rho v_2^2 + P_\infty = \frac{1}{2}\rho\,U^2 + P^-$$

- Subtracting the above equations from one another gives

$$P^+ - P^- = \frac{1}{2}\rho\,(v_\infty^2 - v_2^2)$$

- Substitute back into the previous equation gives

$$F = \frac{1}{2}\rho\, A\,(v_\infty^2 - v_2^2)$$

- Rearranging gives

$$F \;=\; \frac{1}{2}\rho A(v_\infty^2 - v_2^2) = \rho AU(v_\infty - v_2)$$

- Hence

$$U = \frac{(v_\infty + v_2)}{2}$$

- That is to say the wind speed through the wind turbine is the average between wind speed in upstream and downstream of the turbine, and

$$P^+ - P^- = \frac{1}{2}\rho(v_\infty^2 - v_2^2)$$

- Introducing an axial induction factor $a$ defined as :

$$U \equiv v_{\infty}(1-a)$$

- Hence

$$v_{\infty}(1-a) = \frac{v_{\infty} + v_2}{2}$$

- Therefore the wind speed downstream of the turbine

$$v_2 = v_{\infty}(1-2a)$$

- And

$$a = 1 - \frac{v_{\infty} + v_2}{2\, v_{\infty}}$$

- Therefore, if the blade can absorb all wind energy acted upon on, i.e. $v_2 = 0$, the maximum value of $a = 1/2$.

- Since power from the turbine equals to the mass of air times the change of its kinetic energy

$$P_w = \rho\, A\, v\left(\frac{v_\infty^{\ 2}}{2} - \frac{v_2^{\ 2}}{2}\right) = \frac{1}{2}\,\rho\, Av_\infty^3 \times 4a(1-a)^2 = 2\,\rho Av_\infty^3 a(1-a)^2$$

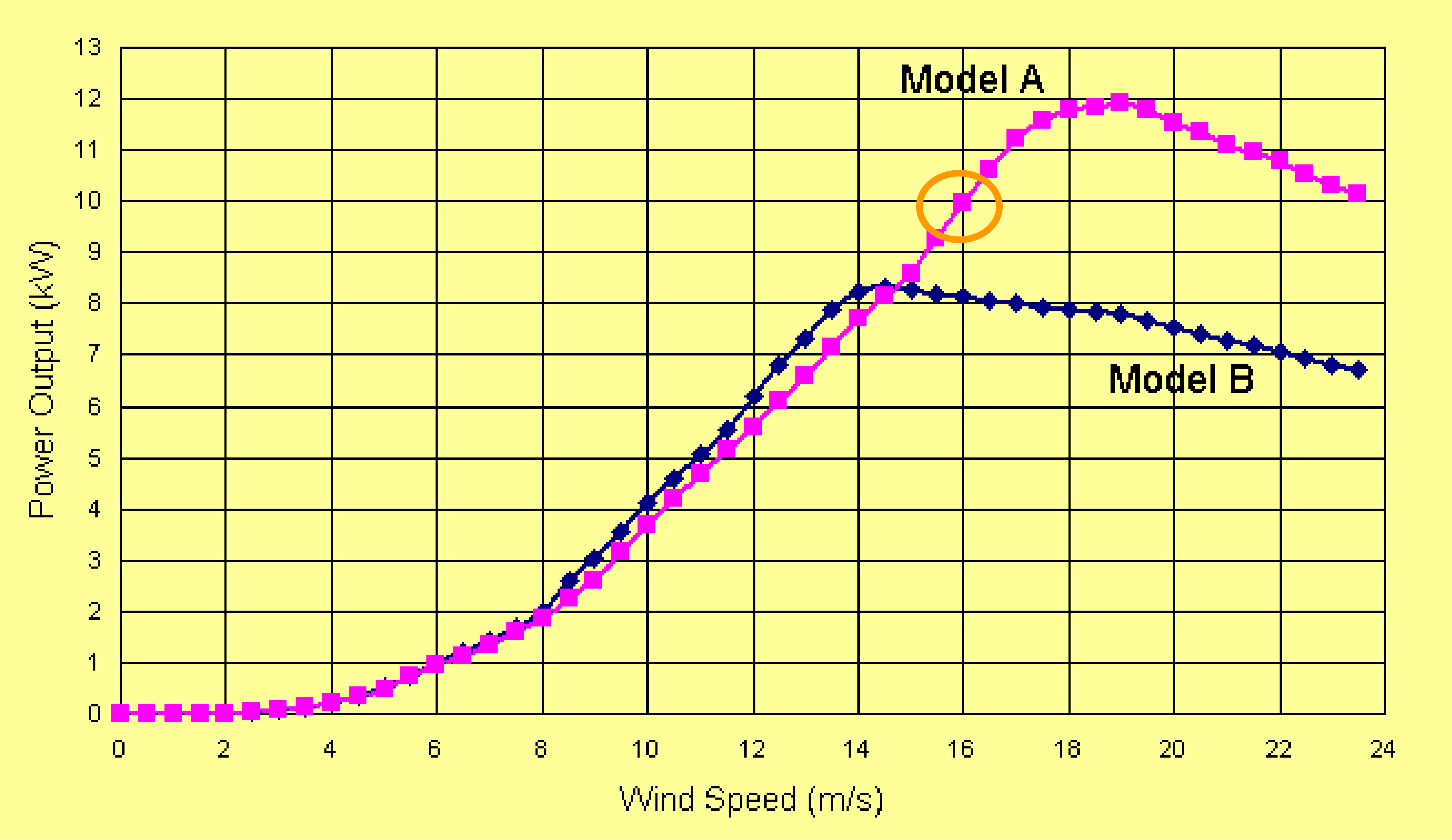
- To find out the maximum power of the wind turbine, differentiate $P_w$ with $a$ and set it to 0 gives :

$$\therefore \frac{\partial P_W}{\partial a} = 2\,\rho\, Av_\infty^3(1-4a+3a^2) = 2\,\rho\, Av_\infty^3(1-a)\,(1-3a) \;=\; 0$$

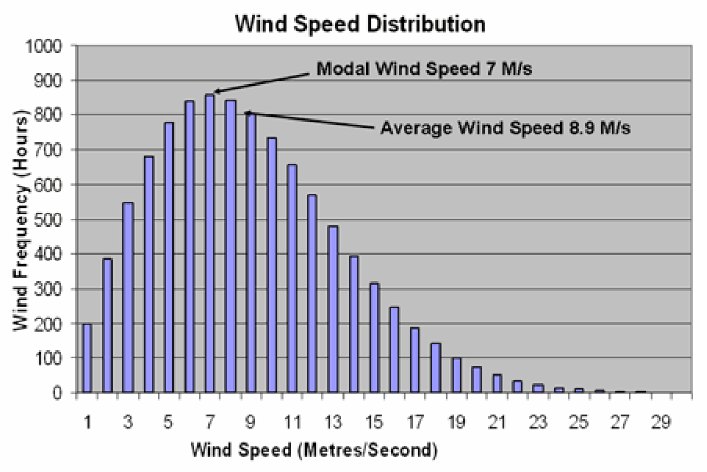
- Hence, $a$ can be 1 or 1/3. Since from above, the maximum value of $a$ is 1/2, the value of $a$ from this equation is 1/3.
- Therefore the maximum power of wind turbine is

$$P_w = \frac{16}{27}\left(\frac{1}{2}\rho\, Av_\infty^3\right)$$

# Rated Power of Wind Turbine



# Electricity Generated by Wind Turbine




- Since the wind turbine is rated as 10 kW at wind speed of 16 m/s, its power at other wind speed is proportional to the cubic power of wind speed accordingly.
- The electricity generated by this wind turbine can then be calculated by summing up the power of the wind turbine times the frequency of the respective wind speed for the period.
- The wind turbine starts generating electricity when the wind speed is higher than the cut-in wind speed and stop generating electricity beyond cut-out wind speed.

Electricity generated (kWh) = $\sum$ power of the wind turbine (kW) x number of hours (hr)

# Advantages and Disadvantages of Wind Energy Systems

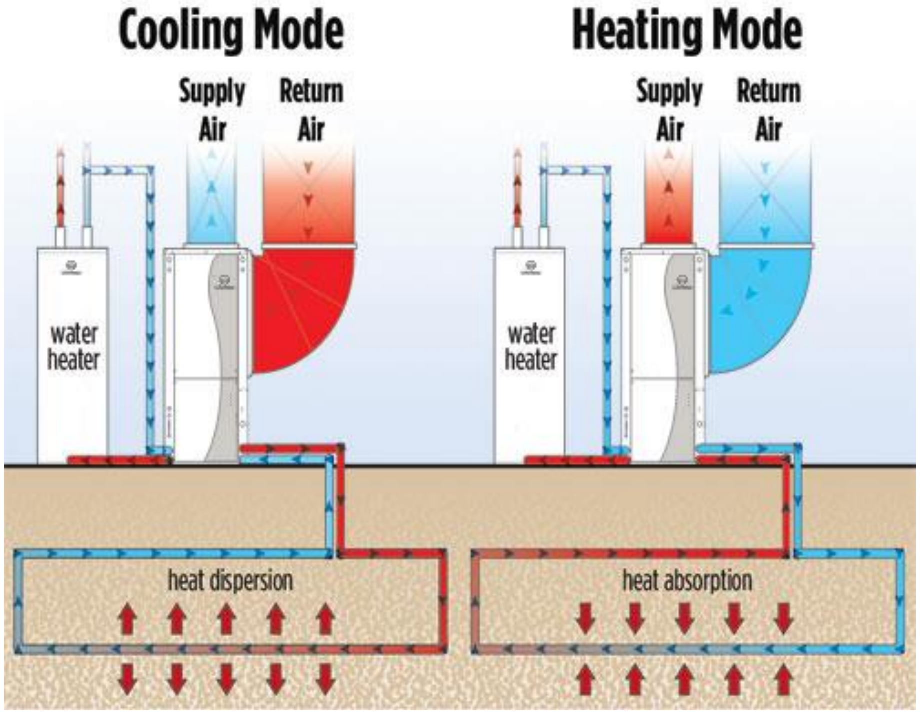
**ADVANTAGE**

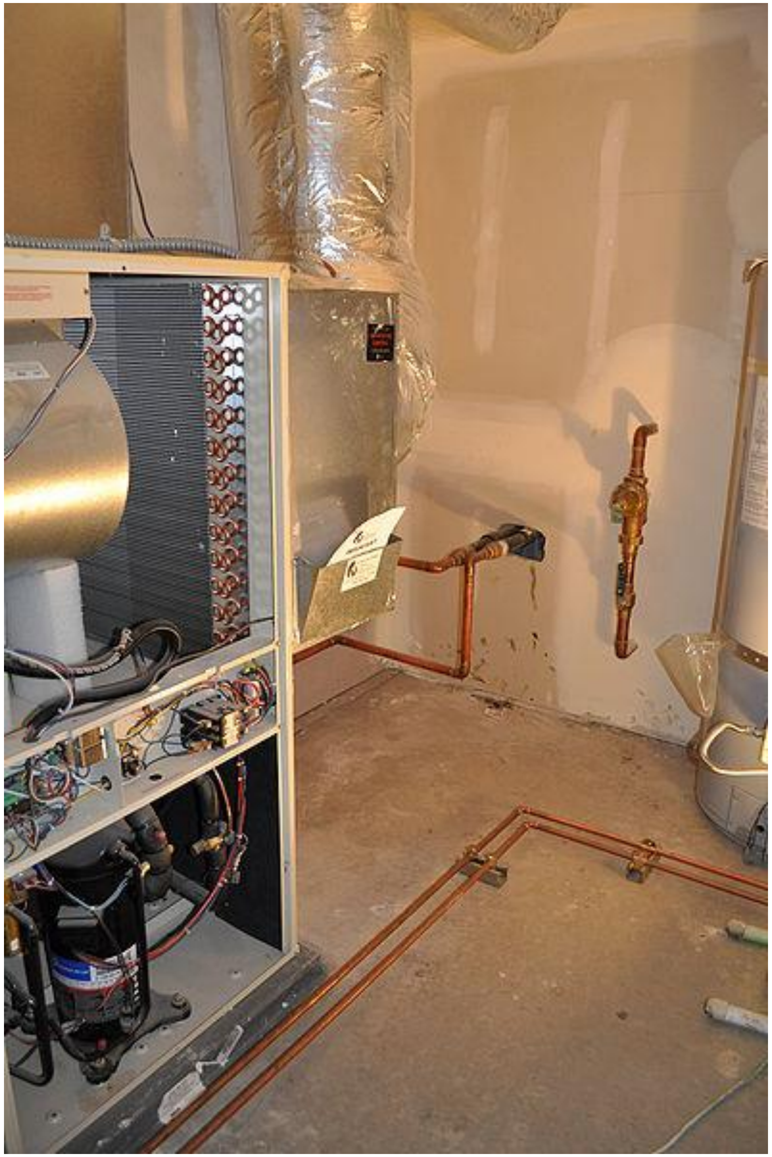
1. Free of charge
2. No greenhouse gas or other pollutants
3. Takes up only a small plot of land, the land below can still be used
4. Wind farms as an interesting feature of the landscape
5. Power for remote areas without grid
6. Relatively simple technology available for developing countries
7. Available in various ranges of power

**DISADVANTAGE**

1. Intermittent availability and power supply not steady
2. Controversial landscape as wind farm is not natural
3. Noisy operations
4. Large wind turbines as unsightly structures and not pleasant or interesting to look at.
5. Pollution associated in production process
6. Power not sufficient for big community
7. Impacts on wildlife – noise and rotating blades may kill birds

# Geothermal Heat Pump



- A **geothermal heat pump**, **ground source heat pump** (GSHP), or **ground heat pump** is a central heating and/or cooling system that pumps heat to or from the ground.
- It uses the earth as a heat source (in the winter) or a heat sink (in the summer).

# What Geothermal Heat Pump Provides

- Heating
- Cooling
- Hot water
- Sound permafrost foundations


Residential Heat Pump

*…but also…*

- Efficiency
- Decreased maintenance
- Decreased space needs
- Low operating costs

- Stable capacity
- Comfort & air quality
- Reduced peak electrical loads for air conditioning

# Advantages and Disadvantages of Geothermal Heat Pumps

**Advantages**

- Energy efficiency
- Simplicity
- Low maintenance
- Water heating
- No auxiliary heat (in most cases)
- No outdoor equipment
- Packaged equipment
- Environmentally “green”
- Lowers peak demand
- Low life-cycle cost
- Allows more architectural freedoms
- Better zone comfort control

**Disadvantages**

- First (capital) cost
  - However, incentives, energy-savings mortgages or loop-leasing are some ways of off-setting costs
- Limited qualified designers
- Geographically limited contractors
- Supply/demand => higher vendor markups

# Hybrid Systems

- Unbalanced loads over annual cycle
  - A school in a cold climate with no summer occupancy, or office/school in warm climate
- A supplemental piece of equipment (or another process) handles some of the building space load
  - Boiler
  - Solar collector array
  - Cooling tower
  - Pond or swimming pool
  - Snow melting system
  - Refrigeration load

# Good and Bad on the Use of Renewable Energy