Non-Conventional Energy Systems

Module 1: Introduction (2)

Fossil fuel based systems. Impact of fossil fuel based systems. Non-conventional energy – Seasonal variations and availability. Renewable energy – sources and features. Hybrid energy systems Distributed energy systems and dispersed generation (DG)

Module 2: Traditional Energy Systems (3)

Sources. Features and characteristics. Applications: Transport – bullock cart, horse carriage, camels; Agriculture – ox plough, water lifting devices; Human power – bicycle, cycle rickshaw etc.; House hold – cooking (bio mass), lighting etc.

Module 3: Solar Thermal Systems (6)

Solar radiation spectrum. Radiation measurement. Technologies. Applications: Heating, Cooling, Drying, Distillation, Power generation

Module 4: Solar Photovoltaic Systems (7)

Operating principles. Photovoltaic cell concepts. Cell, module, array. Series and parallel connections. Maximum power point tracking. Applications: Battery charging, Pumping, Lighting, and Peltier cooling

Module 5: Microhydel (4)

Operating principles. Components of a microhydel power plant. Types and characteristics of turbines. Selection and modification. Load balancing.

Module 6: Wind (3)

Wind patterns and wind data. Site selection. Types of windmills. Characteristics of wind generators. Load matching

Module 7: Biomass (3)

Operating principles. Combustion and fermentation. Anaerobic digester. Wood gassifier. Pyrolysis. Applications: Biogas, Wood stoves, Bio diesel, Combustion engine.

Module 8: Wave Energy Systems (3)

Shoreline systems. Near shore systems. Off shore systems

Module 9: Costing (3)

Life cycle costing (LCC). Solar thermal system LCC. Solar PV system LCC. Microhydel LCC. Wind system LCC. Biomass system LCC

Module 10: Hybrid Systems (4)

Need for Hybrid Systems. Range and type of Hybrid systems. Case studies of Diesel-PV, Wind-PV, Microhydel-PV, Biomass-Diesel systems, electric and hybrid electric vehicles

Lecture Plan

Module	Learning Units	Hours per topic	Total Hours
1. Introduction	1. Fossil fuel based systems, Impact of fossil fuel based systems, Non conventional energy – seasonal variations and availability	1	2
	2. Renewable energy – sources and features, Hybrid energy systems, Distributed energy systems and dispersed generation	1	
2. Traditional energy systems	3. Sources	1	3
	4. Features and characteristics	1	
	5. Applications	1	
3. Solar thermal systems	6. Solar radiation spectrum	0.5	6
	7. Radiation measurement	0.5	
	8. Technologies	2	
	9. Applications	3	
4. Solar Photovoltaic systems	10. Operating principle	0.5	7
	11. Photovoltaic cell concepts	0.5	
	12. Cell, module, array	0.5	
	13. Series and parallel connections	1.5	
	14. Maximum power point tracking	2	
	15. Applications	2	
5. Microhydel	16. Operating principle	1	
	17. Components of a microhydel power plant	1	
	18. Types and characteristics of turbines	1	
	19. Selection and modification	0.5	
	20. Load balancing	0.5	
6. Wind	21. Wind patterns and wind data	0.5	3
	22. Site selection	0.5	
	23. Types of wind mills	1	
	24. Characteristics of wind generators, and load matching	1	
7. Biomass	25. Operating principle	0.5	3
	26. Wood gassifier	0.5	
	27. Pyrolysis	0.5	
	28. Applications	1.5	
8. Wave Energy Systems	29. Shoreline systems	1	3
	30. Near shore systems	1	
	31. Off shore systems	1	
9. Costing	32. Life cycle costing (LCC) of solar thermal, solar PV, and microhydel systems	2	3

	33. LCC of Wind systems, and biomass systems	1	
10. Hybrid Systems	34. Need for Hybrid Systems	1	4
	35. Range and type of Hybrid systems	1	
	36. Case studies of Diesel-PV, Wind-PV, Microhydel-PV, Biomass-Diesel systems, electric and hybrid electric vehicles	2	

SYLLABUS FOR THIS CHAPTER

1. Introduction (2 hours)
    a. Fossil fuel based systems
        i. Petrol, diesel, kerosene etc.
        ii. Energy content
        iii. How long will they last?
    b. Impact of fossil fuel based systems
        i. Global warming
        ii. Green house effects
        iii. Health
        iv. Societal problems
    c. Non conventional energy – seasonal variations and availability
        i. What are they?
        ii. How much is available?
        iii. When are they available?
    d. Renewable energy – sources and features
        i. What are they
        ii. The different types of renewable energies
        iii. Sources and features table (Power and energy densities)
        iv. What are the paybacks – financial and environmental
        v. What is preferable under what conditions
    e. Hybrid energy systems
        i. Need for hybrid energy
        ii. What are the combinations for some typical applications

iii. How can it be done?

iv. What are the paybacks involved?

f. Distributed energy systems and dispersed generation (DG)

i. Need

ii. Applications scenarios

Learning Objectives of the Module

1. Recall

1.1 List the energy densities of petrol, diesel and kerosene.

1.2 What is the effect of CO_2 on environment?

1.3 List the green house gases and their relative impact on the environment.

1.4 What is global warming

2. Comprehension

2.1 Compare the various fossil fuel sources with respect to their impact on the environment

2.2 Describe the difference between the non-conventional energy and the renewable energy

3. Analysis

3.1 Analyse the impact of fossil fuels on peoples' health.

3.2 What other social problems arise out of the deteriorating environment conditions due to the over use of fossil fuels.

4. Synthesis

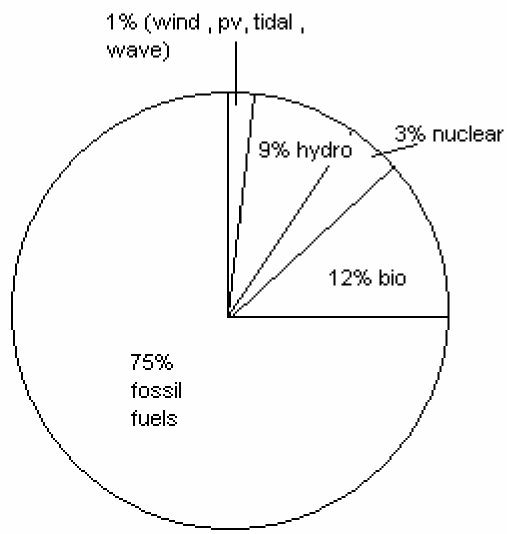
5. Evaluation

5.1 Evaluate the performance of the various non-conventional and renewable energy sources.

5.2 Evaluate the volumetric efficiencies of the various energy sources

Student slide-0-01

What is the current world energy scenario?



GLOBAL ENERGY SCENARIO

Current energy scenario indicates that the 75% of energy requirement is met by fossil fuels. Nuclear energy contributes to about 3% and 9% is met by hydel energy, 12% of energy consumption is met by biogas and remaining sources like wind, tidal, wave, solar, contribute to about 1%.

Why should we look for alternate energy sources?
Fossil fuels, which are main source of energy, are getting depleted. As a consequence the cost of fossil fuels are increasing. Further, the fossil fuel based systems produce detrimental effects on the environments. This in turn will affect our health. This means that indirectly, the medical bills will be rising the world over.

include here the example of earth filled with oil*

What should be the paradigm shift?
We should move from concentrator energy usage pattern to a more diffuse energy usage pattern.

What are the alternative energy possibilities?
Some of the choices that can be taken in to consideration are:

- Muscle power
- Solar photovoltaic
- Solar thermal

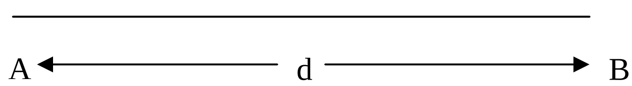
- Wave
- Tidal
- Wind
- Geothermal
- Bio

Owing to the geographical position of India, solar photovoltaic, solar thermal ,wave,wind , bio are good choice as alternatives.

Student slide – 0-03

For any activity involving other than muscle power a base energy and capital energy are required. This can be illustrated considering following two examples:

Consider a person walking between 2 points A B. the energy required will be Fd(=m*a*d) joules.
Now if the person uses a car the total energy will be Etranslational+Ecapital
Where Ecapital is the energy invested in making car.



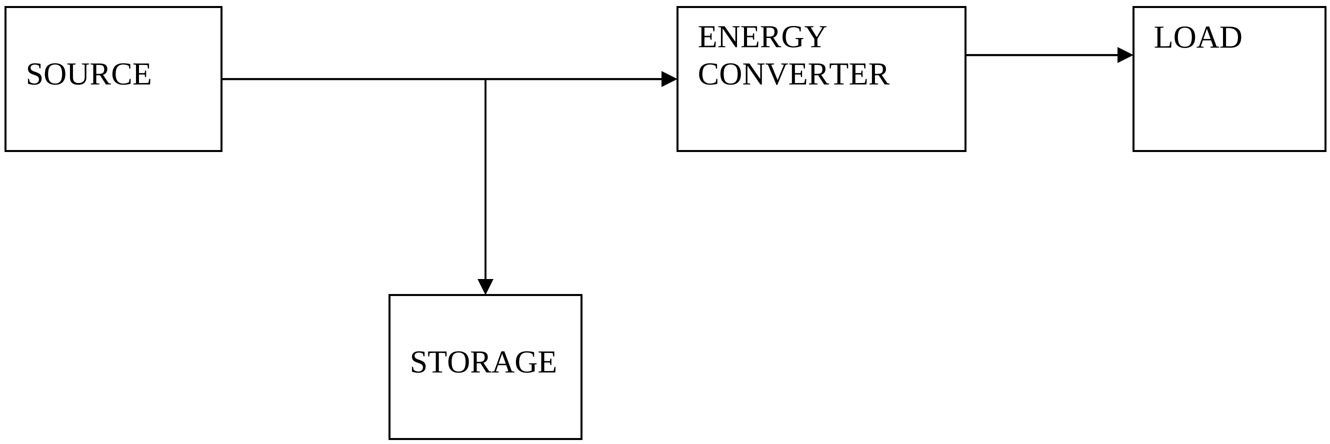
Considering the example of energy required ploughing a field:
When a tractor is used there energy spent on Ecapital. The various values can be tabulated as follows:

	Eplough	Ecapital	Energy efficiency
Traditional farming	6000	60	90%
Modern farming	6000	60000	10%

From above it is clear that though the energy efficiency for traditional farming is high the time required for modern farming is less.
Different formulae to calculate power:
Power=Voltage×current
Force×velocity
Torque×angular velocity
Pressure×rate of discharge
Temperature×rate of change of entropy
Magneto motive force×rate of change of flux

The block diagram for utilizing energy consists of source, energy converter, storage, load as shown in figure.
The source of energy can be:
Solar photovoltaic
Solar thermal
Wave
Tidal
Wind
Geothermal
Bio
Hydro
For storage of energy following options are available:

Battery (energy is stored in electro chemical form.)
Water (energy is stored as potential energy)
Fly wheel (energy is stored in kinetic energy)]
Compressed air
Heat storage
Fuel cell
The energy also can be fed to the grid.
The form of energy obtained from source may not be compatible with load. hence an energy interface (energy converter)unit is required .



Introduction to Non-Conventional Energy Systems

Dr.L.Umanand

Why Fossil Fuel Base?

- Applications need concentrated energy i.e. high energy densities.
- Extraction, storage, distribution and service infrastructure is well established and stable
- Large scale production results in affordable running cost.

Why fossil fuel base?

	Fuel	Wh/kg	density Kg/m^3	Wh/m^3	Wh/lt.
1	Gasoline	12300	~700	9348000	9348
2	Natural Gas	9350	~800	7480000	7480
3	Methanol	6200	791	4904200	4904
5	Kerosene	12300	870	10701000	10701
6	Coal	8200	1250-1550	10250000	10250
7	Battery (lead- acid)	35	-	-	80
8	Flywheel	15	-	-	-
9	Solar thermal**	-	-	900/day	0.9/day
10	Solar PV*	-	-	500/day	0.5/day

*Efficiency is assumed as 10% and 1m height is required for installation with appropriate inclination.
**Efficiency is assumed as 18% and 1m height is required for installation with appropriate inclination.

Why fossil fuel base?

- COSTS
  - Cost of petrol Rs.40/lt > Rs.4.27/KWh
  - Cost of kerosene Rs.15/lt > Rs.1.4/KWh
  - Cost of PV Rs.200/W > *Rs.40000/KWh of capital investment*

Why fossil fuel base?

- Petrol/diesel fuel stations infrastructure is available
- LPG gas is distributed at your doorstep
- LPG and CNG service infrastructure is also well established
- Customer need not bother about storage and service infrastructure costs. Payment is only for running cost of fuel.

Then why move away from fossil fuel base?

- Depletion of fossil fuels
- Environmental hazards
- Health hazards
- Life Cycle costs versus running costs

How long will fossil fuel last?

- Let the earth be made of a thin shell that is filled entirely with fossil fuels.
- Consider the earth as a sphere of radius R=6378.137 kms.
- This amounts to about 1.1×10^{21} m^3 of fossil fuel.
- take the average energy density of fossil fuel to be about 10000Wh/lt or 10000 KWh/m^3

  (refer table on energy densities – slide 03)

How long will fossil fuel last?

- the amount of stored energy within the earth is 1.1×10^{25} KWh
- The current annual world energy consumption is about 55×10^{12} KWh
- Considering a 7% growth in energy consumption annually

How long will fossil fuel last?

- in 372 years with an annual energy consumption growth rate of 7%, all the fossil fuel is emptied within the earth even though we started with earth being full of fossil fuel. However, earth is not composed fully of fossil fuel. Only a fraction of its volume is stored as fossil fuel.

How long will fossil fuel last?

- The pinnacle of fossil fuel usage is passed. Its usage will now decay exponential and in the next 100 years will gradually die.

So now a Paradigm shift...

"Concentrated usage of energy to Distributed usage of energy"

A case for enviroment...

.....rush hour pictures....

1. Majestic railway station
2. MGRoad
3. Shivajinagar bus station

A case for enviroment...

- Green house effects
- Climate change
- Depletion of stratospheric ozone layer

Green house effect

- Green house gases – carbon dioxide, nitrous oxide, methane, chloro fluoro carbons.
- Green house gases are the temperature stabilisers of the earth's atmosphere.
- Temperature stabilisation is by trapping radiated heat from the earth's surface by these green house gases.

Global warming

- Due to emissions from the fossil fuel based systems, the green house gases in the atmosphere increases.
- As a result, the average temperature of the earth is becoming higher.

Effects of Global warming

- changes in rainfall patterns
- rise in sea level
- impacts on flora and fauna
- impacts on human health

Health is an issue!

- CO poisoning.
- Asthma.
- Skin diseases and cancer due to depletion of stratospheric ozone.

Cost in the long run...

- Life cycle costing gives more realistic estimates.
- This gives a much better correlation of cost to energy used.

What are the alternatives?

- Nuclear fuel – is it viable?
- What are its implications?
- Then what?

Non-conventional fuel base

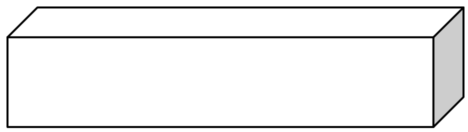
- Muscular
- Solar thermal
- Solar PV
- Wind
- Hydro
- Biomass
- Wave
- Hybrids

Scope for alternative energies...

- 75% of energy comes from fossil fuels such as crude oils, coal and natural gas
- 12% from bio fuels such as methane
- 9% from hydro based
- 3% from nuclear
- 1% from windmills and photovoltaic put together → ↑ Scope to increase

Student slide 2-06

45^0c

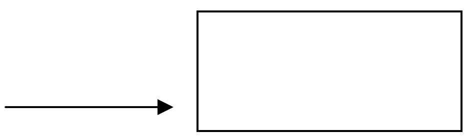


70^0c

$A = g*\beta*X^3\Delta T/(\delta*v)$
$=9.8*(1/330)*.03*(70-45)/(2.6*10e-5*1.8*10e-5)$
$=4.1*10e4$
$N=.062A^{.33}$
$=2.06$
$h\theta v=(N*K)/X$
$=(2.06*.028/.03)$
$=2$
$P=2*1*1*25$
$= 50$ watts

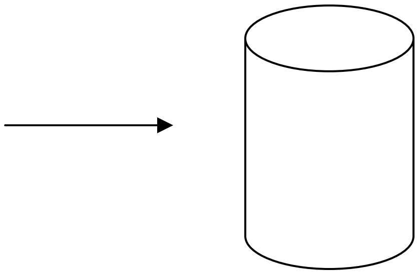
Forced cooling:

1. Flate plate

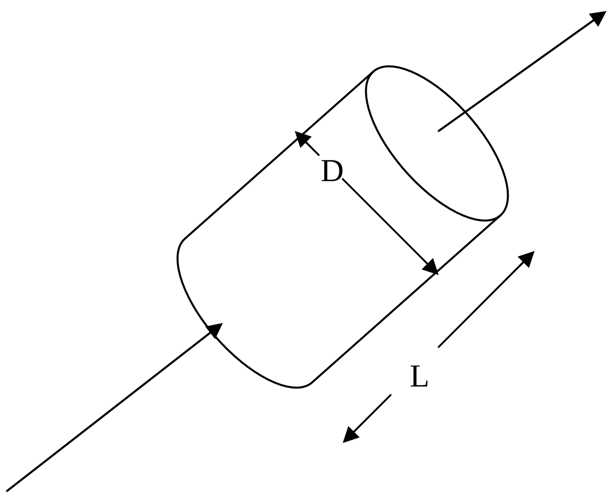


Laminar $R<5*10^5$ $N=.669R^{.5}(\gamma/\delta)^{.33}$

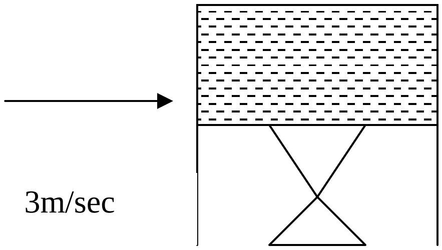
Turbulent $R>5*10^5$ $N=.37R^{.8}(\gamma/\delta)^{.33}$

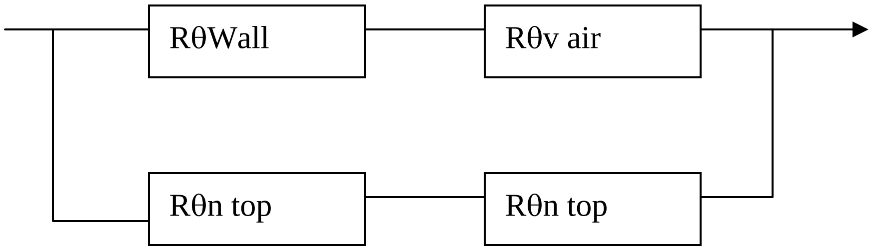


Laminar $.1<R<1000$ $N=(.35+.56R^{.52})(\gamma/\delta)^{.3}$
Turbulent $1000< R<5*10^4$ $N=.26R^{.6}(\gamma/\delta)^{.3}$



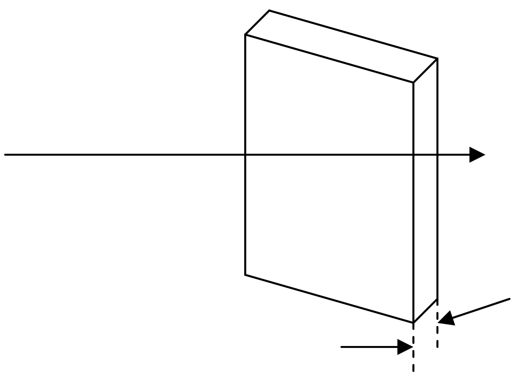
Laminar $R<2300$ $N=1.86R^{.33}(\gamma*D/(\delta*l))^{.33}$
Turbulent $R>5*10^5$ $N=.0027R^{.8}(\gamma/\delta)^{.33}$





Free convection:
Top:
Atop=9.8*. 0033*.22^{3}*80/(2.6*10e-5*1.8*10e-5)
=4.9*10e7
N=. 14A.33
=48.4
Ptop=(48.4*.027*3.14*.22^{2}*80)/(.22)
=18W
Pside:
Aside=(9.8*. 0033*.11^{3}*80)/(2.6*10e-6*1.8*10e-5)
=6.1*10e6
N=.47A$^{.25}$
=. 47*(6.1*10e6)$^{.25}$
=27.8
Pside=(27.8*.027*3.14*.22*.11*80)/.11
=41W
Pfree=59W
Forced:
R=(u*X)/v
=(3*.22)/(1.8*10e-5)
=3.5*10e4
N=.664R$^{.5}$(γ/δ)$^{.33}$
=110
Ptop=42W
Side:
Rside=(u*X)/v
=(3*.22)/(1.8*10e-5)
=3.5*10e4
N=.26R$^{.6}$(γ/δ)$^{.33}$
=124
Pside=93W
Pforced=135W
Ptotal=Pfree+Pforce
=194W

Student slide 2-05



$P=K*A*\Delta T/\Delta x$

Where K is thermal conductivity

A is area of cross-section

Δx is thickness of material

ΔT is the temperature difference

$q=P/A$

$=K*\Delta T/\Delta x$

$R=\Delta x/(K*A)$

$\gamma=\Delta x/K$

$h=K/\Delta x$

The following table gives thermal conductivity of some materials:

Material	Thermal conductivity (W/m/^{0}c)
Cu	385
Al	211
Steel	47.6
Glass	1.05
Brick	0.6
Concrete	1.7
Asbestos	0.319
Polyurethane	0.025
Still air	0.026

Examples:

1. Glass

1mX1mx5mm

$$R=\Delta x/(K*A)$$
$$(5*10^{-3})/(1.05*1*1)$$

$=.005^0 c/W$

2. Brick wall

$$R=\Delta x/(K*A)$$
$$(220*10^{-3})/(0.6*1*1)$$
$$=.36^0 c/W$$

3. Ceiling insulation:

$$R=\Delta x/(K*A)$$
$$(80*10^{-3})/(.04*1*1)$$
$$=2^0 c/W$$

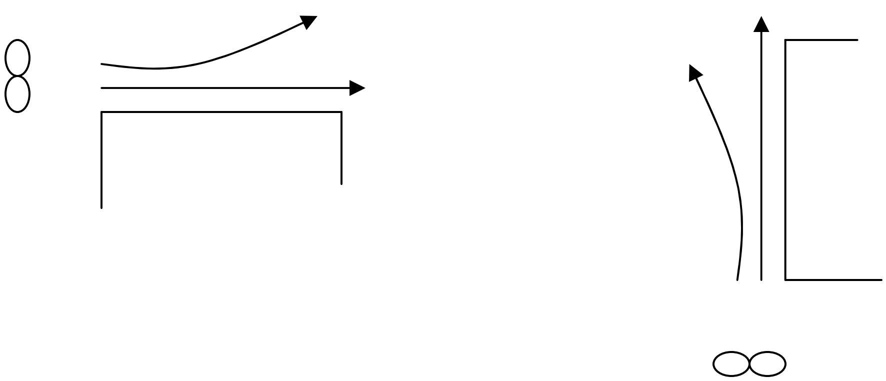
Convection:

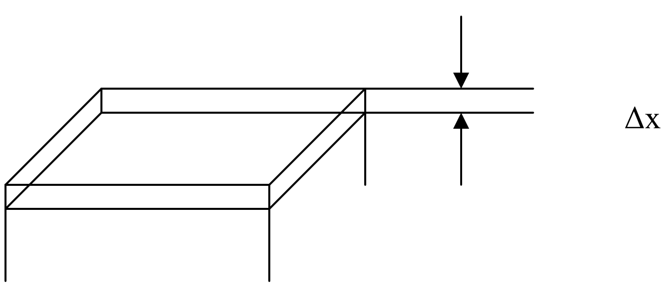
Free convection:

The movement of air is dictated by temperature difference.

Forced convection:

External force dictates the movement of air.





$P=K*A*\Delta T/\Delta x$

Δx is determined experimentally.

$P=K*A*\Delta T/\Delta x$

$=(X/\Delta x)*(K*A*\Delta T/X)$

$=N*(K*A*\Delta T/X)$

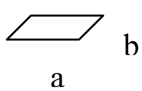
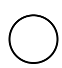
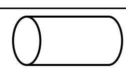
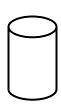
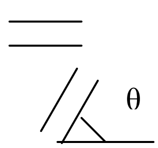
Where N is Nusselt's number

Convection depends on:

1. Speed of flow
2. Property of fluid

3. Geometry

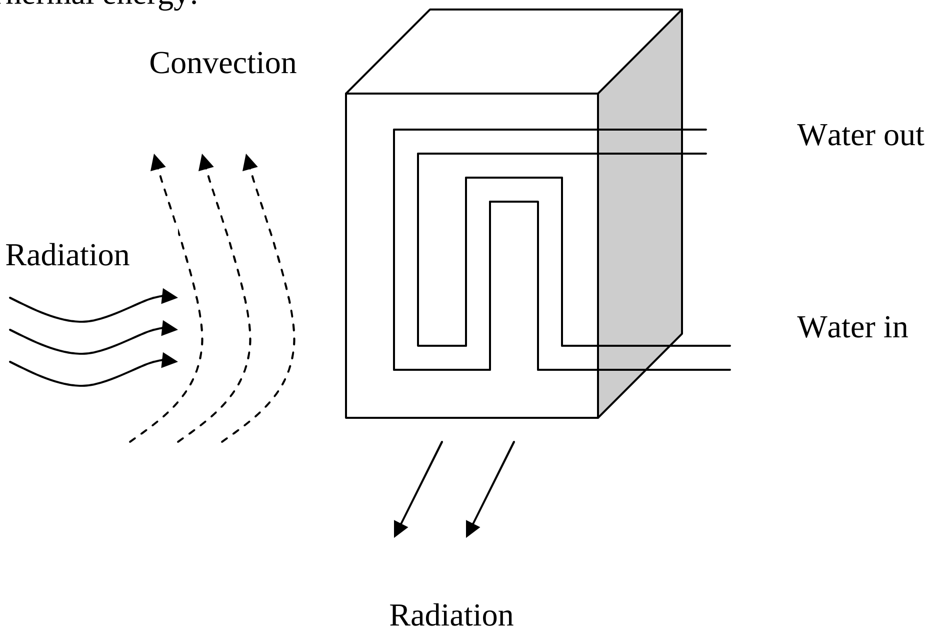
Forced convection (Reynold's number):
R=u*x/v
u mean flow velocity
v kinematic viscosity
N=f(R)
R>2300 turbulent
R<2300 laminar
Free convection (Raliegh number):
A=Rayliegh number=$g*\beta*X^3\ \Delta T/(\delta*v)$
$g=9.81m/s^2$
β coefficient of thermal expansion
δ thermal diffusivity
v kinematic viscosity
N=f (A)
P=N*K*A*ΔT/X
R=X/(N*K*A)
γ=(N*K*A)/X
H=(N*K)/X
Free convection:

			Laminar flow		*Turbulent flow*	
Horizontal flat plate		*X=(a+b)/2*	$10^2<A<10^5$	$N=0.54A^{0.25}$	$A>10^5$	$N=0.14A^{0.33}$
Circular plate		*X is diameter*	$10^2<A<10^5$	$N=0.54A^{0.25}$	$A>10^5$	$N=0.14A^{0.33}$
Horizontal cyilinder		*X is diameter*	$10^4<A<10^9$	$N=0.47A^{0.25}$	$A>10^9$	$N=0.14A^{0.33}$
Vertical cylinder		*X is length of cylinder*	$10^4<A<10^9$	$N=0.47A^{0.25}$	$A>10^9$	$N=0.2A^{0.33}$
Parllel plates		$\theta<50^0$	$A>10^5$ $N=.062A^{0.33}$			

Steps:
1. Draw diagram of application
2. Select the section that relate to the standard geometries.

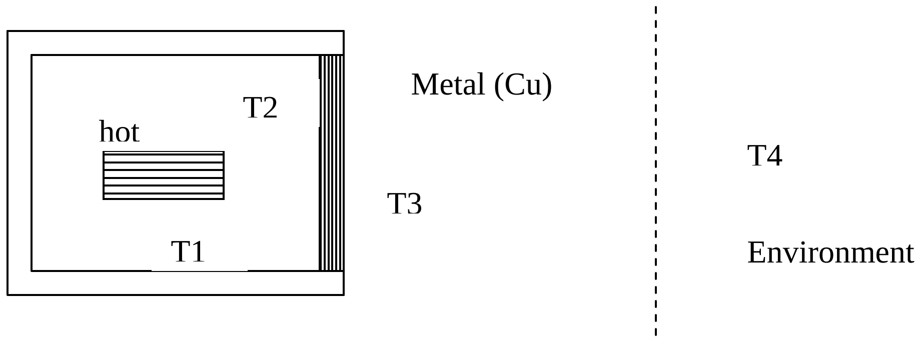
3. For each section:
    a. Identify X
    b. Calculate R or A
    c. Calculate N
    d. Calculate heat flow
    e. Add up heat flows of all sections.

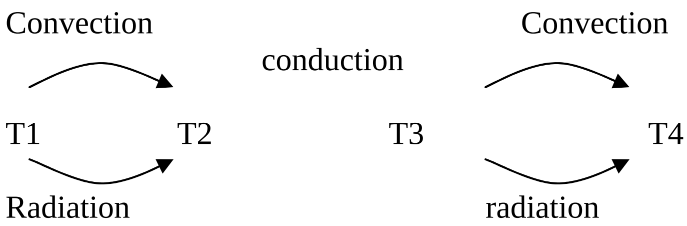
Student slide 2-04
Thermal energy:

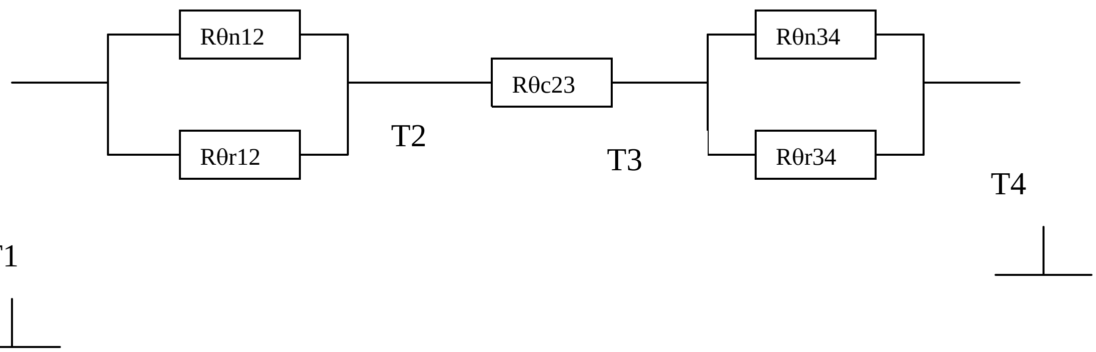


Heat transfer can take place by any of the following methods:
Conduction
Convection
Radiation
Mass transfer
Heat input in above figure is because of radiation. The atmosphere around the pipes is heated and this heat is transferred to pipes by conduction, which is in turn transferred to water by mass transfer. Water is circulated through pipes. Water at lower temperature enters the pipe and its temperature rises. The water coming out is at higher temperature.

THERMAL MODEL OF A SYSTEM:





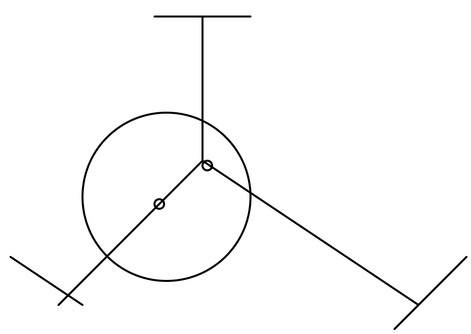


$$P_{ij}=(T_i-T_j)/(R\theta_{ij})$$

R---degree/watt or Kelvin/watt

The above figure gives steady state model. To analyze transient behavior thermal capacitors should be considered.

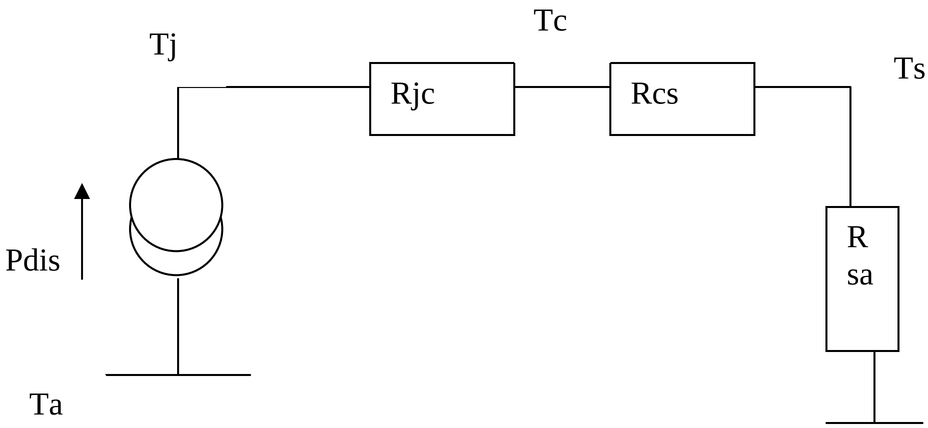
THERMOMECHANICAL MOTOR:



Wires of negative coefficient are used. When current is passed through them they get heated and their length decreases. When a rms power is passed through the wire with 120 degrees phase shift a torque is produced. This is used in space applications.

Thermal model of power electronic device:

The power to be dissipated can be calculated. The junction temperature must not be above 150 degrees. The sink is designed such that the junction temperature is 120 degrees. Rjc can be obtained from data sheet. Ta is known.



$$Tj-Ta=PRjc+PRcs+Prsa$$
$$(Tj-Ta)/P=Rjc-Rcs+Rsa$$

Ta is the maximum ambient temperature.

Heat flow per unit area=q

$$=P/A$$
$$=\Delta T/(RA)$$
$$=\Delta T/\gamma$$
$$=h/\Delta T$$

Where

R is the thermal resistance (^{0} C/W)

γ is thermal resistivity (^{0}C m^2/W)

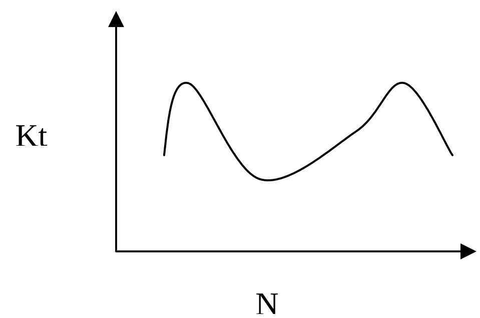
h is thermal coefficient W/^{0}Cm^2)

Student slide 2-03

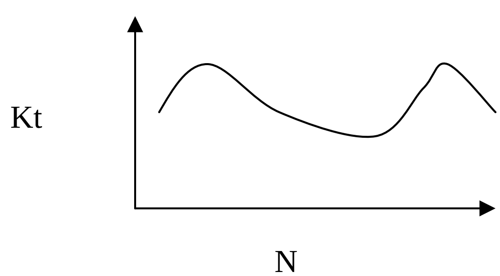
Determination of clearness index Kt:

N	Ht(β=0)	HOA	HO	Kt actual=HOA/HO
1				
2				

The radiation on a unit surface area with tilt angle zero is measured at a location. HOA is obtained using the formula Ht/RD. Extraterrestrial radiation HO is known. Using that Kt actual is calculated for a year (365 days). The above procedure is repeated for different locations and the variation of Kt with respect to days is plotted.



Location 1



Location 2

Location is a function of the latitude of the place. Hence for different locations the value of Kt is found on different days of year. The results are tabulated as follows:

ϕ	
ϕ1	Kt (N=1,2,3……..365)
ϕ2	Kt (N=1,2,3……..365)

Now we need to fit a model for the obtained values. It can be represented as
Kt actual= Kt model + error
Using Fourier fit for the model
Kt=A1+A2sint+A3sin2t+A4sin3t+A5cost+A6cos2t+A7cos2t
For harmonics greater than 3 the coefficient obtained are nearly zero. Hence they are not considered. The coefficients are function of latitude, water vapor, pressure, and height above sea level. The coefficients are weak functions of pressure, height above sea level and strong functions of latitude, water vapor. Now a sub model is required for Ai and it is function of latitude, water vapor. A polynomial fit is used for sub model.

Ai=ai1+ai2x+ai3x.x+ai4w+ai5w.w

Where x=ϕ-35

We need to find constants ai1, ai2…

This is done by minimizing the square of error using least square method.

Kt actual= Kt model + error

$Error^2$= (Kt actual- Kt model) ^{2}

E_1^2= (Kt actual- Kt model) $_1{}^2$ Location 1

E_2^2= (Kt actual- Kt model) $_2{}^2$

E_3^2= (Kt actual- Kt model) $_3{}^2$

…………………..

E_1^2= (Kt actual- Kt model) $_1{}^2$

E_2^2= (Kt actual- Kt model) $_2{}^2$ Location 2

E_3^2= (Kt actual- Kt model) $_3{}^2$

…………………..

Now the problem can be formulated as minimize $E_1^2 + E_2^2 + \ldots\ldots\ldots + E_{365}^2$

Minimize $\sum E_i^2$

= (Kt actual – (A1+A2sint+…)) ^{2}

By solving the above equations constants a11, a12…. Are obtained.

That is solve $\partial E/\partial ai1=0$

$\partial E/\partial ai2=0\ldots$

Student slide 2-02

To find out the total radiation of sun falling on earth following steps are to be followed:

1. Find sun's position with respect earth. Sun's position is a function of latitude, day of the year, hour angle (ω)

Sun rises at 0^0 and sets at 180^0 at equinox.

180^0 = 12hours

1 hour = 15^0

2. Energy per day / m^2 falling on the earth without including atmospheric effects. (H0 KW/m^2/day)
3. Energy per day / m2 falling on the earth including atmospheric effects. (H_{OA} KW/m^2/day)

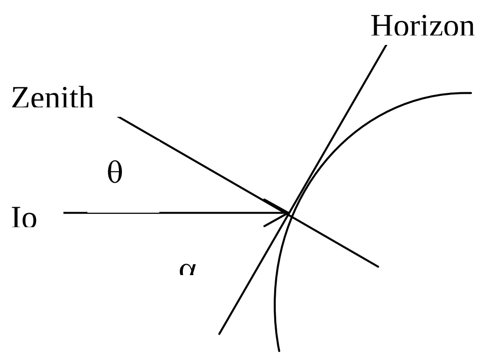
$H_{OA}=K_T H_O$

Where K_T is the clearness index. Clearness index is obtained using statistical data

4. With variation in latitude the angle at which (tilt) surface of unit surface should be placed varies. At equator the optimum tilt is zero degrees. In general the tilt angle is equal to the latitude. When there is a tilt the radiation gets reflected due to mountains. Taking the factors in to consideration the amount of radiation falling on the tilted surface with atmospheric effects included can be found out using $H_T=R_D H_{OA}$

Where R_D is the tilt factor. R_D is found using empirical formula.

Step 1:



The perpendicular component of isolation vector $= I_0 \cos\theta$

$= I_0 \sin\alpha$

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

where δ is the declination

where ϕ is the latitude

$$I = I_0 \sin\alpha$$
$$= I_0(\cos\phi \;\cos\;\delta \cos\omega \;+\; \sin\phi \;\sin\;\delta)$$

$$H \;=\; \int I.dt$$
$$= (1/15) \int I \cdot d\omega$$

the angle ω from sunrise to sunset depends on the latitude of the position.

$$H_O = \int_{\omega_{sr}}^{\omega_{ss}} I \cdot d\omega$$

$$= \; 2\int_0^{\omega_{ss}} I \cdot d\omega$$

$$\alpha = 0$$

$$\cos\phi \cos\delta \cos\omega_{sr} + \sin\phi \sin\delta = 0$$

$$\cos\;\omega_{sr} = \;-\tan\phi\;\tan\delta$$

$$H_O = \left(\frac{2}{15}\right) \int_0^{\omega_{ss}} I \cdot d\omega$$

$$= \left(\frac{2}{15}\right) \int_0^{\omega_{ss}} I_0(\cos\phi\;\cos\;\delta \cos\omega \;+\; \sin\phi\;\sin\;\delta) \cdot d\omega$$

$$= \left(\frac{2}{15}\right) \int_0^{\omega_{ss}} I_0 K(\cos\phi\;\cos\delta \cos\omega_{sr} \;+\; \omega_{sr} \sin\phi\;\sin\delta) \text{ KWh/m2/day}$$

$$I_O = I_{sc}\;(1+.033\cos\left(\frac{360N}{365}\right)$$

N=1 for first January

I_{sc}=1.37 KW/m2

H_O=($24I_{sc}/\pi$) Isc $\left(1+.033\cos(360N/365)\right)$ K ($\cos\omega\;\cos\delta\;\cos\;\omega_{sr} + \omega_{sr}\;\sin\phi\;\sin\delta$) KWh/m2/day

$H_{OA} = K_T H_O$

$H_T = R_D H_{OA}$

$H_T = K_T R_D H_O$ KWh/m2/day

To find R_D (tilt factor):

Effects of scattering, diffusion, ground effects are taken in to account.

$$R_D = 1.13\ K_T\ K_D + (1 - 1.13K_T)\left(\left(\frac{(1+\cos\beta)}{2}\right) + \rho\left(\frac{(1-\cos\beta)}{2}\right)\right)$$

Where ρ is reflection coefficient. It value lies in between 0.2 to 0.7.

$$K_D = \left(1/\cos\phi\right)\left(1/(\sin\omega_{sr} - \omega_{sr}\cos\omega_{sr})\right) \text{ summer for northern hemisphere}$$

$$= \left(\sin\omega_{sr}/\cos\phi\right)\left(1/(\sin\omega_{sr} - \omega_{sr}\cos\omega_{sr})\right) \text{ winter for northern hemisphere}$$

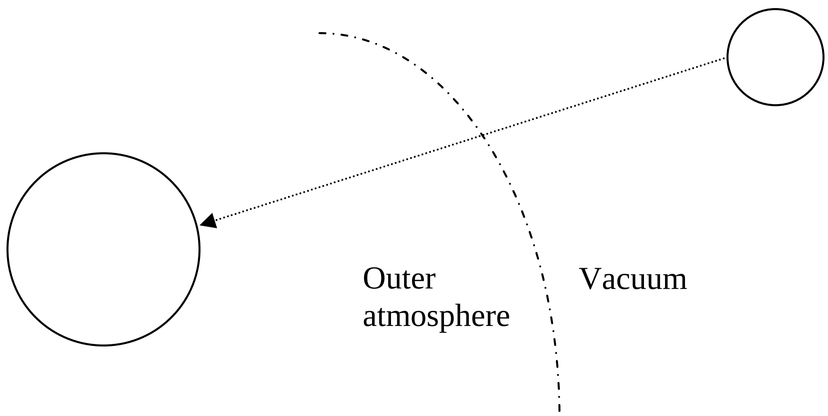
Student slide-2-01

The energy source can be considered to comprise of two parts:

- The actual energy source
- The energy collector and receiver.

In case of solar energy PV cells and thermal plates are used for collection of energy. Windmills are used for wind energy. Wave turbines are used to collect energy from the waves.

In case of solar energy the sun is the source of energy. The output of sun is 2.8×10^{23}KW. But the energy reaching the earth is 1.5×10^{18}KWH/year.



To install energy collecting device (PV cells or thermal plates) it is required to find out the energy available at a place. When light travels from vacuum to outer atmosphere to earth, solar energy is lost because of following reasons:

Scattering:
The rays collide with particles present in atmosphere

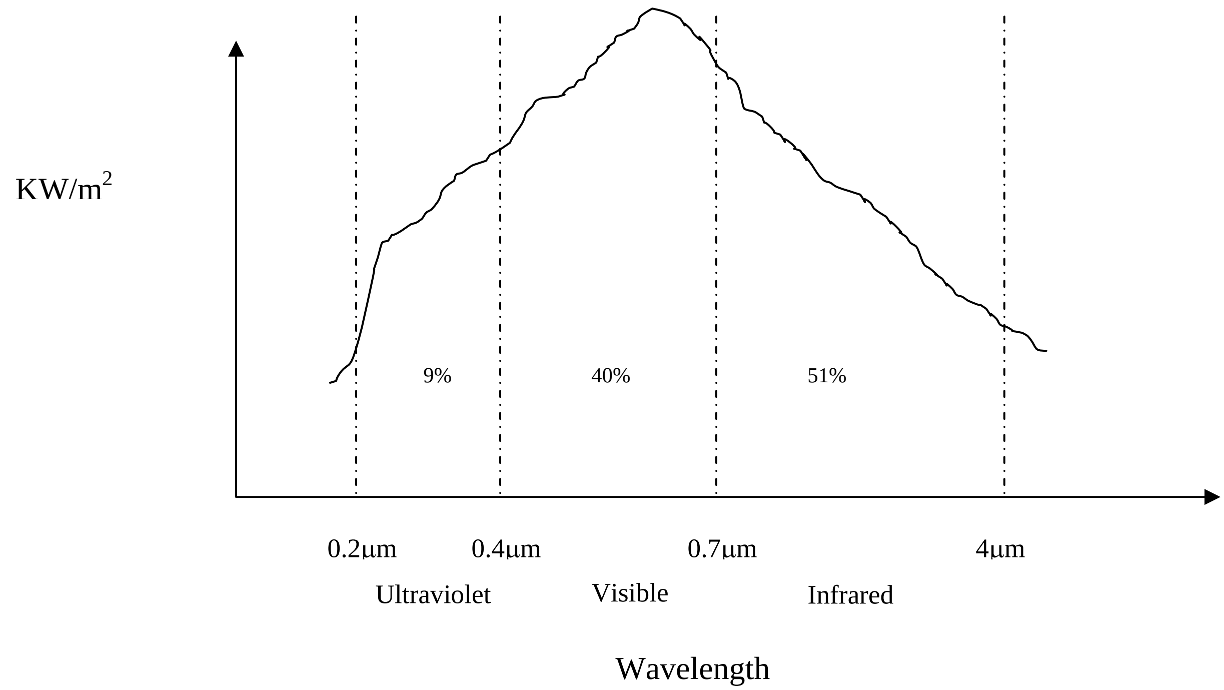
Absorption:
Because of water vapor there is absorption.

Cloud cover:
The light rays are diffused because of clouds.

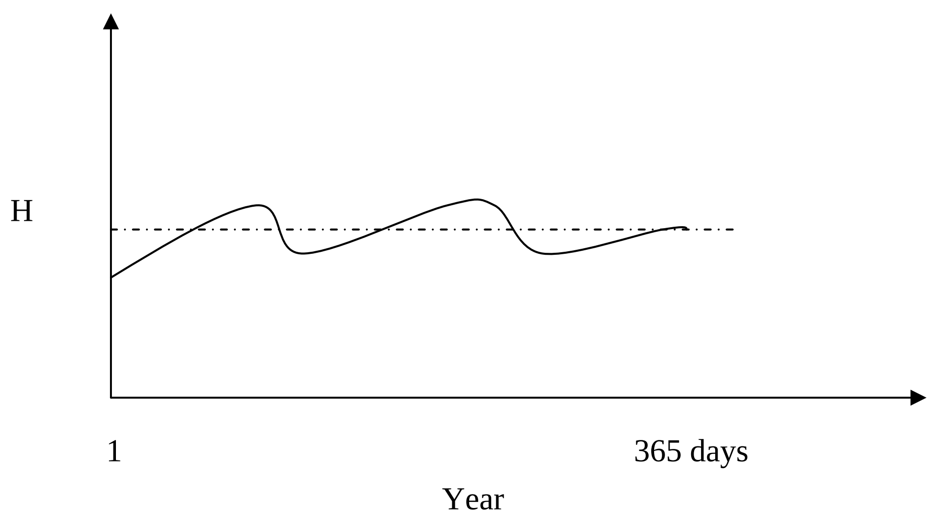
Reflection:
When the light rays hit the mountains present on the earth surface there is reflection.

Climate:
Latitude of the location, day (time in the year) also effect the amount of solar energy received by the place.

The above mentioned factors determine the amount of power falling on the surface. Amount of power that is falling on unit surface area is defined as *insolation*. The graph shown gives the amount of power present in different wavelengths of radiation. It can be seen from the graph that 50% of solar energy is in the form of thermal energy. Solar PV uses the energy in visible region. Solar thermal uses energy in infrared region.



As mentioned before to install energy collecting device it is required to find out the energy available at a place. By considering above factors the, energy available is determined in KWH/m^2/day (defined as H). Energy curve gives variation of H with respect to days in year.



Energy curve is drawn by taking atmospheric effects in to account.

Extra terrestrial radiation

Extra terrestrial radiation is defined as energy on $1\times1m^2$ plate placed at earth's outer atmosphere.

Solar constant

Solar constant is defined as average power per unit area on surface positioned at earth's outer atmosphere perpendicular to the incident radiation.

Solar constant (Isc)=1.36KW/ m^2

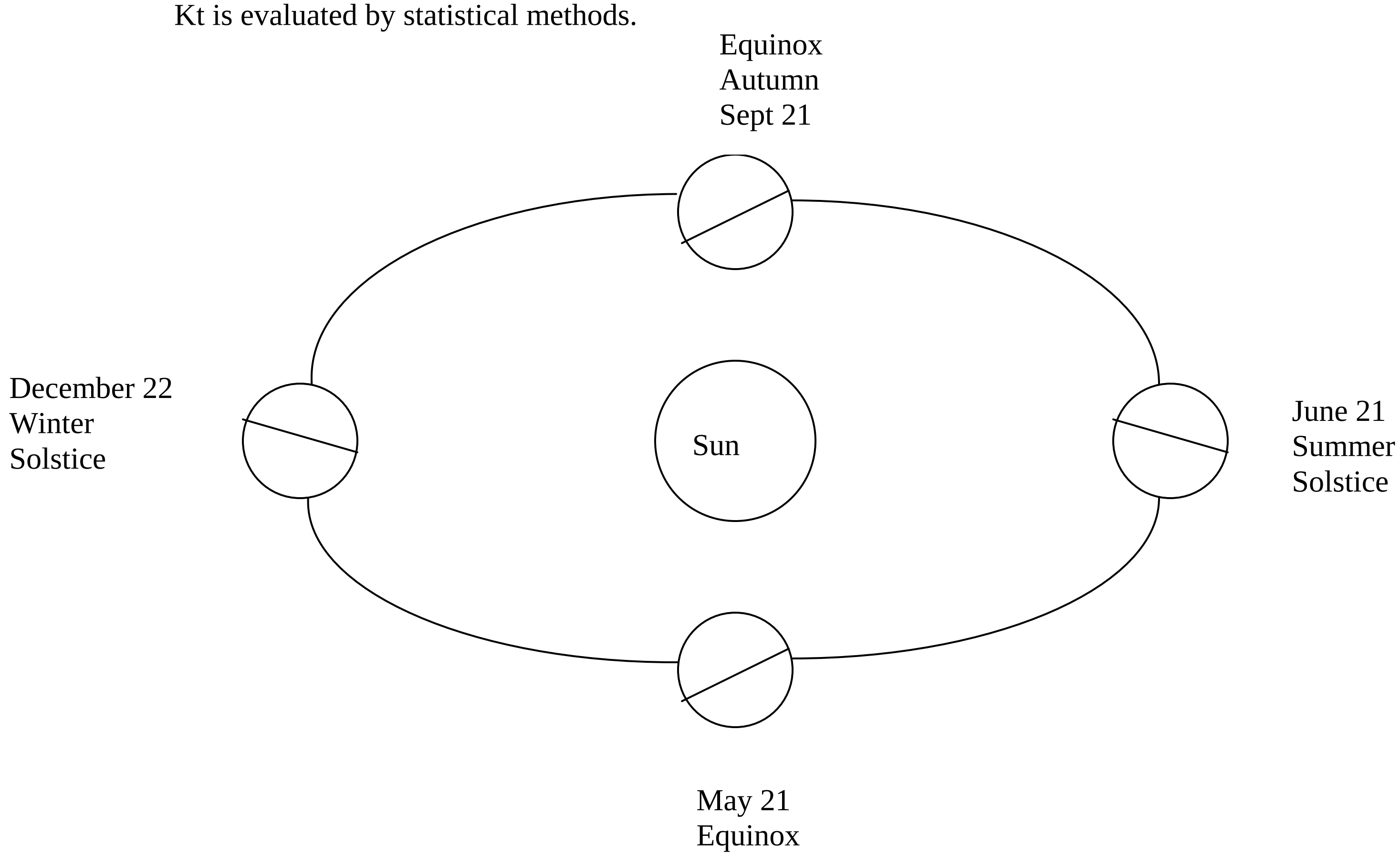
H ($KWH/m^2/day$) on earth is a function of

Latitude (ϕ)

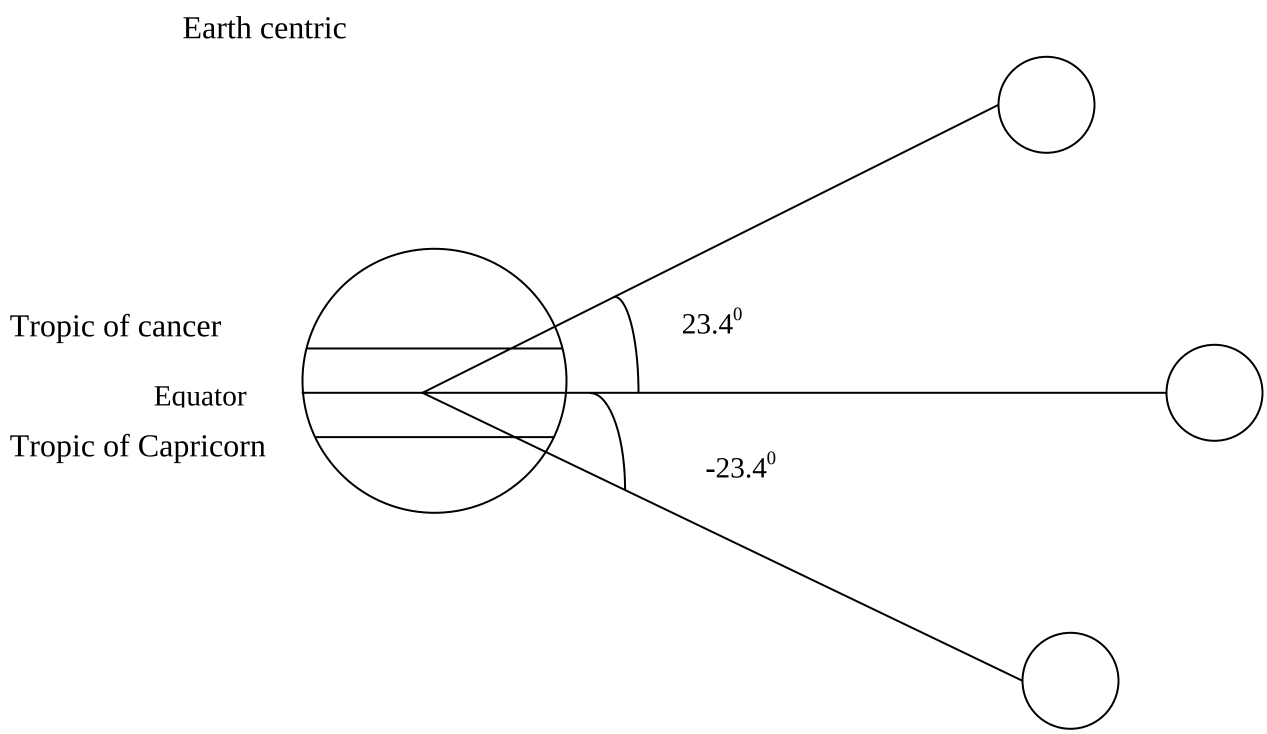
Day of year (n)

Atmospheric effects (clearness index) Kt

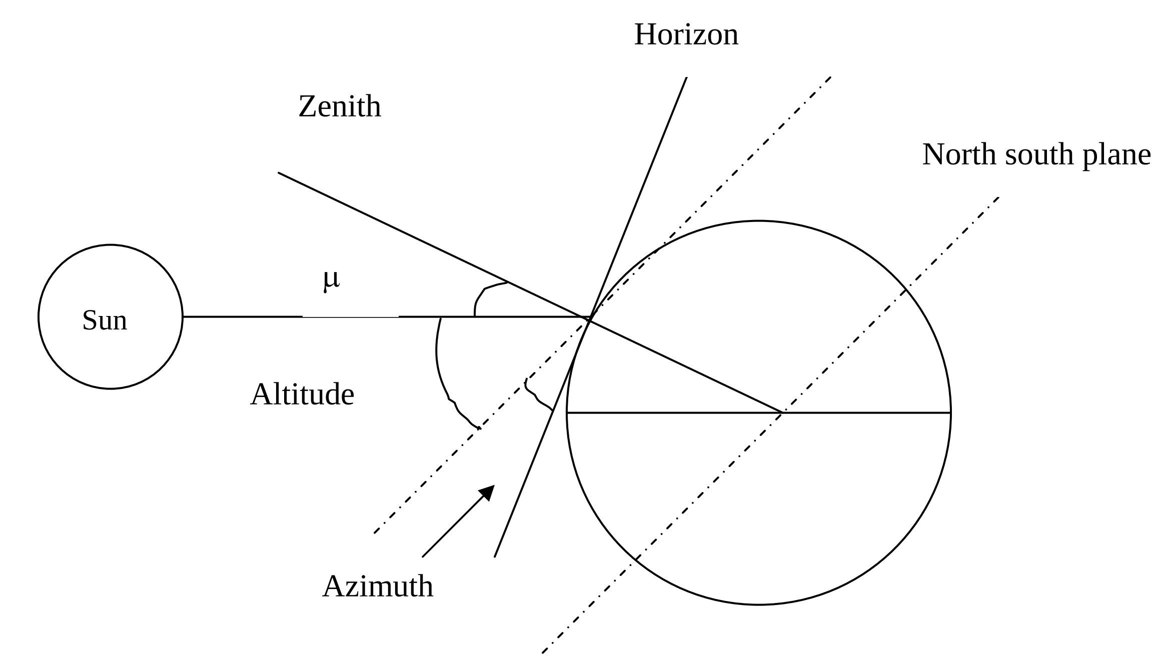
Kt is evaluated by statistical methods.



Earth takes 365 days to revolve around the sun. The amount of solar energy received by earth depends on earth's rotation and position in orbit.



Earth centric
Tropic of cancer
Equator
Tropic of Capricorn
23.4^0
-23.4^0



Horizon
Zenith
North south plane
μ
Sun
Altitude
Azimuth

Horizon is a plane tangential to earth's surface.
If a person is standing on the surface of earth the direction normal to him is called zenith.
The angle between north south plane and horizon is called *azimuth* angle.
The *zenith* angle is angle between the direction normal to surface of earth and sun. It is represented by angle μ.
The angle between sun and the north south plane is called *altitude*.

Student slide 2-07

Radiation:

Power radiated is proportional to ΔT^4

$P = h\theta rA\ \Delta T$

$= \sigma\ \Delta T^4$

σ is Stephan boltzmann constant=$5.67e\text{-}8 W/m^2/K^4$

$h\theta r = 4 * \sigma * \varepsilon * (1-\varphi)((T1+T2)/2)^3$

ε is emittance

=. 09 for aluminum

=. 18 for aluminum rough

=. 85 for aluminum anodized

=. 17 for iron

=. 33 for tungsten

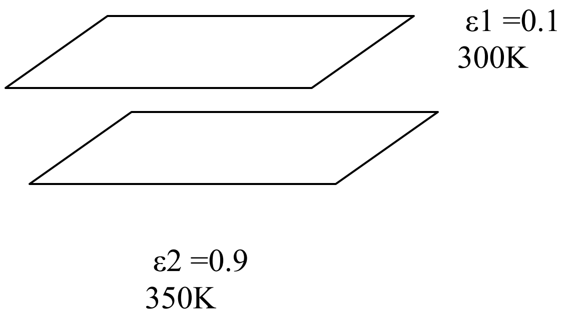
=. 93 for brick

=. 93 for concrete

φ is shelding factor

1-φ is shape factor

φ=0 for single plate or 2 plates in parallel



$h\theta r = 4 * \sigma * \varepsilon * (1-\varphi)((T1+T2)/2)^3(\varepsilon1\ \varepsilon2/(\varepsilon1 + \varepsilon2 - \varepsilon1\ \varepsilon2))$

$P = h\theta rA(T1-T2)$

$= 75w$

$Ptop = h\theta r * (3.174/4) * (.22^2) * 80$

$= 2.546w$

$Pside = 4 * \sigma * .1 * (333)^3 * (.22 * .11) * 80$

$= 5W$

burner rating =194+5+2.546

=201.546W

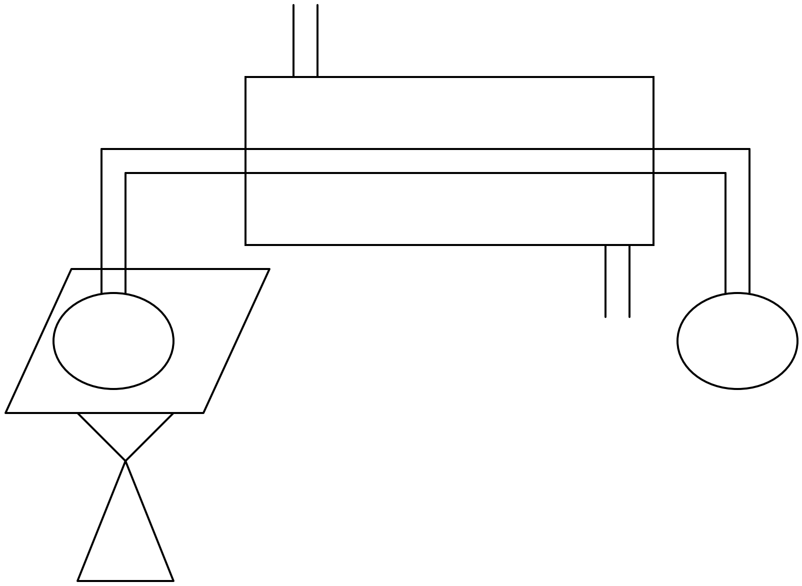
Mass Transfer:

$P = (dm/dt) * s * (T1-T2)$

$R\theta m = (T1-T2)/P$

S specific heat

4KJ is energy required to raise the temperature of 1Kg of water by 1^0c



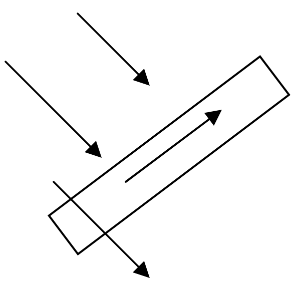
Latent heat of vaporization of water 2.4MJ/Kg

$P=(dm/dt)*L$

$R\theta m=(Ts0-Ts1)/P$

To vaporize 1 Kg of water energy required is 0.666KWh

Consider light ray falling on the surface of the object. Part of the light is reflected , part is absorbed and remaining is transmitted.



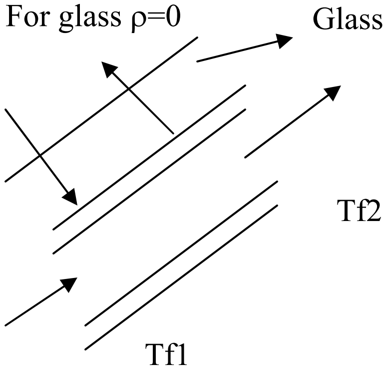
Transmittance τ

Absorptance α

Reflectance ρ

For opaque solids $\tau=0$

For glass $\rho=0$



Power input $=\alpha\tau AI$

$(\alpha\tau AI-((Tp-Ta)/R\theta)=(dm/dt)*s*(Tf2-Tf1)$
$1/R\theta = 1/R\theta r + 1/R\theta v$

Non conventional energy systems

Solar thermal technology:

Solar thermal technologies uses the sun to generate heat directly and include the following:

Solar concentrator power systems:

They generate electricity with heat. Concentrating solar collectors use mirrors and lenses to concentrate and focus sunlight onto a receiver, mounted at the systems focal point. The receiver absorbs and converts sunlight into heat. This heat is then transported by means of heated water through pipes to a steam generator where it is converted into electricity.

Flat plate solar collectors:

They are usually large flat boxes with one or more glass covers. Inside the boxes are dark colored metal plates that absorb heat. Air or water flows through the tubes and is warmed by heat stored in the plates.

Passive solar heating:

Passive solar heating design methods use features such as large south facing windows and building materials that absorb the sun's thermal energy.

Application

Let us take a simple application where this technology is used. The application is a water heating system. Let us calculate the power required for raising temperature of a 100-liter tank water from the room temperature by 20 °C.

The energy required = Volume of water in liters x Rise in temp x Specific heat of water

Specific heat of water = 1.16 kWh/°C /m^3

= 1.16 Wh/°C /Liter

Hence, the energy required = 100 Liters x 20 °C x 1.16 Wh/°C /Liter

= 2320 Wh

If we assume 5 Peak Sun Hours in a day, then the power required in a day to rise the temperature of 100 liters of water by 20 °C = 2320 Wh/5 h = 464 Watts.

We know that the standard insolation on a clear day is 1000 watts/m^2. With 20% efficiency of the thermal heater, the insolation available is 200 watts/m^2.

Hence, the area required to get 464 watts of power = = 2.32 m^2.

We can design the solar thermal collector to have an area of 2.5 m^2.

Solar Radiation

Dr.L.Umanand

Insolation

- It is a quantity indicating the amount of incident solar power on a unit surface, commonly expressed in units of kW/m^2
- At the earth's outer atmosphere, the solar insolation on a 1 m^2 surface oriented normal to the sun's rays is called SOLAR CONSTANT and its value is ~1.37 kW/m^2

Insolation

- Due to atmospheric effects, the peak solar insolation incident on a terrestrial surface oriented normal to the sun at noon on a clear day is on the order of 1 kW/m^2
- $1 KW/m^2$ is generally called Peak Sun.

Irradiance

- It is an amount of solar energy received on a unit surface expressed in kWh/m^2
- When solar irradiance data is represented on an average daily basis, the value is often called PEAK SUN HOURS (PSH)

Irradiance

- PSH is the number of equivalent hours/day the solar insolation is at its peak level of 1 kW/m^2
- The worldwide typical PSH is ~5kWh/m^2

Factors affecting Energy incident on a panel

- Latitude and longitude of the geographical location.
- Climatic conditions such as presence of clouds, water vapor etc.
- Time of the day.
- Time of the year.
- Angle of tilt.
- Collector design.

Solar energy at a panel

STEPS:

1. Find the sun position with respect to the location. This is a function of latitude (φ), hour angle (ω) and declination angle (δ).

$$SunPosition = f(\phi, \varpi, \delta)$$

Solar energy at a panel

STEPS:

2. Find the available solar energy or irradiance with no atmosphere, H_O. This is a function of sun position

$$H_O = f(SunPosition)$$

Solar energy at a panel

STEPS:

3. Find the solar energy available on horizontal surface with atmospheric effects, H_{OA}. This is a function of H_O and clearness index K_T

$$H_{OA} = K_T H_O$$

Solar energy at a panel

STEPS:

4. Find the actual solar energy available at the panel, H_t. This is a function of H_{OA} and the tilt factor R_D

$$H_t = R_D H_{OA}$$

Algorithm for calculation of incident solar energy

$$Enter\ \phi, \beta$$

$$N = 1 \rightarrow 365$$

$$\delta = 23.45 * \sin\left(\frac{2\pi(N-80)}{365}\right)$$

Degrees, N = 1 on Jan 1st, N = 365 on Dec 31st

$$\omega_{sr} = \cos^{-1}(-\tan\phi \cdot \tan\delta)$$

$$I_O = I_{SC}\left(1 + 0.033\cos\left(\frac{360N}{365}\right)\right)$$

Algorithm for calculation of incident solar energy

$$H_{ot} = \frac{24I_O}{\pi} * \left(\cos(\phi - \beta)\cos\delta\cos\omega_{sr} + \omega_{sr}\sin(\phi - \beta)\sin\delta\right)$$

kWh/m²/day on a tilted surface with no atmospheric effects

$$H_o = \frac{24I_O}{\pi} * \left(\cos(\phi)\cos\delta\cos\omega_{sr} + \omega_{sr}\sin(\phi)\sin\delta\right)$$

kWh/m²/day

$$K_T = (curve \cdot fitting \cdot data)$$

Clearness Index

$$R_D = K_R(1 - K_D) + K_D\left(\frac{1 + \cos\beta}{2}\right) + \rho\left(\frac{1 - \cos\beta}{2}\right)$$

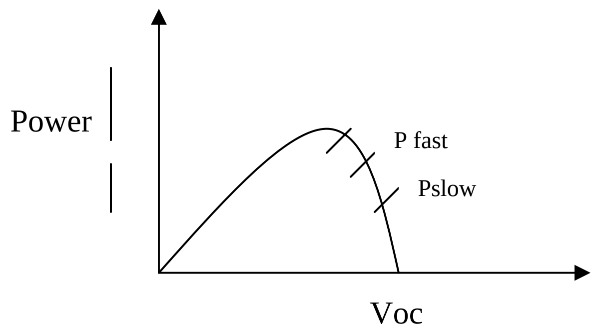
Tilt Factor

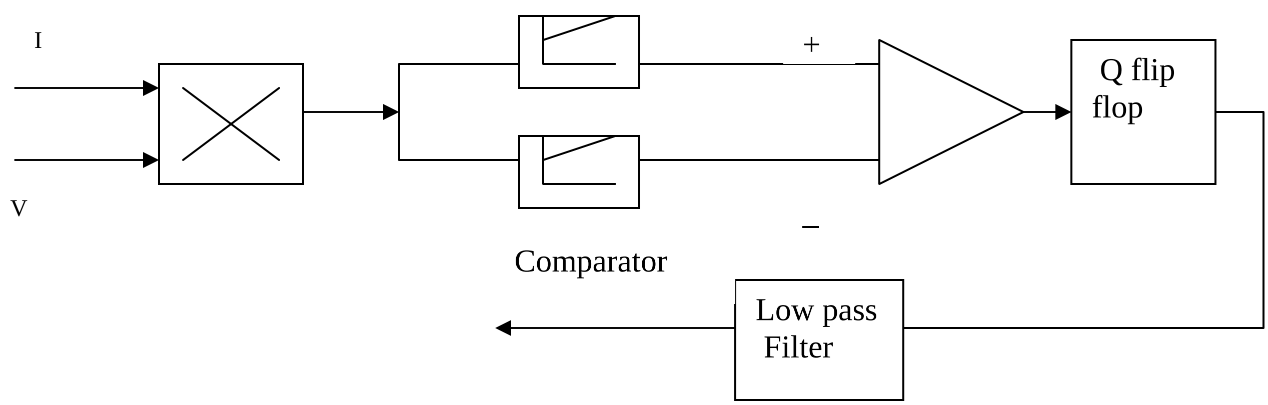
where ρ is the reflection factor which ranges between 0.2 to 0.7.

$$H_t = K_T * R_D * H_o$$

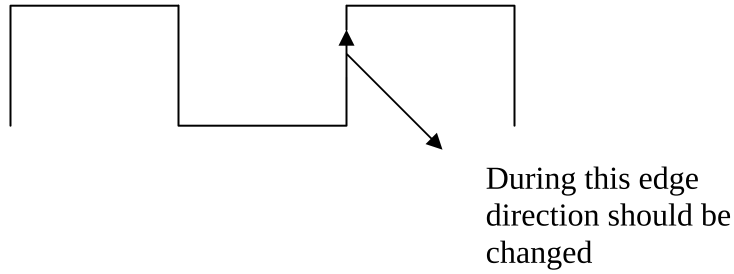
kWh/m²/day

Student slide 3-05
Algorithm 4:
This algorithm is independent of panel load, isolation.

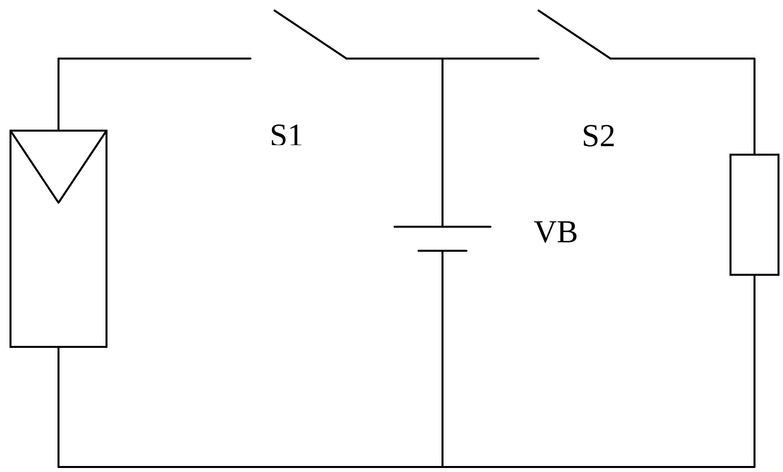




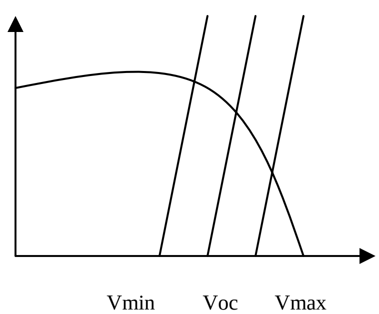
When ever Pfast is less than Pslow duty cycle is reversed.



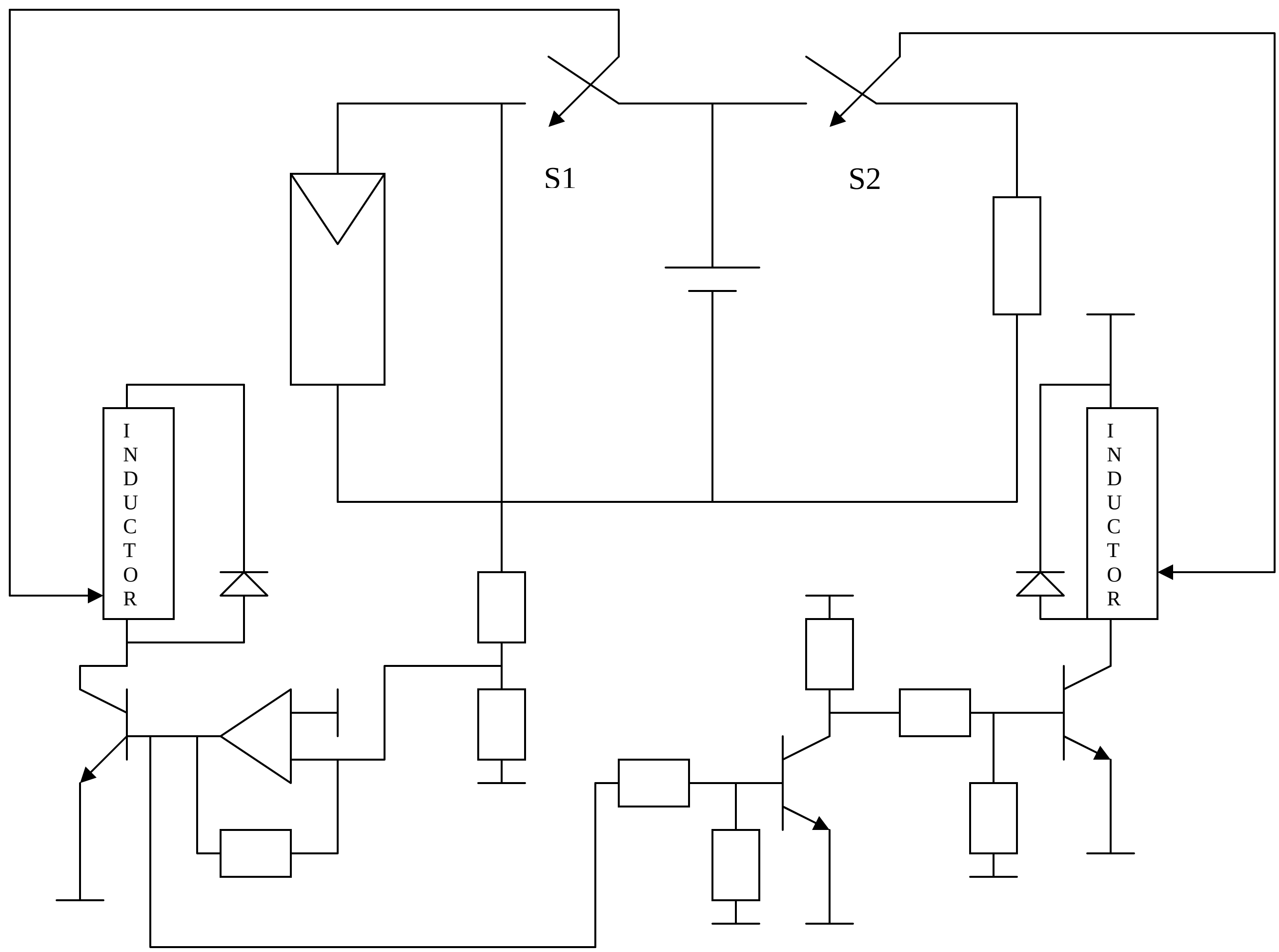
PV cell can used to charge battery.

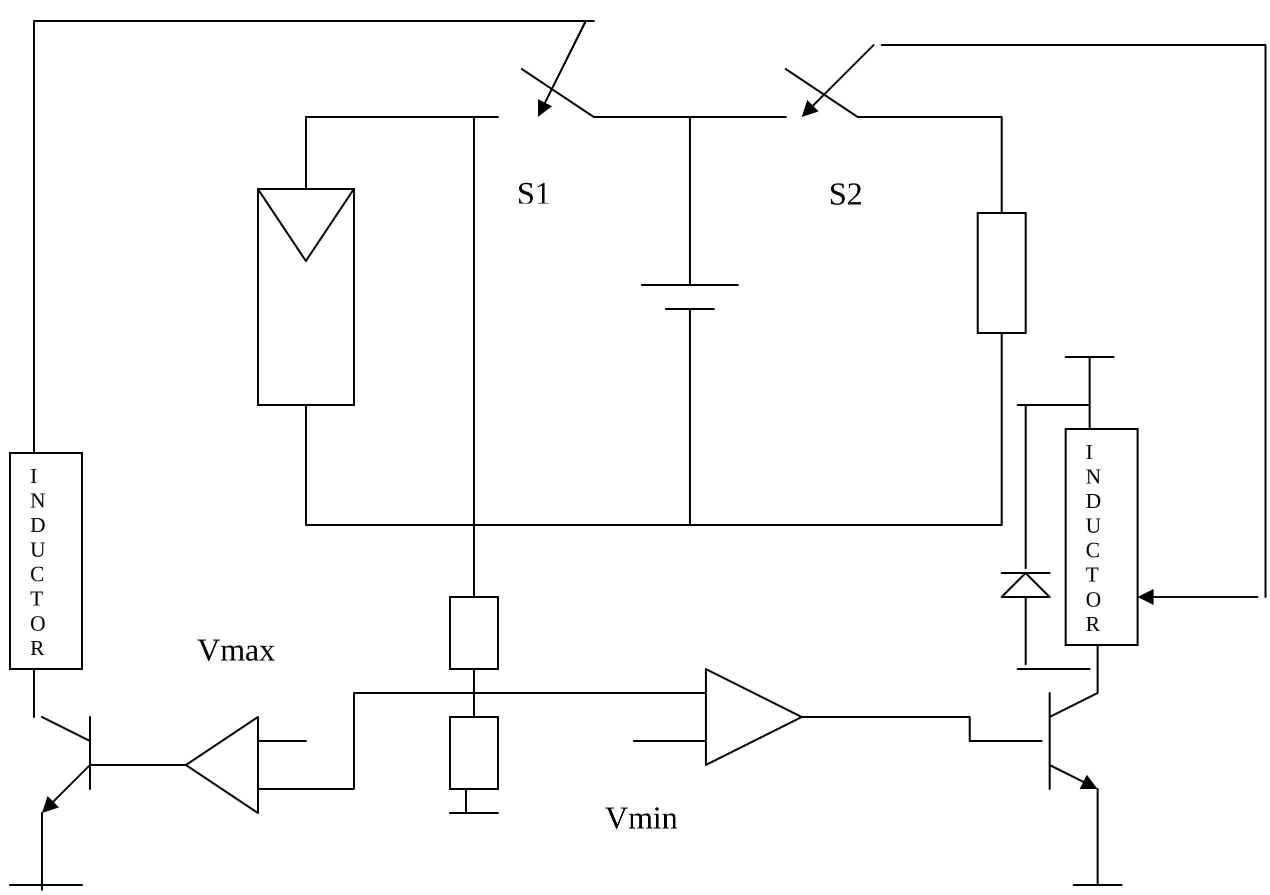


VB>V*max   open S1   close S2
VB<V*min   close S1   openS2
Vmin<VB<Vmax   close S1 close S2



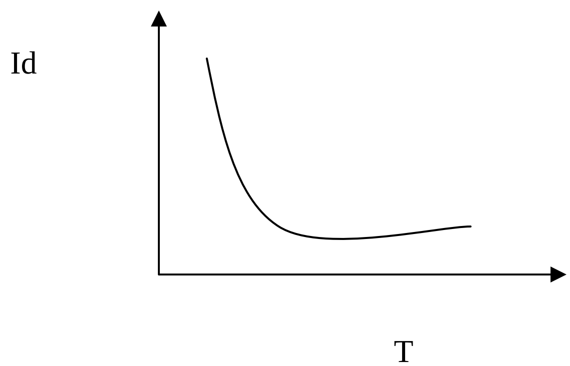
Battery sizing:
Lead acid 35W/Kg
NiCd 60W/Kg
NiMH 100W/Kg
Li polymer batteries 250W/Kg


S1
S2
INDUCTOR
INDUCTOR


S1
S2
INDUCTOR
INDUCTOR
Vmax
Vmin

The capacity of the battery is expressed in Wh or in Ah. C_{10} battery implies that the battery can be discharged in 10 hours. If the rating of the battery is 50Ah , then discharge current is (50/10) = 5 amper.

In general for Cn battery Ah amper hour capacity the discharge current is id=Ah/n.
If the battery is discharged at a current greater than id, the capacity of the battery will reduce.



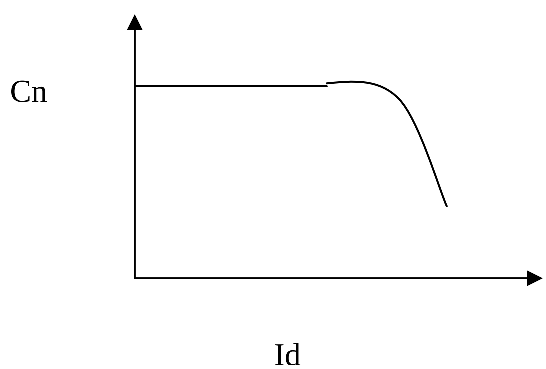
Capacity of the battery is constant

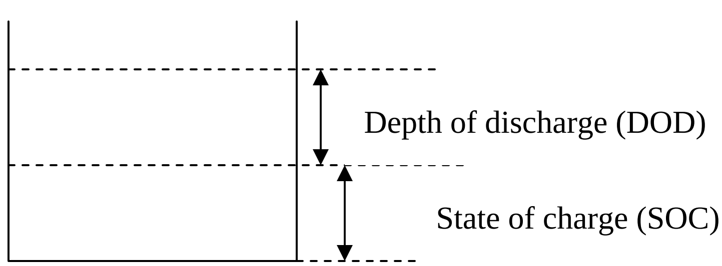
$C=Ah$

When $Id>Ah/n$

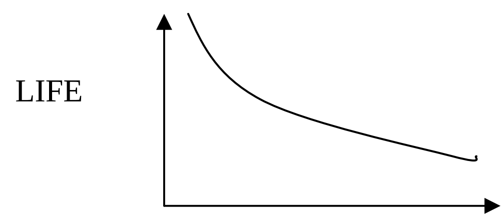
$C=Id^2t$

$T=C/Id^2$





A battery is not generally discharged completely.
Utilizable energy=Wh(load)
Total capacity of battery=Wh(load)/DOD
SLI batteries have depth of discharge of 20%. Life (number of charge discharge cycles) of battery is function of DOD and its variation is as shown:

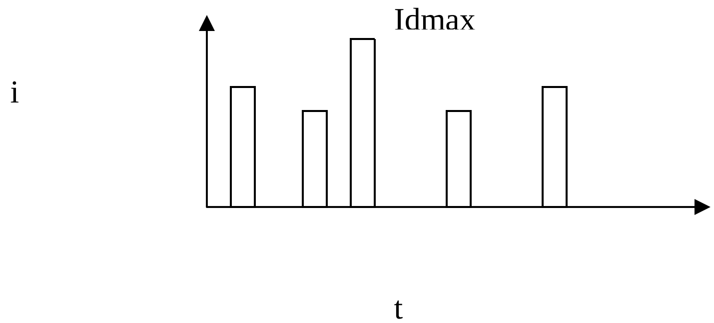


1 charge cycle+1 discharge cycle=1 cycle
Life of lead acid batteries is around 1000 cycles.
Let Vb be the nominal voltage of the battery.
Wh(load)/(Vbnominal * DOD)=Ah(battery capacity)
Total load (Wh) → Wh(day)
→ Wh(night)

Considering that PV cell is not in action for a day. On next day PV cell has to replenish part of battery charge lost when PV was not in action, supply day load, charge night load to the battery.

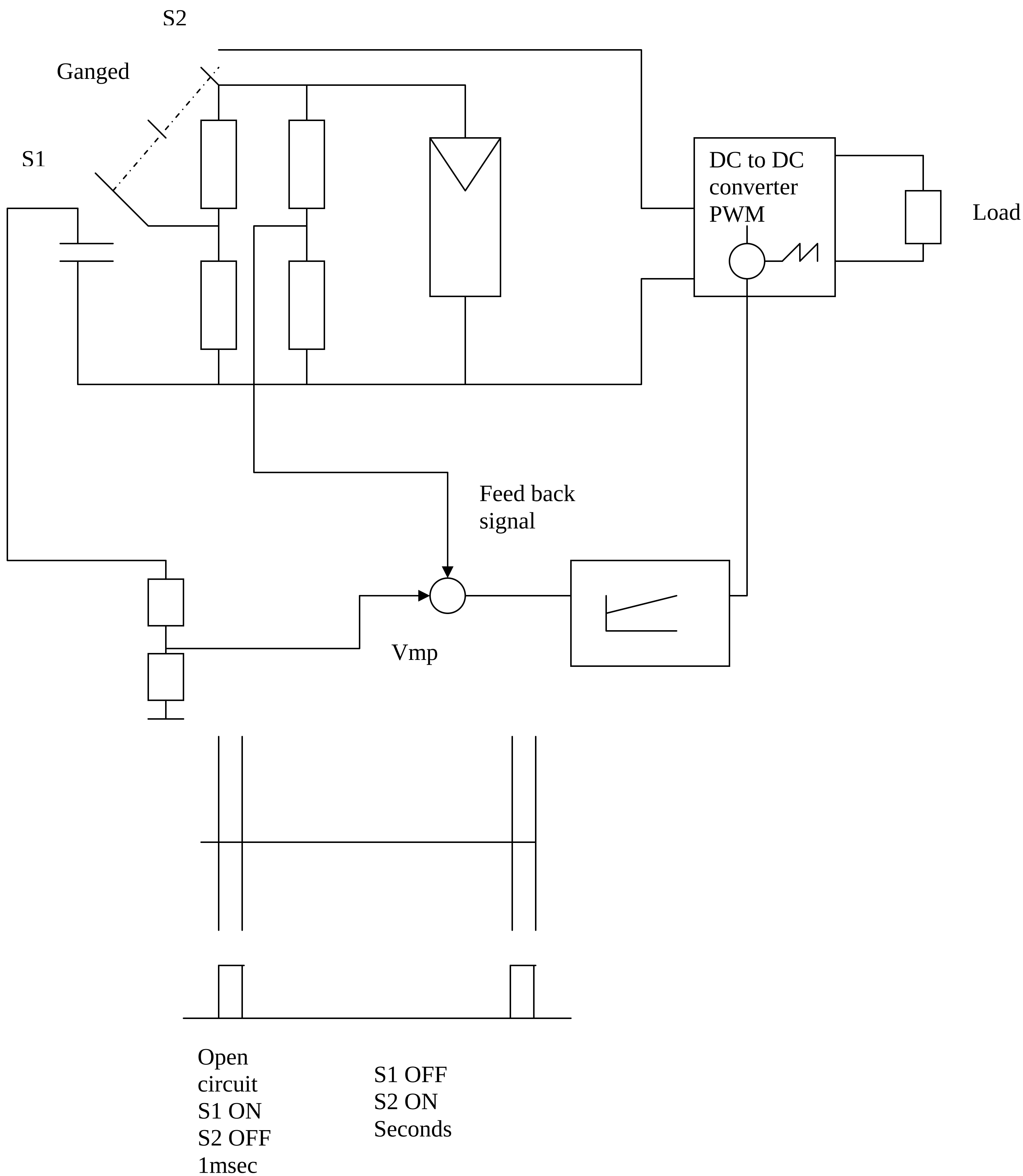
PV rating= replenish part of battery charge lost when PV was not in action + supply day load +charge night load to the battery.

Efficiency of battery=Ah out/(Ah in)
=95% to 98%
Efficiency =Wh out/(Wh in)
=Vbdischarge/(Vbcharge)*ηAh
PV rating=Wh(load)/(m*ηb)+Wh day+Wh night/ηb
Where m is number of days taken to recharge
=(Wh(load)*number of days PV is not operational)/(m*ηb)+Wh day+Wh night/ηb
To get the rating in watts divide the rating by number of hours peak isolation is available.
PV rating=Wh/h1
To find h1=4.83KWh/m^2/day/(1KW/m^2)
Battery sizing=Wh(load)*number of no sun days/(DOD*Vbmax)
PV sizing:
W peak= (1/h1)* {Wh(load)/(m*ηb)+Wh day+Wh night/ηb}
Rating of battery Cn
To find n:=Ah/Idmax

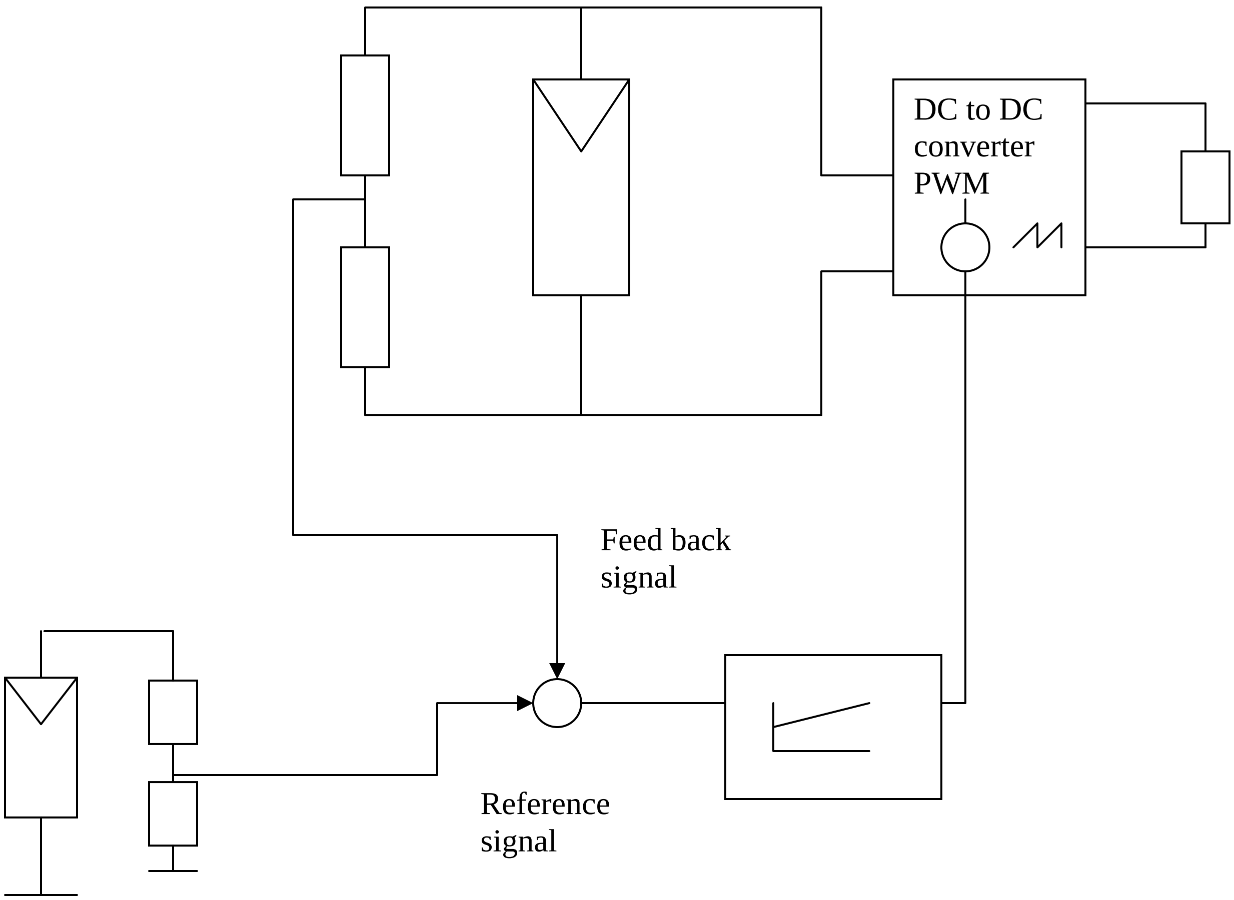


Idmax
i
t

Student slide 3-04
Algorithm for maximum power tracking:
Algorithm 1:
This algorithm can be realized using sample hold circuit or by using a reference cell. The two realizations are as shown:

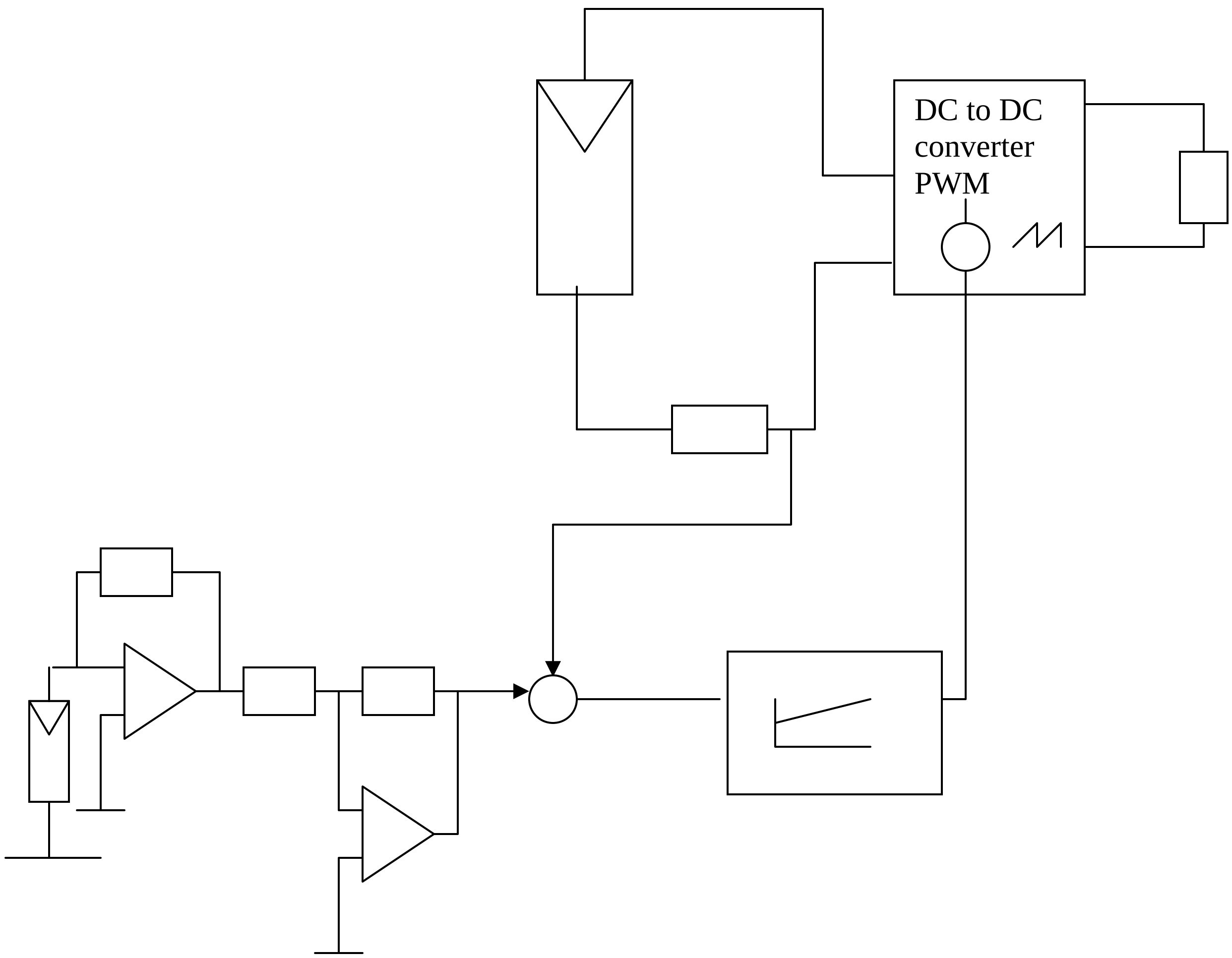


Using reference cell:



Algorithm 2:
Imp/Isc=K

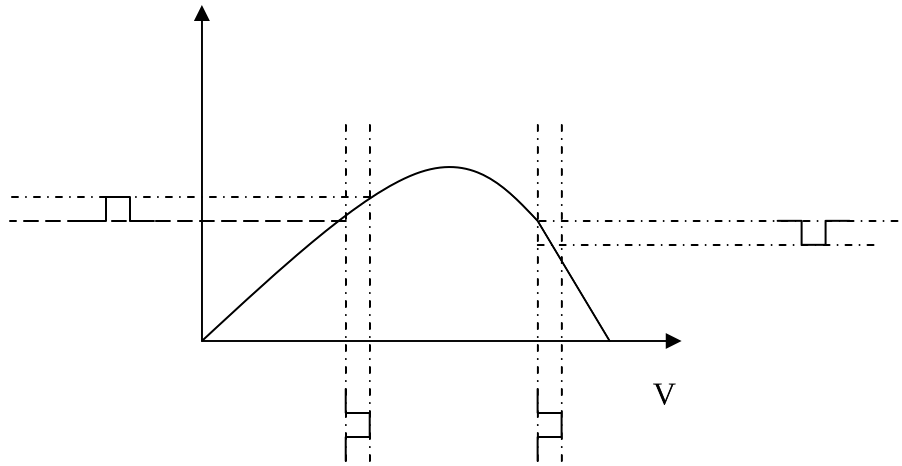
To measure current Hall effect sensor or resistance can be used.
To get Isc a current to voltage converter is used.
The circuit to implement this algorithm is as shown:

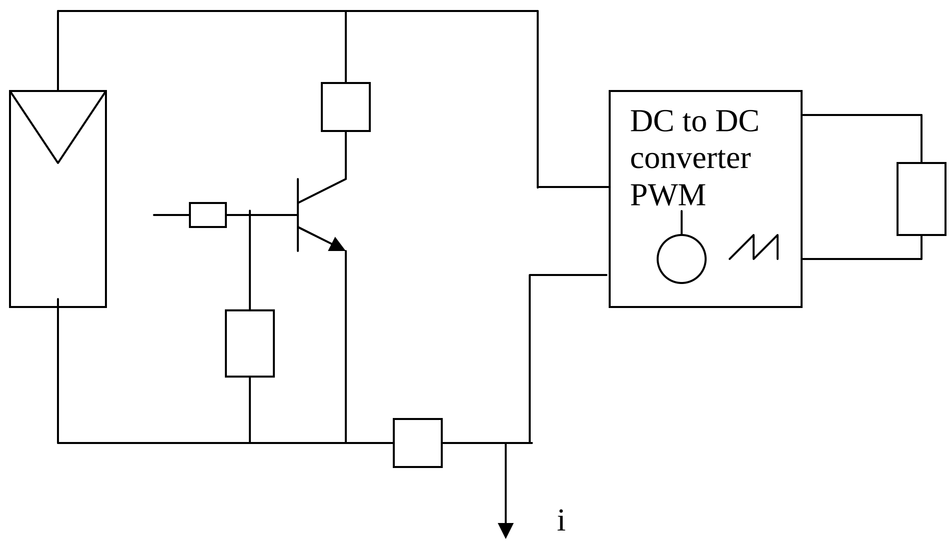


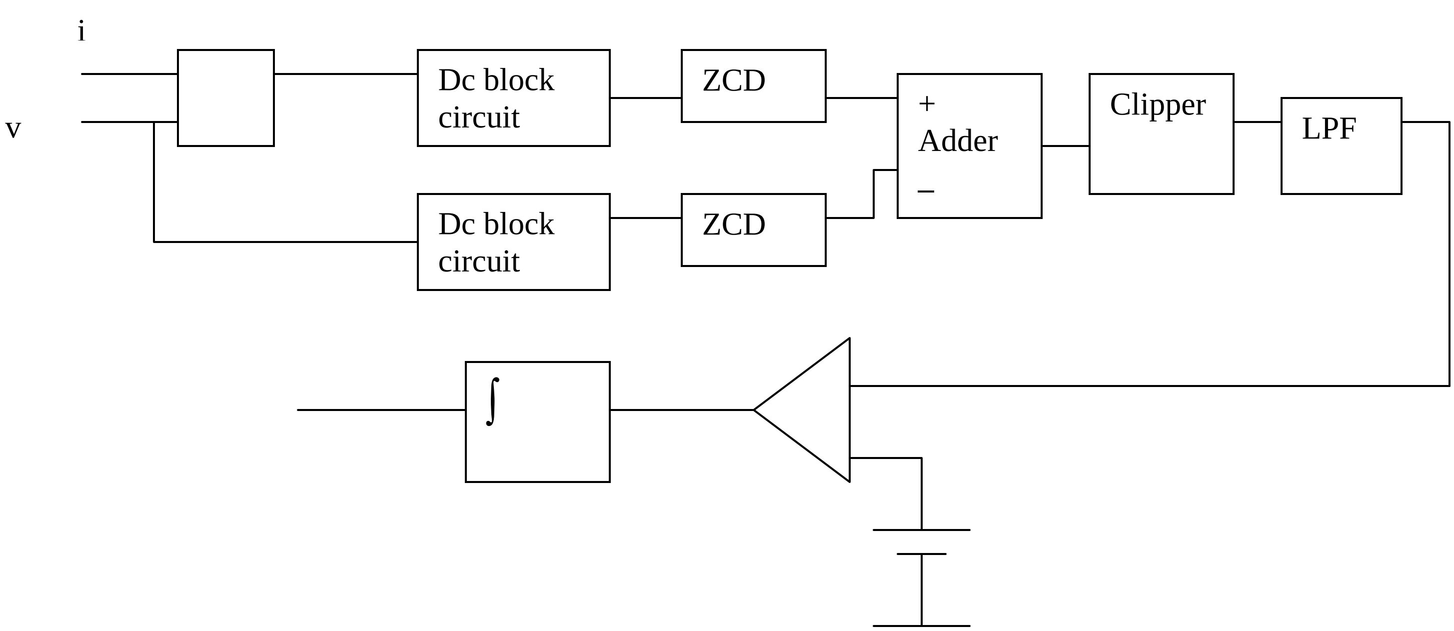
Algorithm 3:

In this method a signal with known phase is superimposed. By observing phase difference between output and voltage D is varied by a small value accordingly.

The circuit that can be used to implement it as shown:

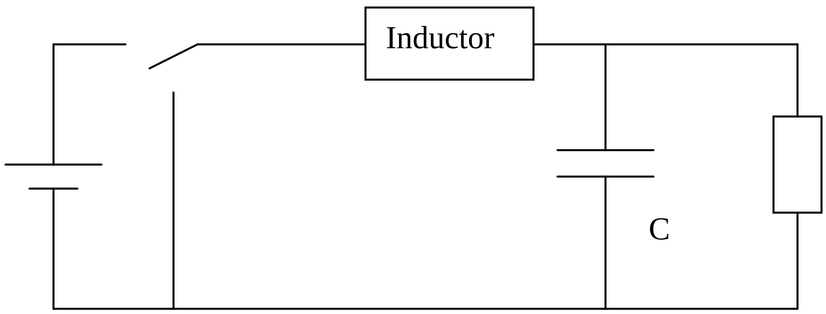

V


DC to DC
converter
PWM
i


i
v
Dc block
circuit
ZCD
+
Adder
–
Clipper
LPF
Dc block
circuit
ZCD
∫

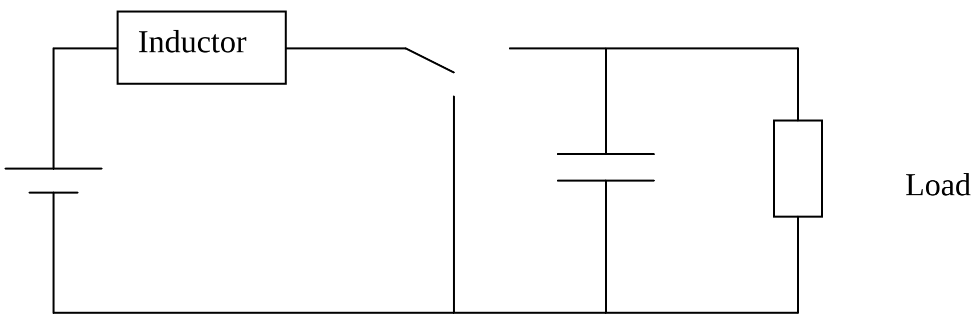
Student slide 3-03
To operate the PV cell at maximum power point an electronic converter (switched mode converter) is used as interface between source and load.
The basic converters are:
Buck
Boost
Buck boost

BUCK CONVERTER:



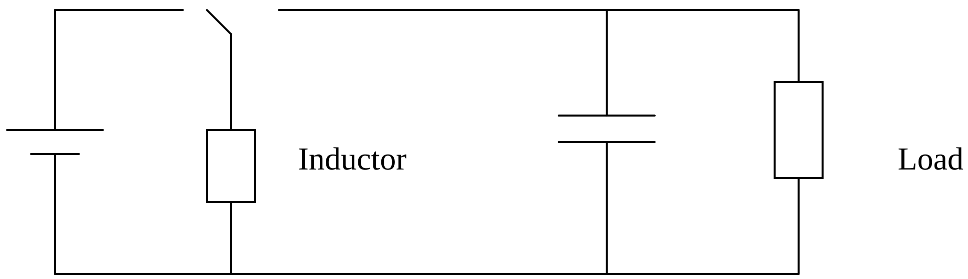
Vo=Dvin
Rin=Vin/Iin
Vin=Vo/D
Iin=Io.D
$Rin=Ro/D^2$

BOOST CONVERTER:



Vo=Vin/(1-D)
$Rin=Ro(1-D)^2$

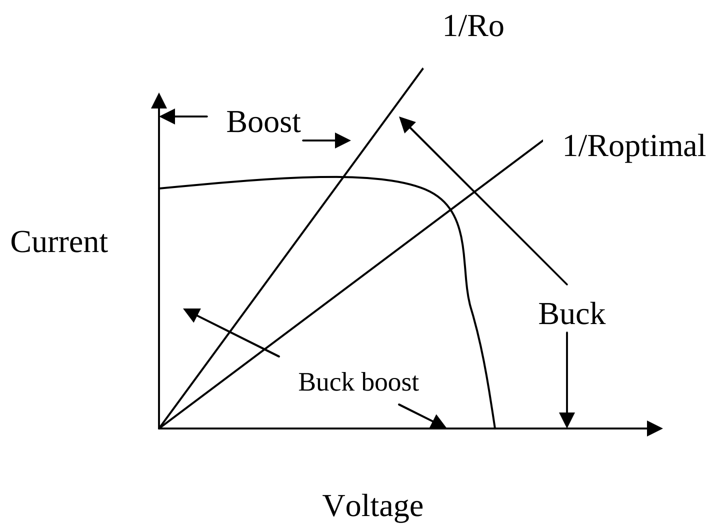
BUCK BOOST CONVERTER:



$V_o = -D v_{in}/(1-D)$

$R_{in} = R_o (1-D)^2/D^2$

By using any of the converters depending on the requirement, D is adjustede such that Rin is equal to Roptimal.



The above graph gives the various ranges in which buck, boost, buck boost converters are used. Ro is the output load.

For a buck converter:

D=0, Rl=infinity

D=0,Rl=Ro

Therefore the range in which the Rin can be varied is between X axis and load line 1/Ro.(as shown in figure)

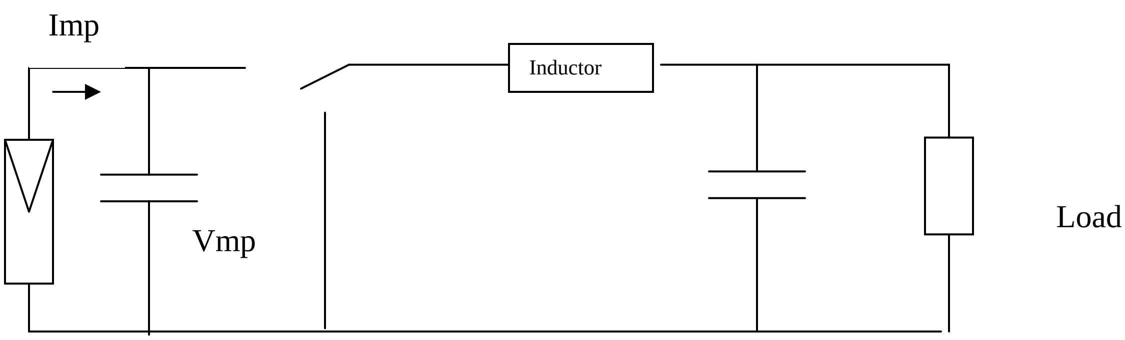
For a boost converter:

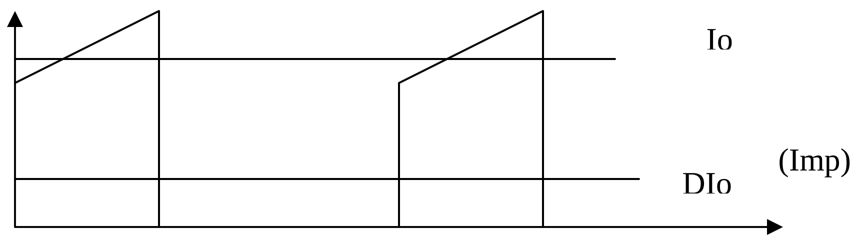
D=0, Rl=Ro

D=0,Rl=0

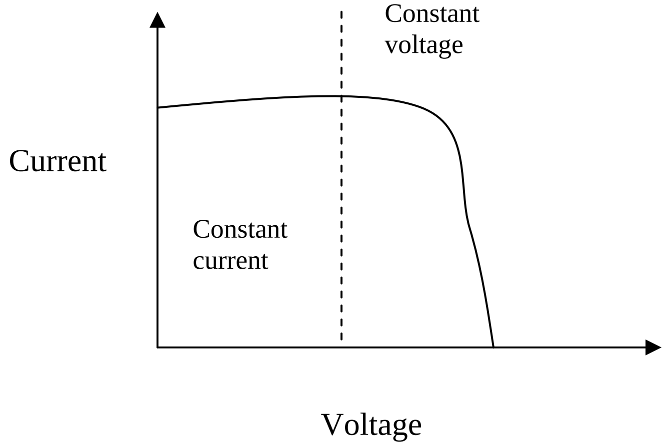
Therefore the range in which the Rin can be varied is between Yaxis and load line 1/Ro.(shown in figure)

Buck boost converter:
Using a buck boost converter Rin can be varied with in the entire range. But this is not used because the cost of the capacitor required is very high.
Buck capacitor is preferable. Boost capacitor also requires a large capacitor but it is less when compared to the Buck boost converter.
In the particular example shown a buck converter can be used to bring the load line to Roptimal.
When a buck converter is used for interface a capacitor need to be used as shown in figure.





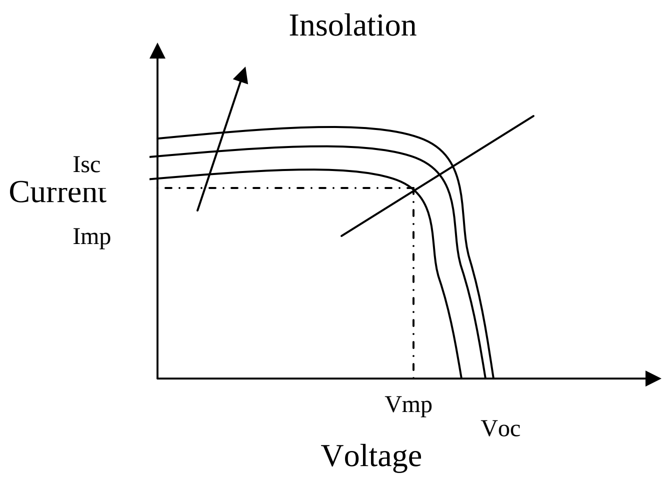
During off time the PV cell charges the capacitor. When switch is on D.Io is supplied by Pv cell and remaining current is supplied by the capacitor.



The graph shows constant current operating region and constant voltage operating region. The stable operating point never stays in constant current region. It moves to constant voltage region.

In order that PV cell always operates at maximum efficiency, a control circuit is required such that it makes D such that operating point is always maximum power point. This is called maximum power tracking. If load line is close to MPP then there is no need of MPPT.

ALGORITHM FOR MPPT:



Vmp/Voc=K

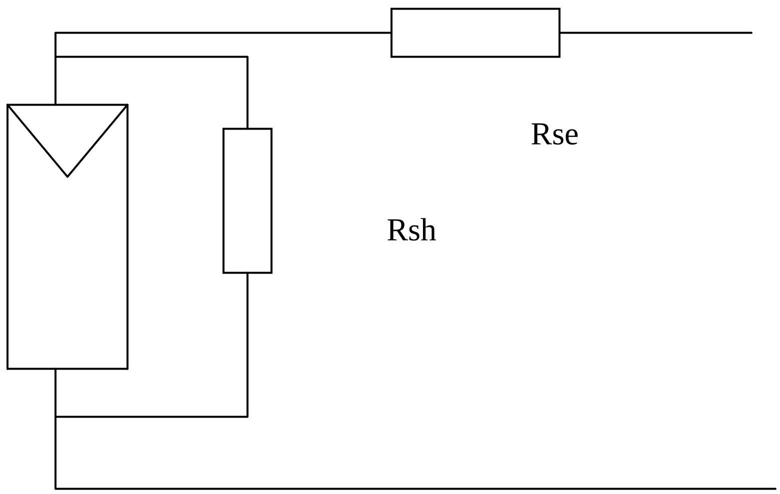
Imp/Ioc=K

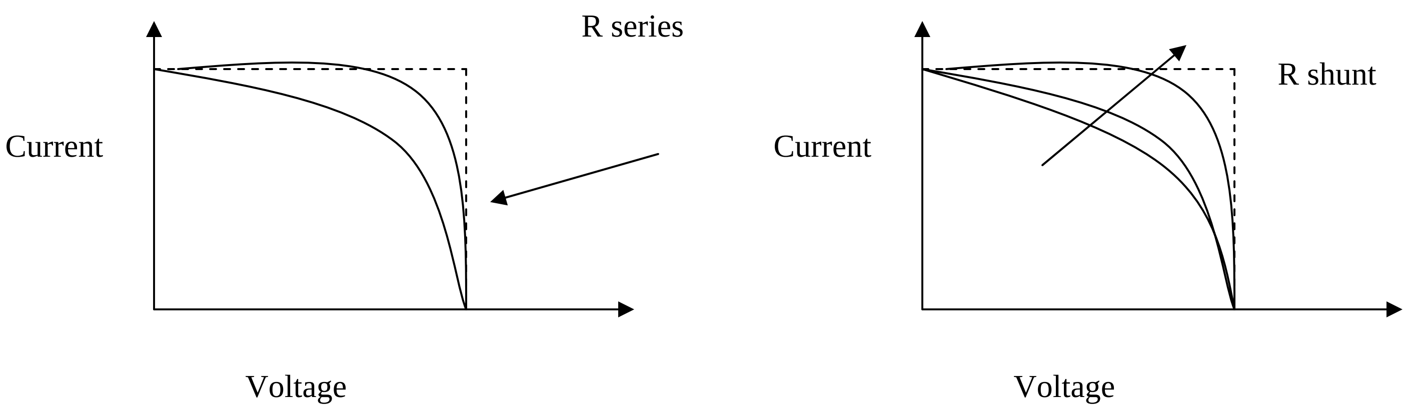
Find Voc. multiply with K and adjust D such that terminal voltage is Vmp.

Similar procedure can be followed to find D using Imp.

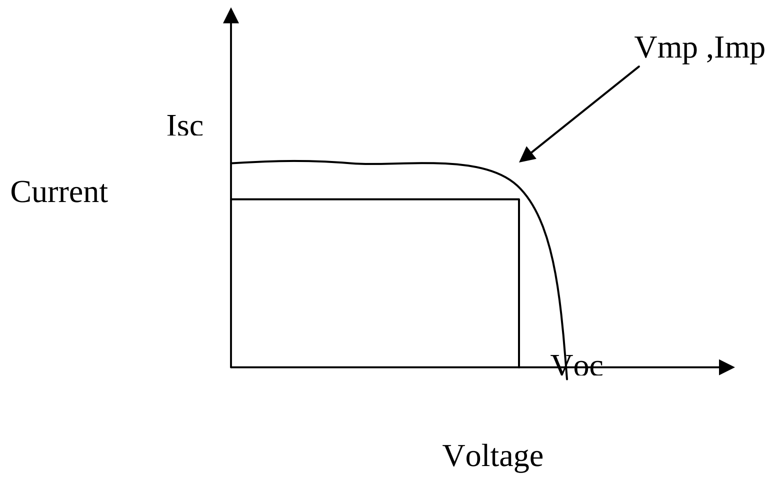
It is easy to sense Isc when compared to Voc.

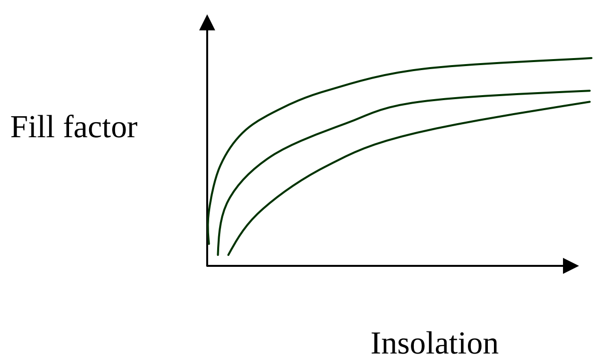
Student slide 3-02





To find the quality of the solar panel fillfactor is used.
It is defined as (Vmp*Imp)/ (Voc*Isc)
A good panel has fill factor in the range of 0.7 to 0.8. for a bad panel it may be as low as .4
Vmp, Imp, Voc Isc are defined as shown in figure.
The variation fill factor with insolation is as shownin figure 2.

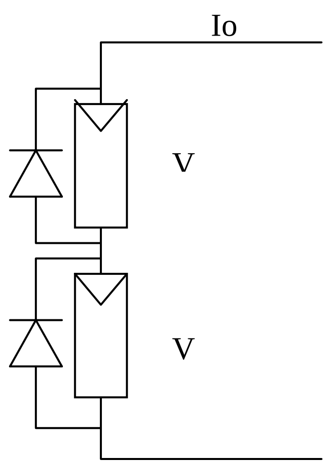


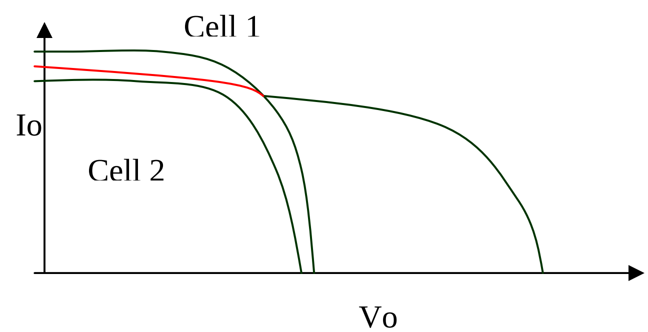


Series and parallel connections of PV panels:

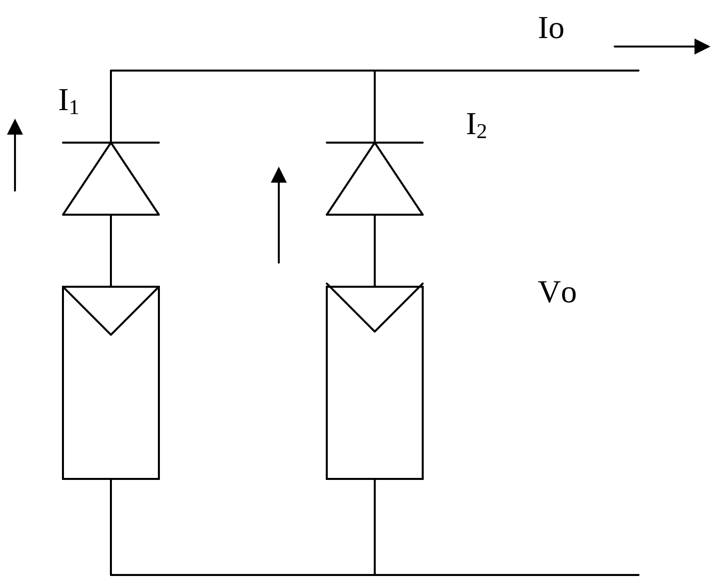
To avoid the any cell to become sink when connected in parallel a diode in series with each cell is connected. To avoid the cell to become sink when the load reduces, a diode is connected in the parallel of the each PV Cell.

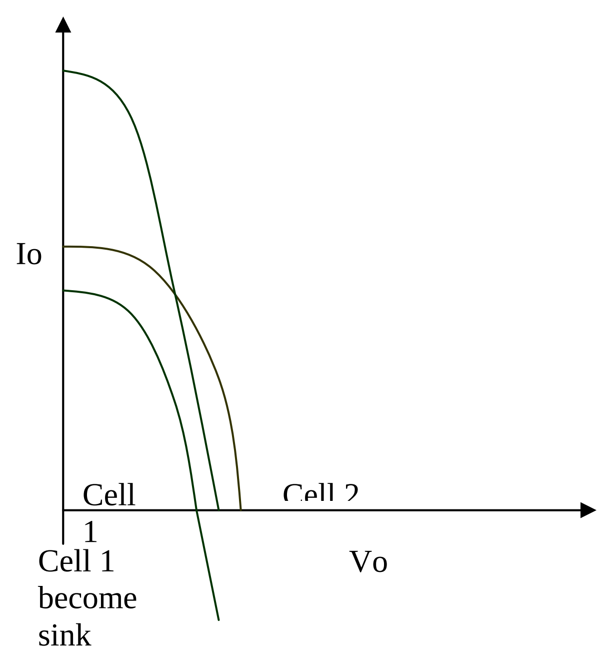
Series connection:





Parallel connection:

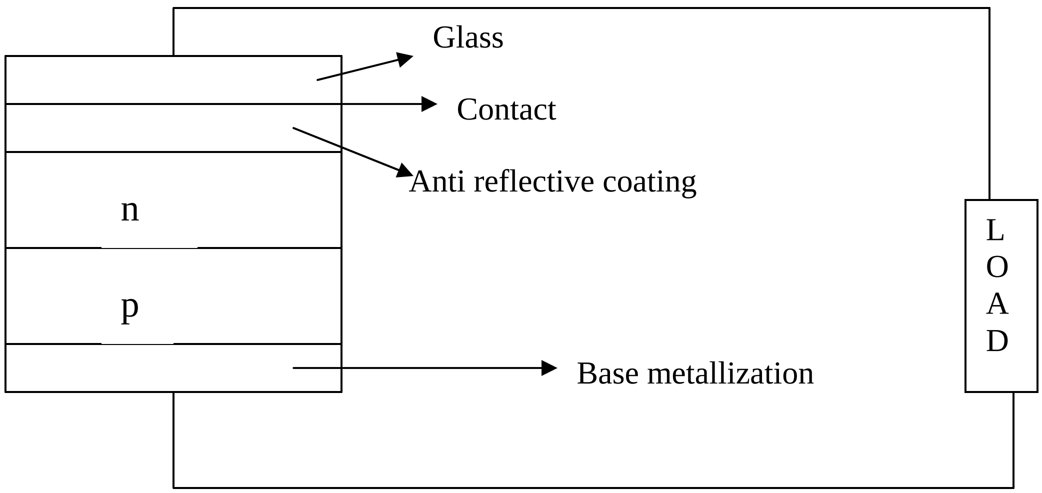




Student slide 3-01

In 1839 Edmond Becquerel accidentally discovered photovoltaic effect when he was working on solid-state physics.
In 1878 Adam and Day presented a paper on photovoltaic effect.
1n 1883 Fxitz fabricated the first thin film solar cell.
In 1941 ohl fabricated silicon PV cell but that was very inefficient.
In 1954 Bell labs Chopin, Fuller, Pearson fabricated PV cell with efficiency of 6%.
In 1958 PV cell was used as a backup power source in satellite Vanguard-1. this extended the life of satellite for about 6 years.

Construction of PV cell:



A PV cell can be either circular in construction or square.

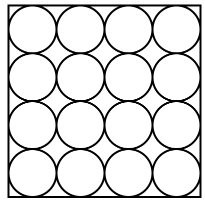
Cells are arranged in a frame to form a module. Modules put together form a panel. Panels form an array. Each PV cell is rated for 0.5 – 0.7 volt and a current of 30mA/cm2. Based on the manufacturing process they are classified as:

Mono crystalline: efficiency of 12-14 %. This are now predominantly available in market

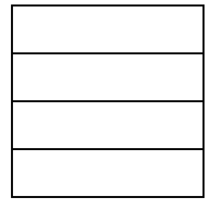
Poly crystalline: efficiency of 12%

Amorphous: efficiency of 6-8%

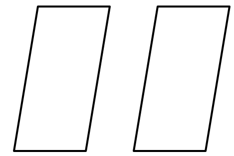
Life of crystalline cells is in the range of 25 years where as for amorphous cells it is in the range of 5 years.



PV module

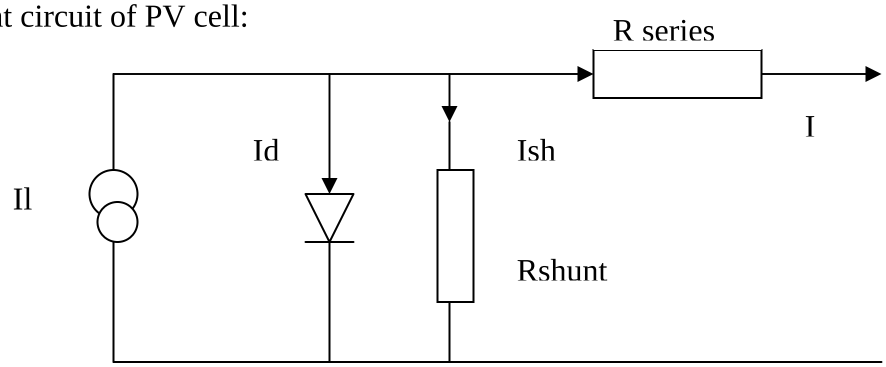


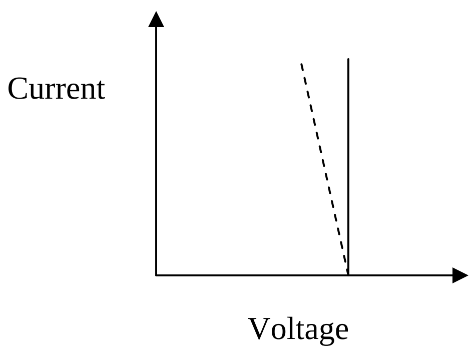
PV panel



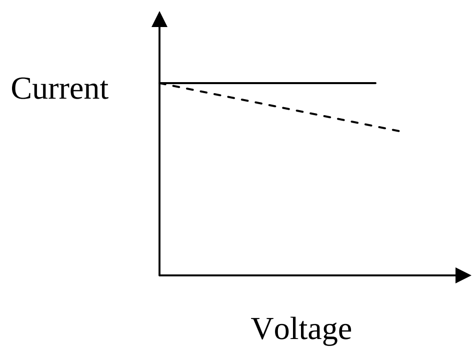
Array

Equivalent circuit of PV cell:

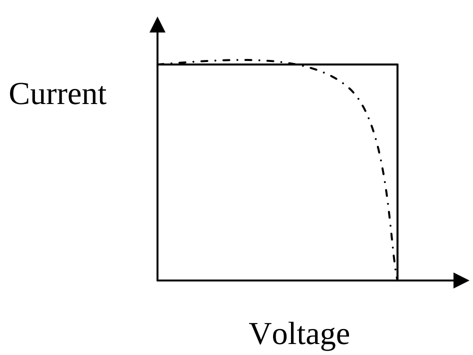




Constant voltage source

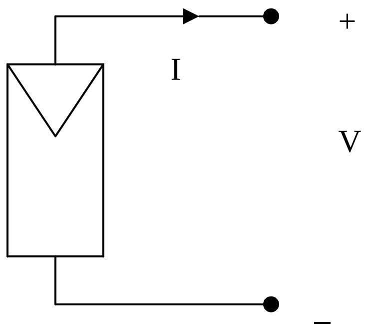


Constant current source



Characteristics of photovoltaic cell

Symbol of PV cell:



$I = I_l - I_d - I_{sh}$

$= I_l - (I_0 \exp(qV_D/nKT) - I_0) - (V_D/R_{sh})$

$V_D = V + Ir_s$

$I = I_l - (I_0 \exp(q(V+Ir_s)/nKT) - I_0) - ((V+Ir_s)/R_{sh})$ -------- 1

Short-circuiting terminals:

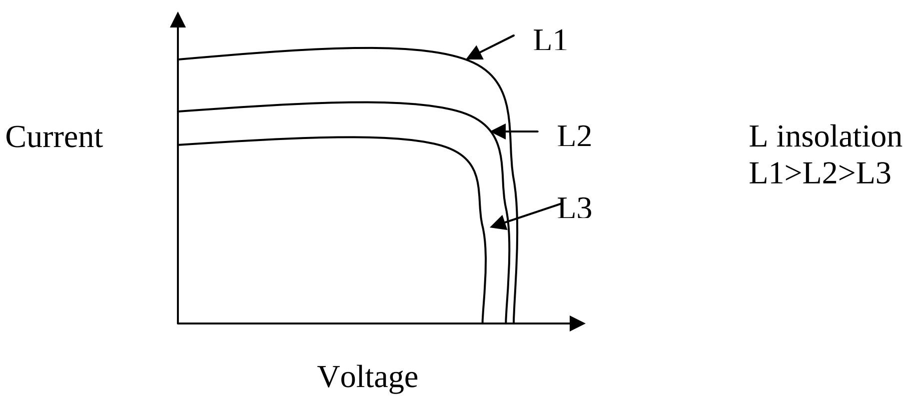
In equation 1 if V=0 and Rs tends to zero. Rsh tends to infinity.

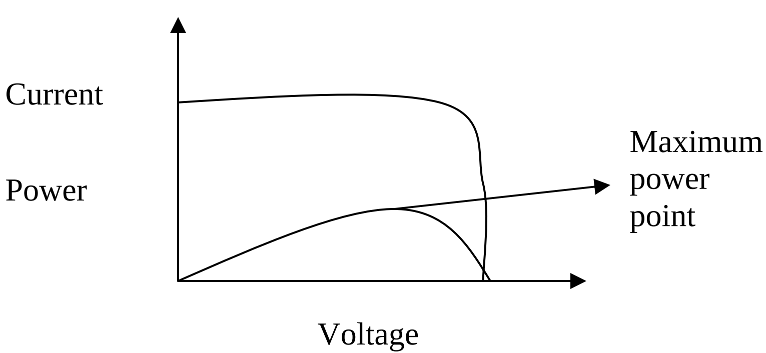
$I_{sc} = I_l$

Open circuit condition:

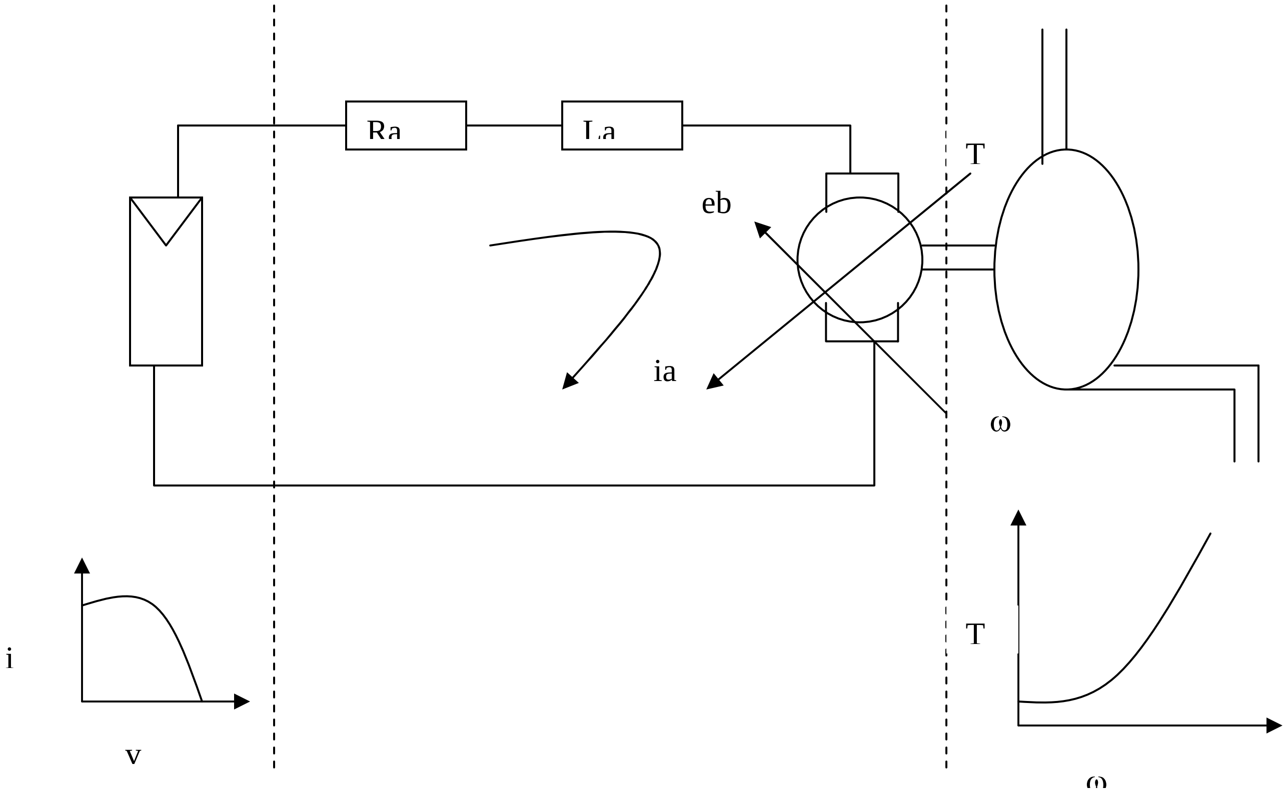
In equation 1 if I=0 and Rs tends to zero. Rsh tends to infinity.

$V_{oc} = nKT/q \ln((I_l/I_0)+1)$

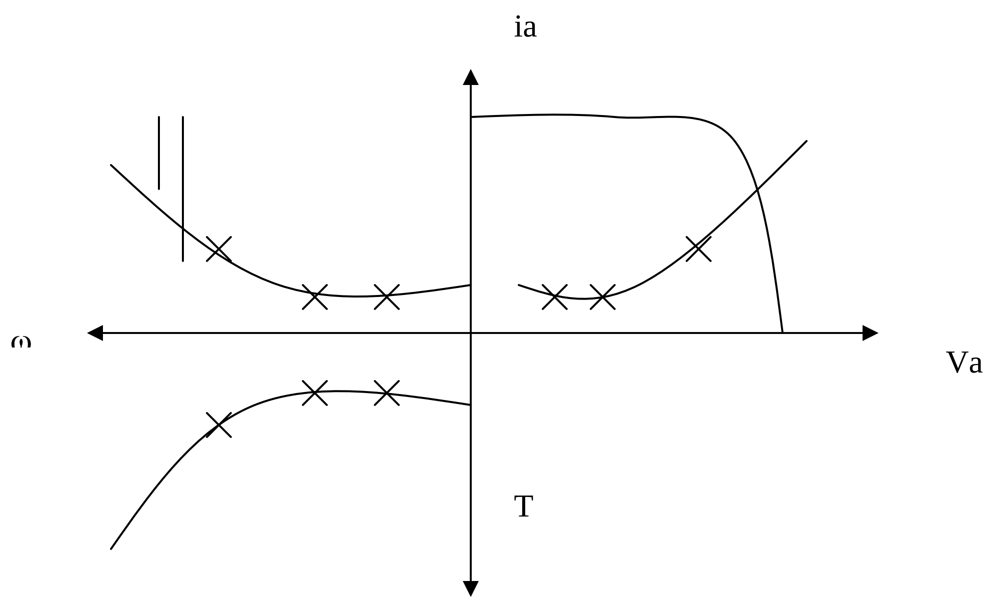




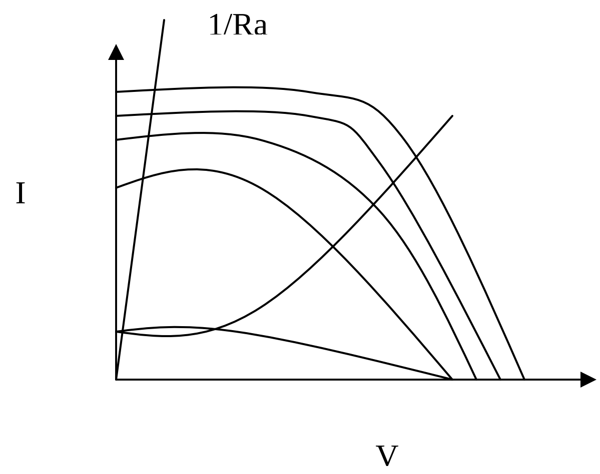
Student slide 3-06
Considering PV cell is supplying a pump load.



In gyrator action
Flow (ia) → Effort (T)
Effort(Eb) → Flow(ω)



	Effort	Flow	Power
Electrical	V	I	VI
Mechanical	F	dx/dt	Fdx/dt
Mechanical	T	ω	Tω
Hydraulic	P	dQ/dt	PdQ/dt
Thermal	temp	dS/dt	
Magnetic	mmf	dφ/dt	



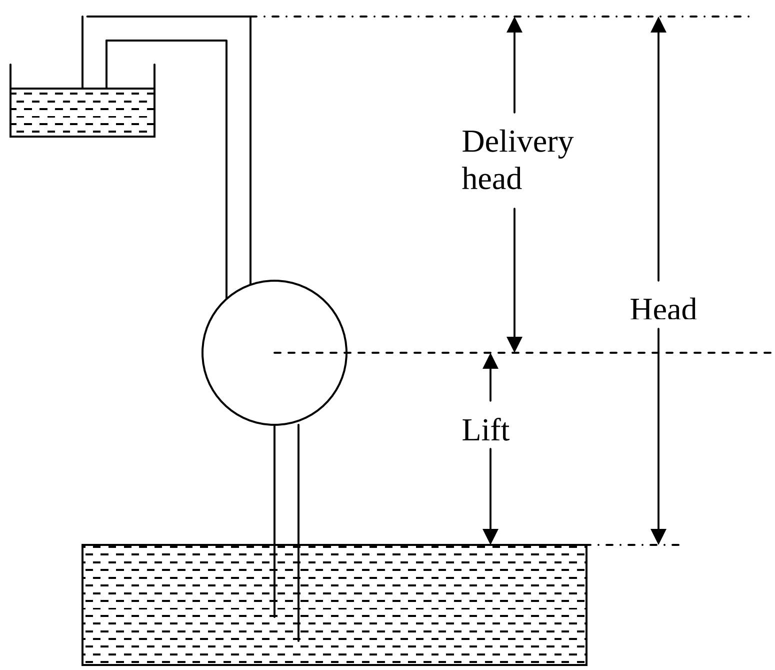
At starting of motor the current drawn by the motor is high, corresponding to va/ra. Hence to supply the starting current minimum isolation is required.

Hydraulic energy:

Centrifugal pump is used.

Hydraulic energy=mgh=ρQgh=1000*9.81*Qh

Power=ρ*dQ/dt



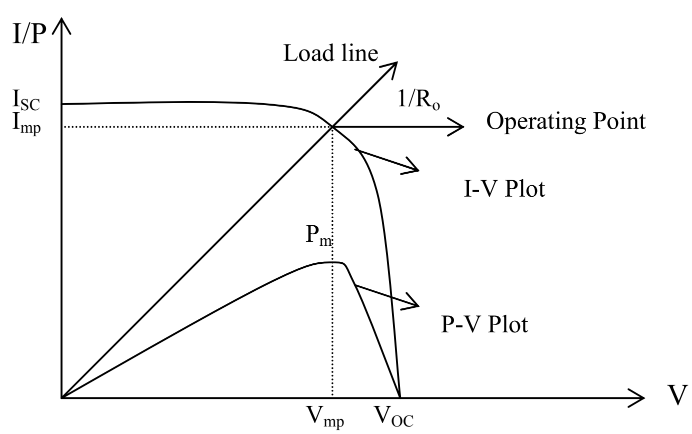
Non-conventional energy systems

Maximum Power Point:

We have seen in earlier section that the quality of a cell can be determined once we know 'open circuit' voltage, 'short circuit' current, and voltage at maximum power point and current at maximum power point.

How do we get the last two points?

It is a two-step procedure. First step is to plot 'voltage' Vs 'power' graph of the cell. Power is calculated by multiplying voltage across the cell with corresponding current through the cell. From the plot, maximum power point is located and corresponding voltage is noted. The second step is to go to the V-I characteristics of the cell and locate the current corresponding to the voltage at maximum power point. This current is called the current at maximum power point. These points are shown in the following figure:



The point at which I_{mp} and V_{mp} meet is the maximum power point. This is the point at which maximum power is available from the PV cell. If the 'load line' crosses this point precisely, then the maximum power can be transferred to this load. The value of this load resistant would be given by:

$$R_{mp} = \frac{V_{mp}}{I_{mp}}$$

What do we do such that PV always sees this constant load resistance $R_o = R_{mp}$?

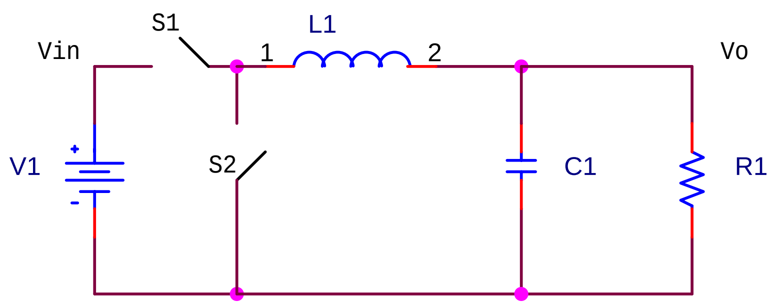
Before we can answer this question, first let us review some basic DC-DC converters. Following are the three basic types of DC-DC converters:

Buck Converter: This is a converter whose output voltage is smaller than the input voltage and output current is larger than the input current. The circuit diagram is shown in the following figure. The conversion ratio is given by the following expression:

$$\frac{V_o}{V_{in}} = \frac{I_{in}}{I_o} = D \quad \text{………………………………………………………………………(1)}$$

Where D is the duty cycle. This expression gives us the following relationships:

$$V_{in} = \frac{V_o}{D} \quad \text{………………………………………………………………………..(2)}$$



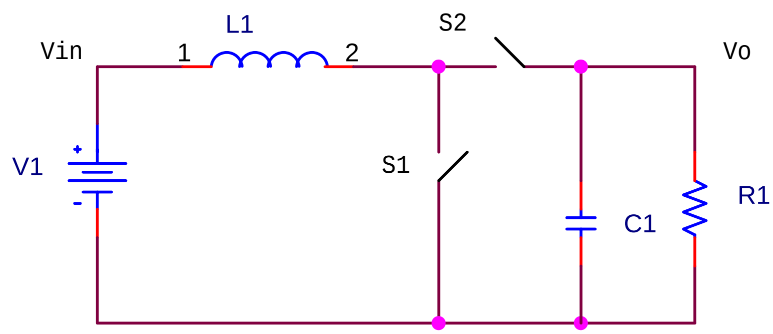
$$I_{in} = I_o D \quad \text{………………………………………………………………………(3)}$$

Knowing V_{in} and I_{in}, we can find the input resistance of the converter. This is given by

$$R_{in} = \frac{V_{in}}{I_{in}} = \frac{(V_o/D)}{I_o D} = \frac{(V_o/I_o)}{D^2} = \frac{R_o}{D^2} \quad \text{……………………………………………..(4)}$$

Where R_o is the output resistance or load resistance of the converter. We know that D varies from 0 to ∞(0 to 1 not inf). Hence R_{in} would vary from ∞ to R_o as D varies from 0 to 1 correspondingly.

Boost Converter: This is a converter whose output voltage is larger than the input voltage and output current is smaller than the input current. The circuit diagram is shown in the following figure.



The conversion ratio is given by the following expression:

$$\frac{V_o}{V_{in}} = \frac{I_{in}}{I_o} = \frac{1}{1-D} \quad \ldots\ldots(5)$$

Where D is the duty cycle. This expression gives us the following relationships:

$$V_{in} = V_o(1-D) \quad \ldots\ldots(6)$$

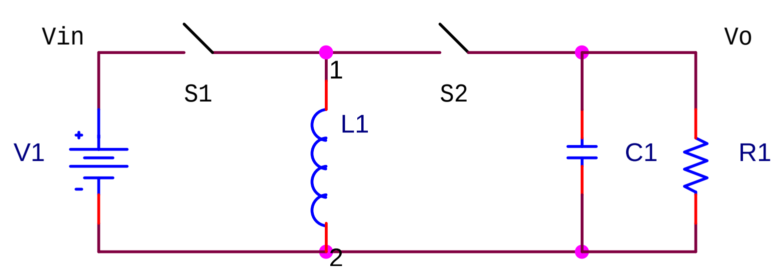
$$I_{in} = \frac{I_o}{1-D} \quad \ldots\ldots(7)$$

Knowing V_{in} and I_{in}, we can find the input resistance of the converter. This is given by

$$R_{in} = \frac{V_{in}}{I_{in}} = \frac{V_o(1-D)}{\left(I_o/(1-D)\right)} = \left(\frac{V_o}{I_o}\right)(1-D)^2 = R_o(1-D)^2 \quad \ldots\ldots(8)$$

Here, R_{in} varies from R_o to 0 as D varies from 0 to 1 correspondingly.

Buck-Boost Converter: As the name indicates, this is a combination of buck converter and a boost converter. The circuit diagram is shown in the following figure:



Here, the output voltage can be increased or decreased with respect to the input voltage by varying the duty cycle. This is clear from the conversion ratio given by the following expression:

$$\frac{V_o}{V_{in}} = \frac{I_{in}}{I_o} = \frac{D}{1-D} \quad \text{.......(9)}$$

Where D is the duty cycle. This expression gives the following relationships:

$$V_{in} = V_o\left(\frac{1-D}{D}\right) \quad \text{.......(10)}$$

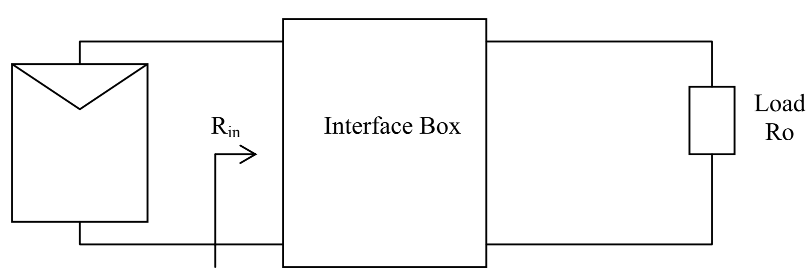
$$I_{in} = I_o\left(\frac{D}{1-D}\right) \quad \text{.......(11)}$$

Knowing V_{in} and I_{in}, we can find the input resistance of the converter. This is given by

$$R_{in} = \frac{V_{in}}{I_{in}} = \left(\frac{V_o}{I_o}\right)\left(\frac{(1-D)^2}{D^2}\right) = R_o\left(\frac{(1-D)^2}{D^2}\right) \quad \text{.......(12)}$$

Here, R_{in} varies from ∞ to 0 as D varies from 0 to 1 correspondingly.

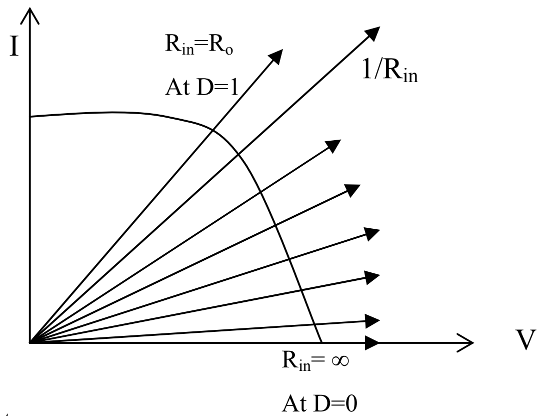
Now let us see how these converters come into picture of PV. We had seen earlier that maximum power could be transferred to a load if the load line lies on the point corresponding to V_m and I_m on the V-I characteristics of the PV cell/module/panel. We need to know at this point that there is always an intermediate subsystem that interfaces PV cell/module and the load as shown in the following figure:



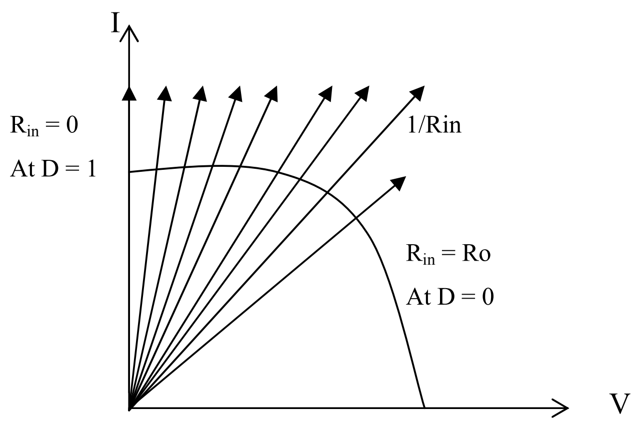
This subsystem serves as a balance of system that controls the whole PV system. DC-to-DC converter could be one such subsystem. So far we have seen three different types of converters and its input resistance R_{in}'s dependency on the load resistance and the duty cycle. To the PV cell/module, the converter acts as a load and hence we are interested in the input resistance of the converter. If we see that R_{in} of the converter lies on the V_{mp}-I_{mp} point, maximum power can be transferred to the converter and in turn to the load.

Let us see the range of R_{in} values for different converters as shown in the following figures:

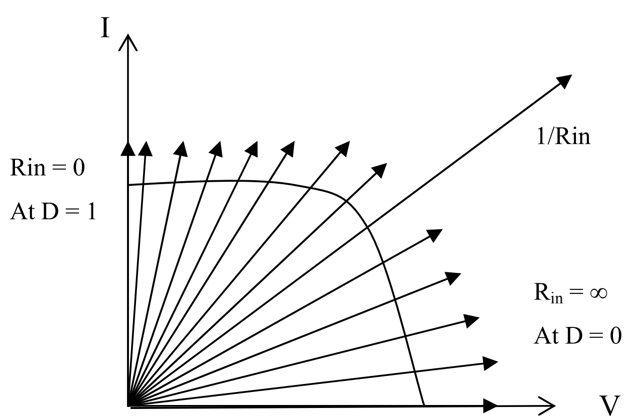
1. Buck Converter:



2. Boost Converter:



3. Buck-Boost Converter:



Now we know the range of R_{in} for various converters. This also implies the range of load that the PV cell/panel can deliver maximum power. Hence, we need to look at the following requirements from an application:

a. Range of load variation.

b. Maximum power point P_{mp} (V_{mp}, Imp).

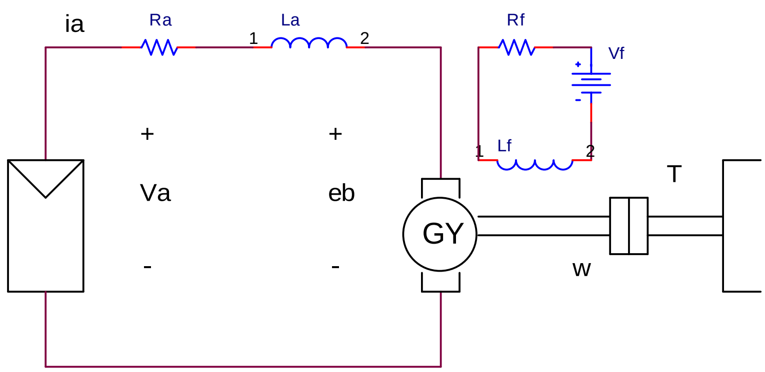
c. Converter type that satisfies the range.

It is apt at this point to mention the need for a capacitor across the PV cell and explain why it is needed.

Non-conventional energy systems

A typical Application: PUMP

Let us consider the following application where a DC motor is connected to PV panel on one side and some load such as a pump on the other side as shown in the following figure:



Ra represents the armature resistance of the motor, La represents the armature inductance of the motor, eb is the back emf developed across the motor, Va is the voltage developed across the armature of the motor, Lf is the inductance of the field coil, Rf is the resistance of the field coil and Vf is the voltage source for the field coil. Field coil is used to excite the motor resulting in constant flux. T represents the torque developed by the motor and ω the angular velocity of the shaft connected to the pump. The DC motor works as a Gyrator. To understand the concept of gyrator first we need to understand the concept of a transformer. If we call voltage as an effort and current as flow, in a transformer, effort on the primary side is related to the effort on the secondary side as a multiple by a constant depending on the turns ratio of the transformer. Similarly, the flow on the primary side is related to the flow on the secondary side as a multiple by a constant again, depending on the turns ratio. If we call the primary side as input and the secondary side as the output then we see that input effort is related to the output effort and input flow is related to the output flow. This is the concept of a transformer. In a gyrator, the relationships are different. The effort on the input side is related to the flow on the output side and the effort on the output side is related to the flow on the input side. Now, let us consider the DC motor. For a DC motor, eb is the input effort, Ia is input flow, T is the output effort and ω is the output flow. Now, let us look at some of the relationships for a DC motor. The first relation ship is given by:

$$T_d \, \alpha \, \phi \cdot I_a \qquad \text{.......... (1)}$$

$$T_d = K \cdot I_a \qquad \text{.......... (2)}$$

where K is a constant proportional to constant flux.

Here, Td is the output effort and Ia is the input flow. We see a cross relationship. Let us see the second relationship given by:

$$\varpi \, \alpha \, \frac{e_b}{\phi} \qquad \text{.......... (3)}$$

$$\varpi = \frac{e_b}{K} \qquad \text{.......... (4)}$$

where K is a constant proportional to constant flux.

Here, eb is the input effort and ω is the output flow. We again see a cross relationship. Hence, we can see that the DC motor is a gyrator.

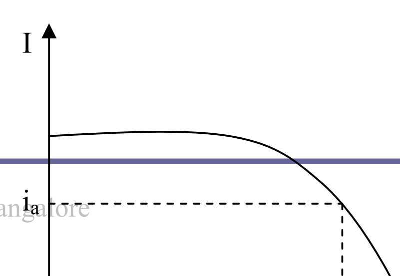
For the above circuit, we can write the following relationship:

$$v_a = i_a \cdot R_a + e_b \qquad \text{.......... (5)}$$

va is the voltage across the PV panel and ia is the current from the panel. Substituting equations (2) and (4) in equation (5), we get the following expression:

$$v_a = \frac{T_d}{K} \cdot R_a + K \cdot \varpi \qquad \text{.......... (6)}$$

Here Td is the load torque required at the motor shaft. From equation (2), this depends on the panel current. The corresponding panel voltage needed can be obtained from the V-I characteristics of the panel as shown in the following figure:

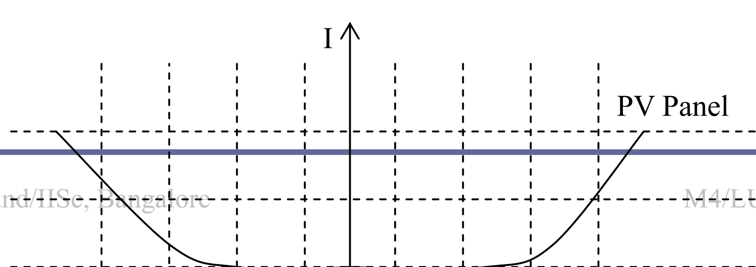


From equation (4), we have seen that the angular velocity of the shaft is related to the back emf, eb developed at the motor. Re-arranging equation (5), we can write the expression for eb as:

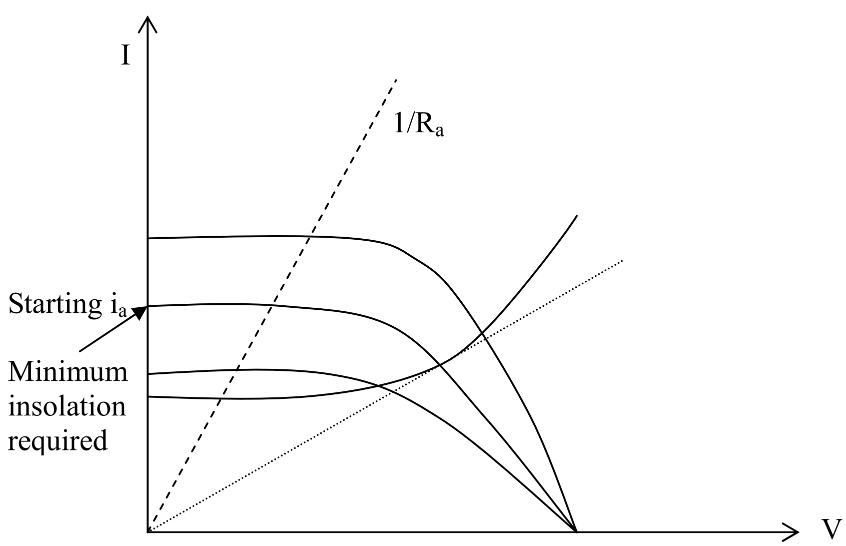
$$e_b = v_a - i_a \cdot R_a \quad \text{......} \quad (7)$$

Here, we can see the relationship between eb and va. Equation (4) gives an important relationship between eb and ω that specifies eb required for the desired speed of the motor. From the equations (4) and (7), we would know va required for desired speed of the motor.

It is clear from the above discussion that DC motor takes electrical input and delivers mechanical output. This output may be used for driving a load such as a pump. Hence, in a big picture, we need to match the characteristics of the PV panel providing the electrical input to the characteristics of the load that is being driven by the mechanical output. The parameters describing the characteristics of the panel are voltage and current. The parameters describing the characteristics of the load are torque and angular velocity or speed. The following figure explains how we match the characteristics of the source and load.



We see the load characteristics in the third quadrant given as a function of torque (T) and the speed (ω). This characteristic is translated into second quadrant using equation (2) that relates torque to the current. Finally, the characteristic is translated into first quadrant using equation (4). This characteristic is superimposed on the characteristics of the PV panel to do the matching, as shown in the following figure:



When the motor is at rest, it does not have eb. Hence the current required for starting the motor can be obtained from equation (5) by substituting eb = 0.

$$i_a = \frac{v_a}{R_a} \qquad \text{.......... (8)}$$

The point indicated by the arrow gives the minimum insolation required for producing the starting current.

This was an example where the characteristics of the PV panel were matched to the mechanical (rotational) characteristics of the load. Following table gives the parameters describing characteristics of different types of loads:

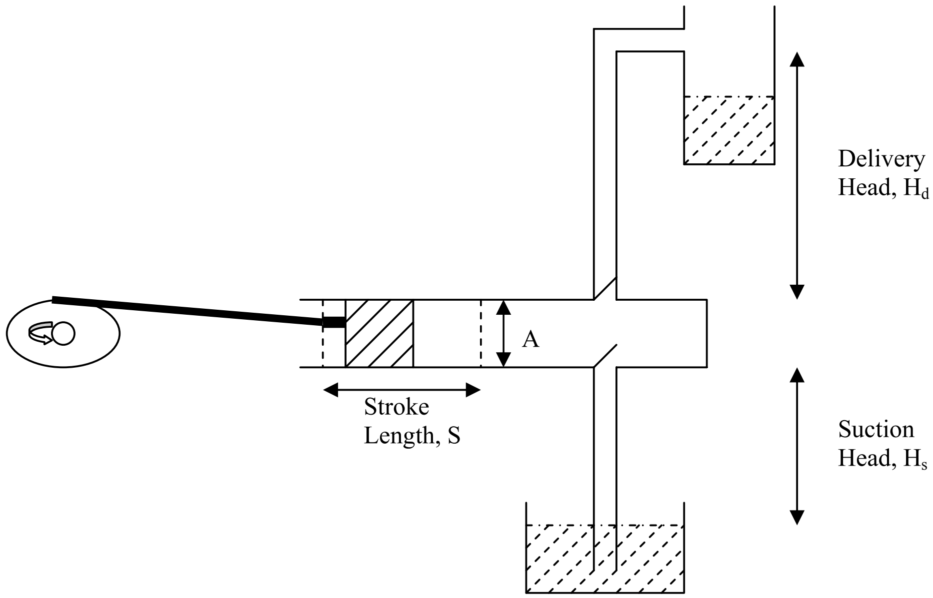
Electrical	Mechanical (Linear)	Mechanical (Rotational)	Hydraulic
Voltage	Force	Torque	Pressure
Current	Linear velocity	Angular velocity	Rate of discharge

Pumps:

We had seen briefly how the characteristics of PV panel are matched to the characteristics of a load such as a pump. Let us know about the pump itself now. Pumps are of two types, reciprocating and centrifugal. Reciprocating pumps have positive displacement and the rate of discharge does not depend on the height to which the water has to be lifted. Centrifugal pumps have dynamic displacement. Its rate of discharge is a function of height to which the water has to be lifted. Let us take these pumps in little more detail:

Reciprocating Pump:

Following figure shows the working of the pump:



In the figure, A is the cross sectional area and S is the stroke length. If ω is the angular velocity then the rate of discharge is given as:

$$\frac{dQ}{dt} \alpha A \cdot S \cdot \omega$$

Since area of the sectional area, and the stroke length are constants for a given piston, we can write:

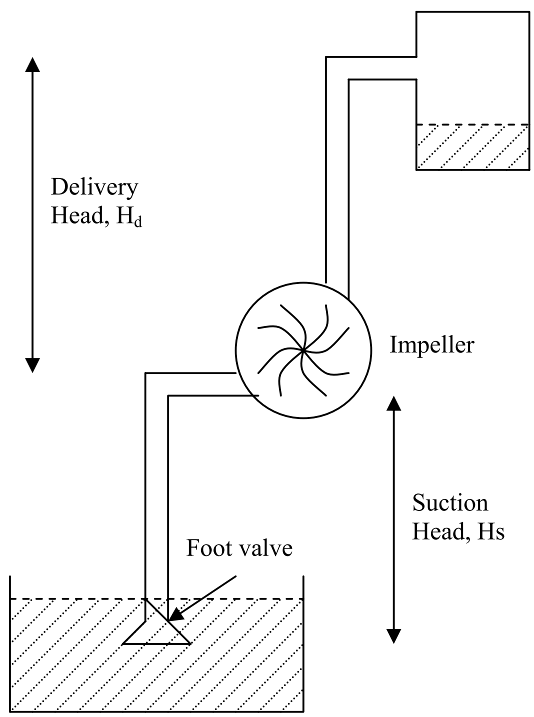
$$\frac{dQ}{dt} \alpha \omega$$

We can see that the rate of discharge is independent of head. However, there is a theoretical limit of 10.33 meters and a practical limit of 6 meters on the suction head, Hs. The static head of the reciprocating pump is the sum of delivery head and suction head.

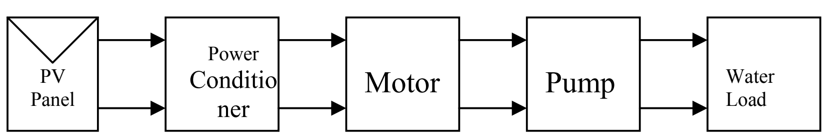
$$StaticHead = H_S + H_d$$

Centrifugal Pump:

The rate of discharge of these pumps depends on the head. A simple centrifugal pump setup is shown in the following figure:



The static head is equal to the sum of the delivery head and suction head. We need to know at this point the amount of energy required to pump the water overhead. Following block diagram gives the entire system, starting from the PV panel as source.



Before we calculate the energy required, we need to know the following expressions:

$Energy = m \cdot g \cdot h$ Joules, where

m = mass of water = Kg

g = acceleration due to gravity = 9.81 m/s2

h = height = meter

$Energy = \rho \cdot Q \cdot g \cdot h$ Joules, where

ρ = density of water = Kg/m3

Q = discharge = m3

g = acceleration due to gravity = 9.81 m/s2

h = height = meter

$Power = \rho \cdot \frac{dQ}{dt} \cdot g \cdot h$ watts, where

ρ = density of water = Kg/m3

dQ/dt = rate of discharge = m3/s

g = acceleration due to gravity = 9.81 m/s2

h = height = meter

1 Kilowatt-Hour = 1000 watts x 3600 seconds = 3.6e6 watt-second = 3.6e6 Joules

1 m3 = 1000 liters

Example: Let us take a simple example for calculating size of a PV panel required to provide power for lifting 1000 liters of water per day to an over-head tank placed at a height of 10 meters.

Discharge required (Q) = 1000 liters/day

= 1 m3/day

Head = 10 meters

g = 9.81 m/s2

Assuming 4 hours of good insolation over a day, we can calculate the rate of discharge as:

$$\frac{dQ}{dt} = \frac{1m^3}{(4x3600)\sec} = \frac{1m^3}{14400\sec}$$

$$\rho_{water} = \frac{1gram}{1ml} = \frac{1e-3Kg}{1e-3liters} = \frac{1Kg}{1liter} = \frac{1Kg}{1e-3m^3} = \frac{1000Kg}{m^3}$$

$$Power = \rho \cdot \frac{dQ}{dt} \cdot g \cdot h = \frac{1000Kg}{m^3} \cdot \frac{1m^3}{14400s} \cdot \frac{9.81m}{s^2} \cdot 10m = \frac{981Kg \cdot m^2}{144s^3} = 6.81watts$$

This is the power required by the pump for pumping water into over head tank. Assuming 80% efficiency of the motor, the power generated by the motor should be:

$$\frac{6.81watts}{0.8} = 8.5125watts$$

Assuming 80% efficiency of the power conditioner unit, the power supplied by the power conditioner unit is:

$$\frac{8.5125watts}{0.8} = 10.641watts$$

Assuming 80% efficiency of the PV panel, the panel should generate:

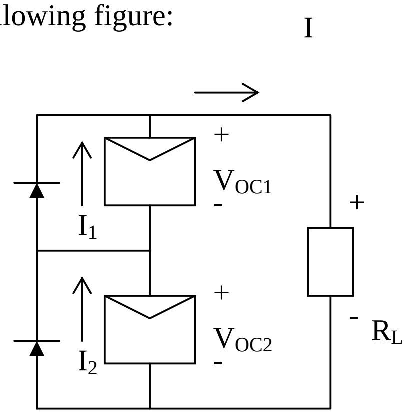
$$\frac{10.641watts}{0.8} = 13.3watts$$

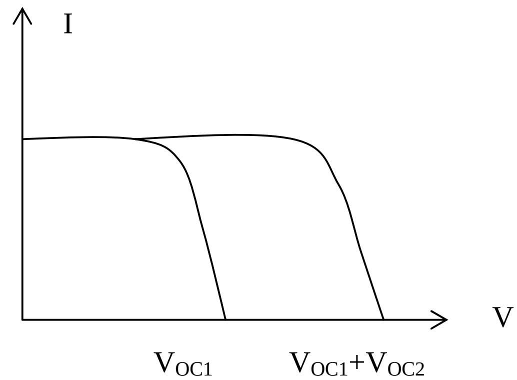
Hence, a 20watt PV panel should serve the purpose.

Non-Conventional Energy Systems

Cells in Series:

When two identical cells are connected in series, the short circuit current of the system would remain same but the open circuit voltage would be twice as much as shown in the following figure:



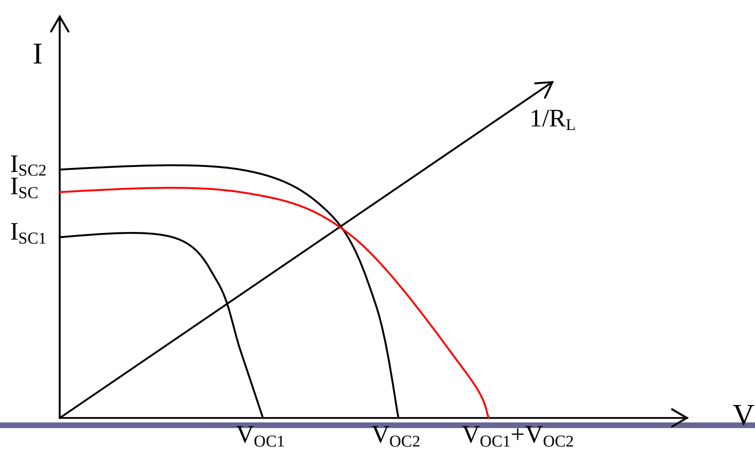


We can see from the above figures that if the cells are identical, we can write the following relationships:

$I_1 = I_2 = I$

$V_{OC1} + V_{OC2} = 2V_{OC}$

Unfortunately, it is very difficult to get two identical cells in reality. Hence, we need to analyze the situation little more closely. Let I_{SC1} be the short circuit current and V_{OC1} be the open circuit voltage of first cell and I_{SC2} and V_{OC2} be the short circuit current and open circuit voltage of the second cell. When we connect these in series, we get the following V-I characteristics:

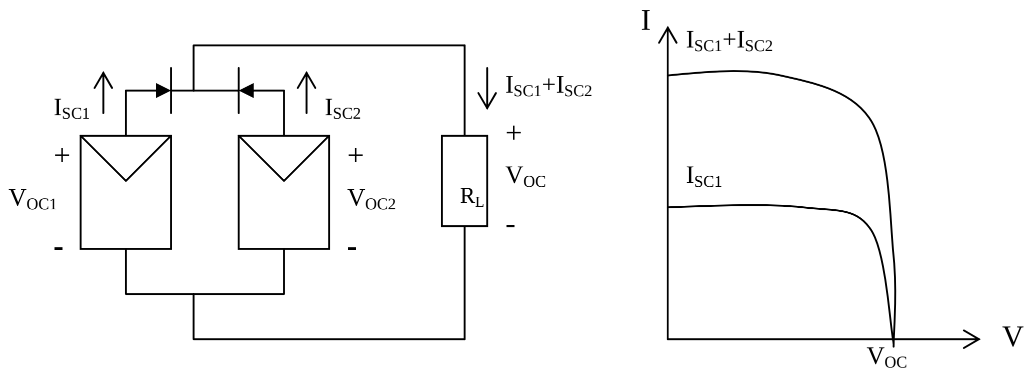


We can see from the V-I characteristics that when we connect two dissimilar cells in series, their open circuit voltages add up but the net short circuit current takes a value in between I_{SC1} and I_{SC2} shown by red color curve. To the left of the operating point, the weaker cell will behave like a sink. Hence, if a diode is connected in parallel, the weaker cell is bypassed, once the current exceeds the short circuit current of the weaker cell. The whole system would look as if a single cell is connected across the load. The diode is called a series protection diode.

The characteristics of the PV cell along with the protection diode should also be shown.

Cells in parallel:

When two cells are connected in parallel as shown in the following figure, the open circuit voltage of the system would remain same as a open circuit voltage of a single cell, but the short circuit current of the system would be twice as much as of a single cell.

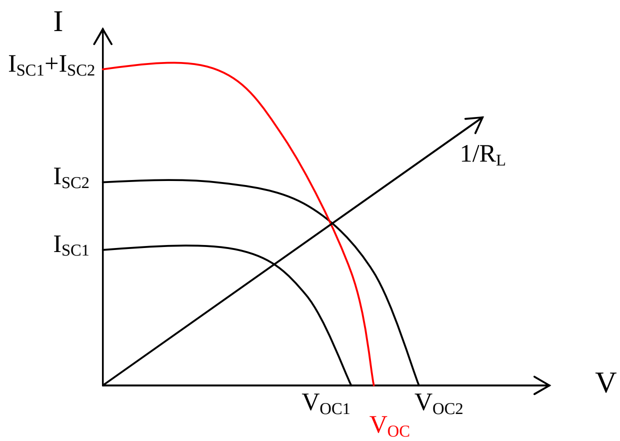


We can see from the above figures that if the cells are identical, we can write the following relationships:

$I_{SC1} + I_{SC2} = 2I_{SC}$

$V_{OC1} = V_{OC2} = V_{OC}$

However, we rarely find two identical cells. Hence, let us see what happens if two dissimilar cells are connected in parallel. The V-I characteristics would look as shown in the following figure:

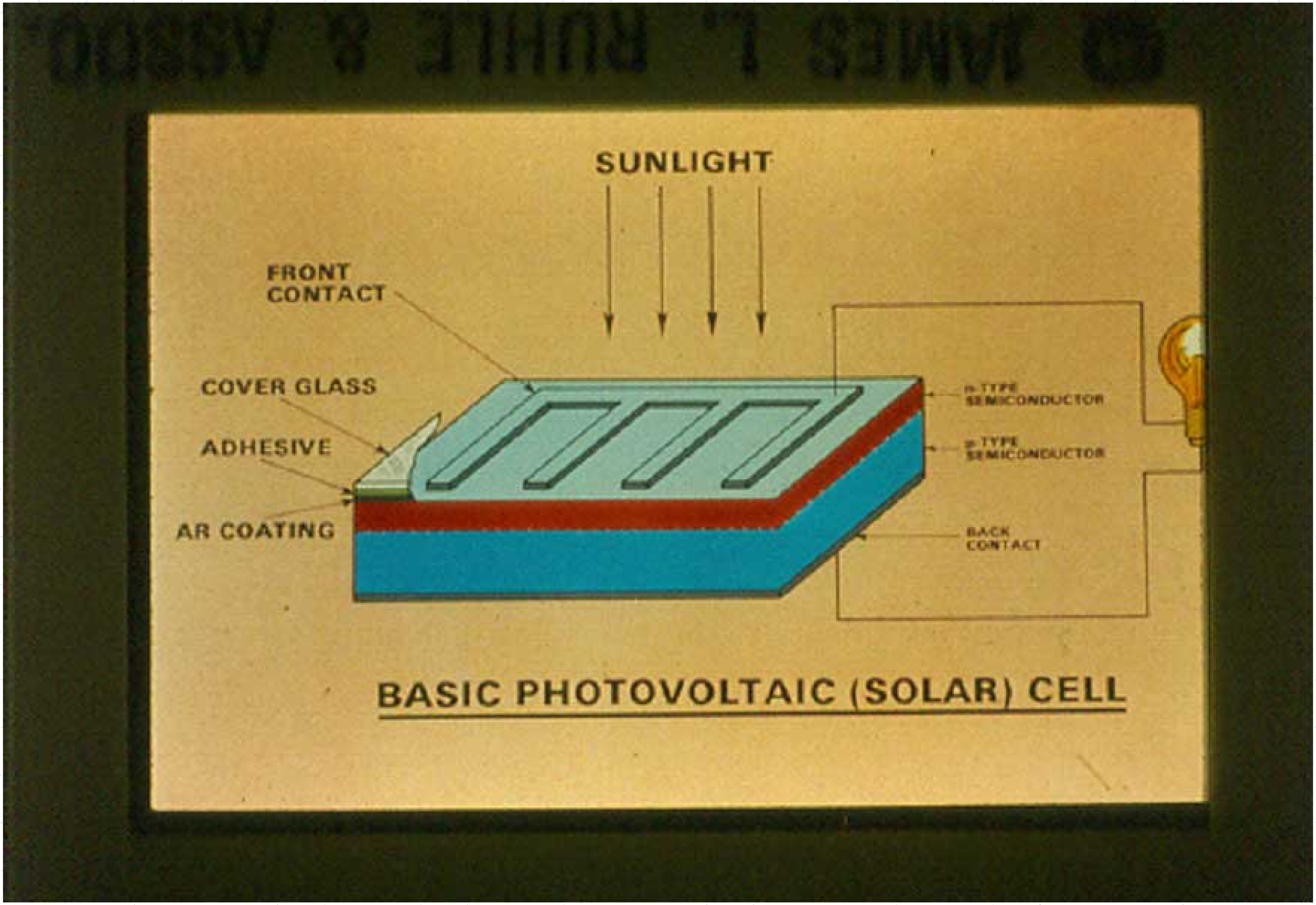


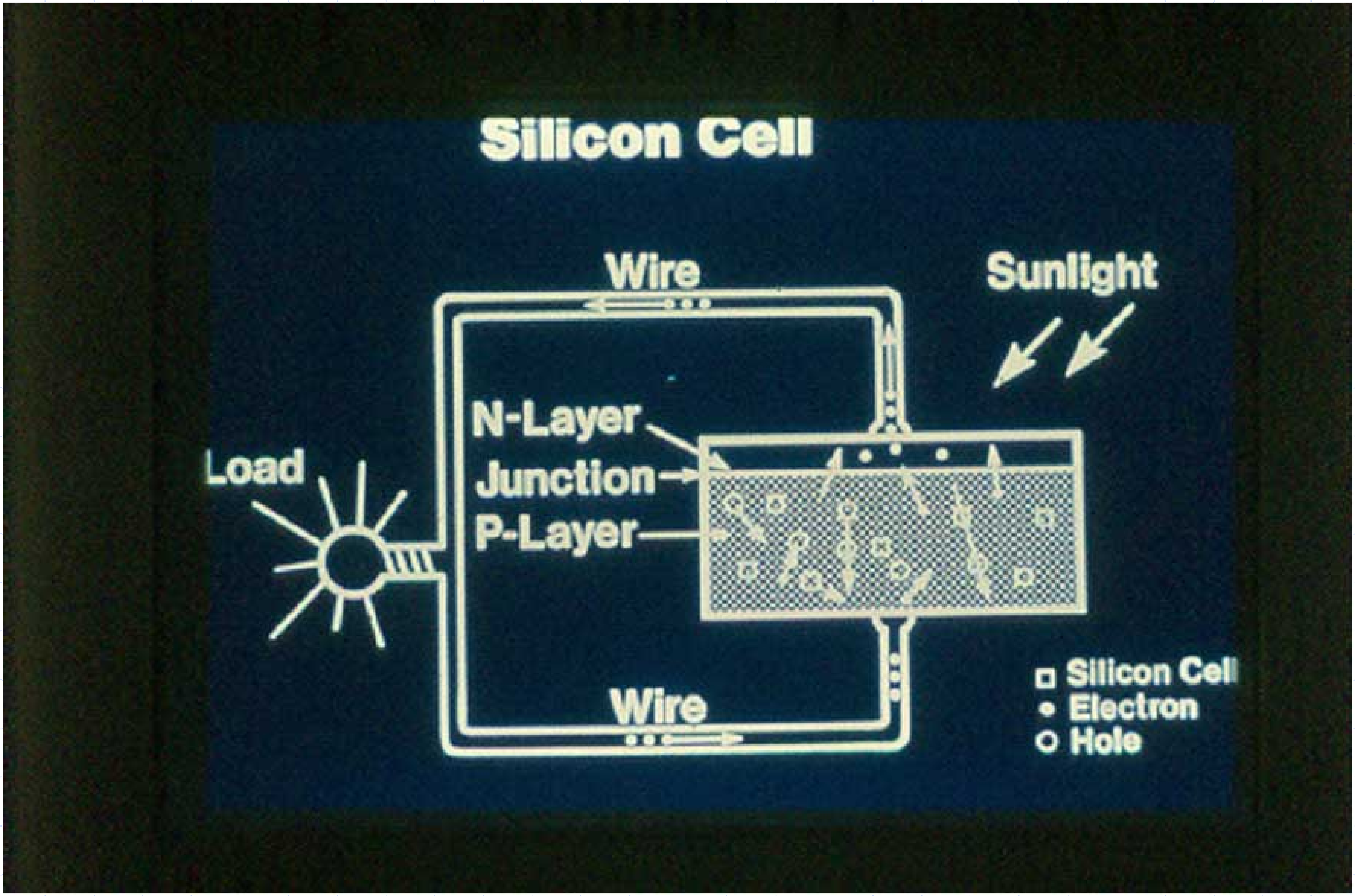
From the above figure we can infer that, when two dissimilar cells are connected in parallel, the short circuit currents add up but the open circuit voltage lies between V_{OC1} and V_{OC2}, represented by V_{OC}. This voltage actually refers to a negative current of the weaker cell. This results in the reduction of net current out of the system. This situation can be avoided by adding a diode in series of each cell as shown earlier. Once the cell is operating to the right of the operating point, the weaker cell's diode gets reverse biased, cutting it off from the system and hence follows the characteristic curve of the stronger cell.

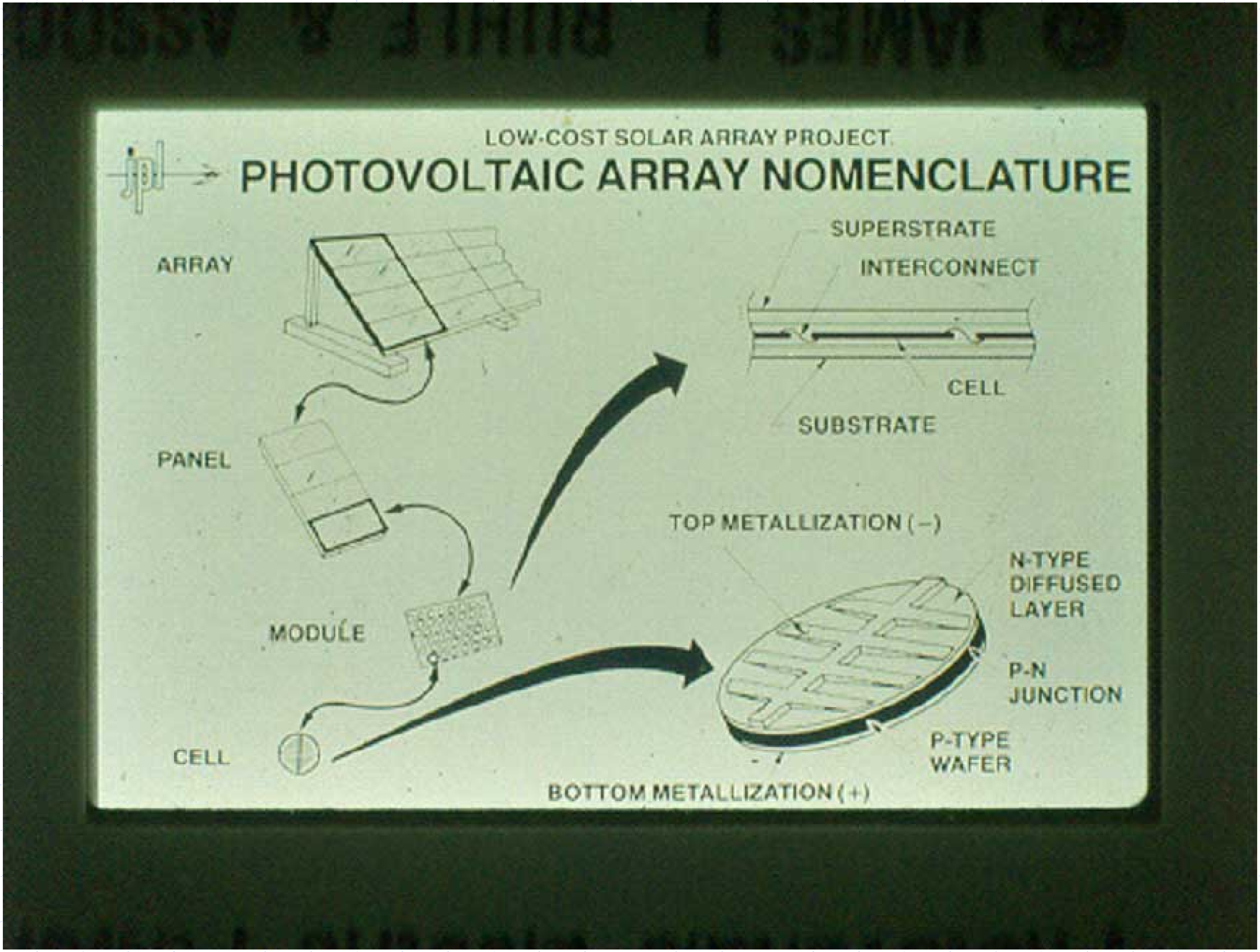
Here also the characteristics of the PV cell along with the protection diode should also be shown.

PV Cell

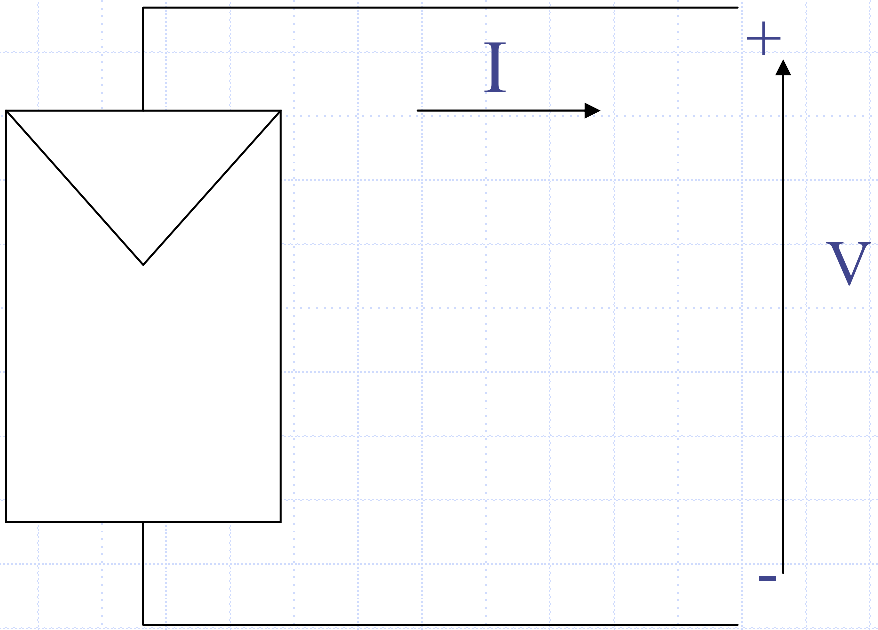
Dr.L.Umanand


SUNLIGHT
FRONT CONTACT
COVER GLASS
ADHESIVE
AR COATING
n-TYPE SEMICONDUCTOR
p-TYPE SEMICONDUCTOR
BACK CONTACT
BASIC PHOTOVOLTAIC (SOLAR) CELL

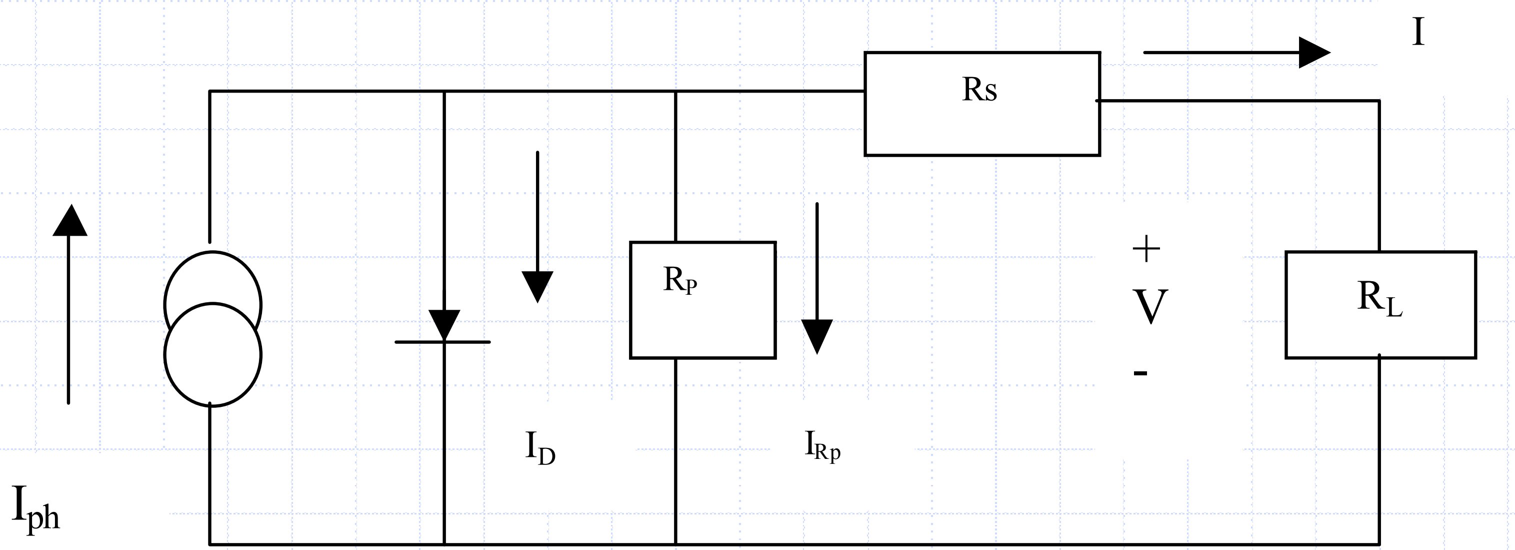

Silicon Cell
Wire
Sunlight
N-Layer
Junction
P-Layer
Load
Wire
Silicon Cell
Electron
Hole


LOW-COST SOLAR ARRAY PROJECT
PHOTOVOLTAIC ARRAY NOMENCLATURE
ARRAY
PANEL
MODULE
CELL
SUPERSTRATE
INTERCONNECT
CELL
SUBSTRATE
TOP METALLIZATION (–)
N-TYPE DIFFUSED LAYER
P-N JUNCTION
P-TYPE WAFER
BOTTOM METALLIZATION (+)

PV Cell Symbol



Model of a PV Cell



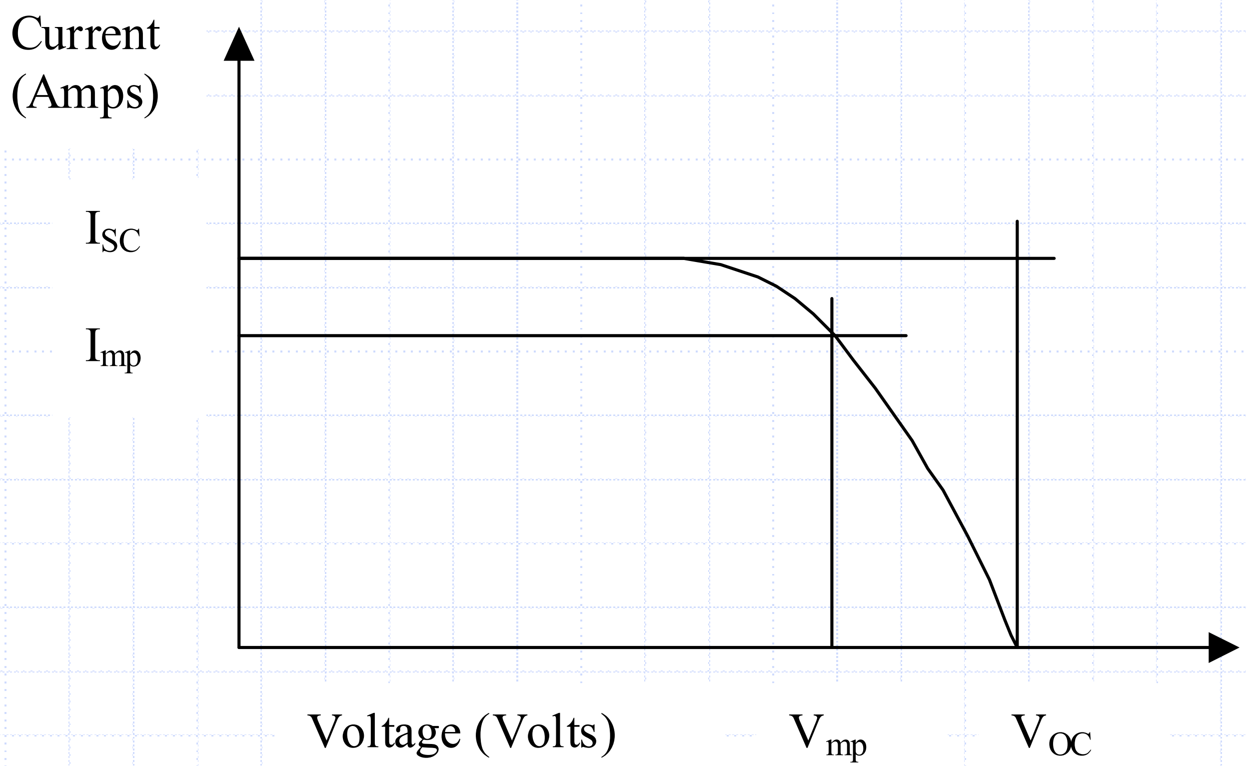
Model of a PV Cell

$$I = I_{ph} - I_o \cdot \left[\exp\left(\frac{V + I \cdot R_s}{V_T} \right) - 1 \right] - \left[\frac{V + I \cdot R_s}{R_p} \right]$$

I_{ph} = Insolation current
I = Cell current
I_o = Reverse saturation current
V = Cell voltage
R_s = Series resistance
R_p = Parallel resistance

V_T = Thermal voltage = KT/q
K = Boltzman constant
T = Temperature in Kelvin
q = charge of an electron

V-I Characteristics



Short circuit current

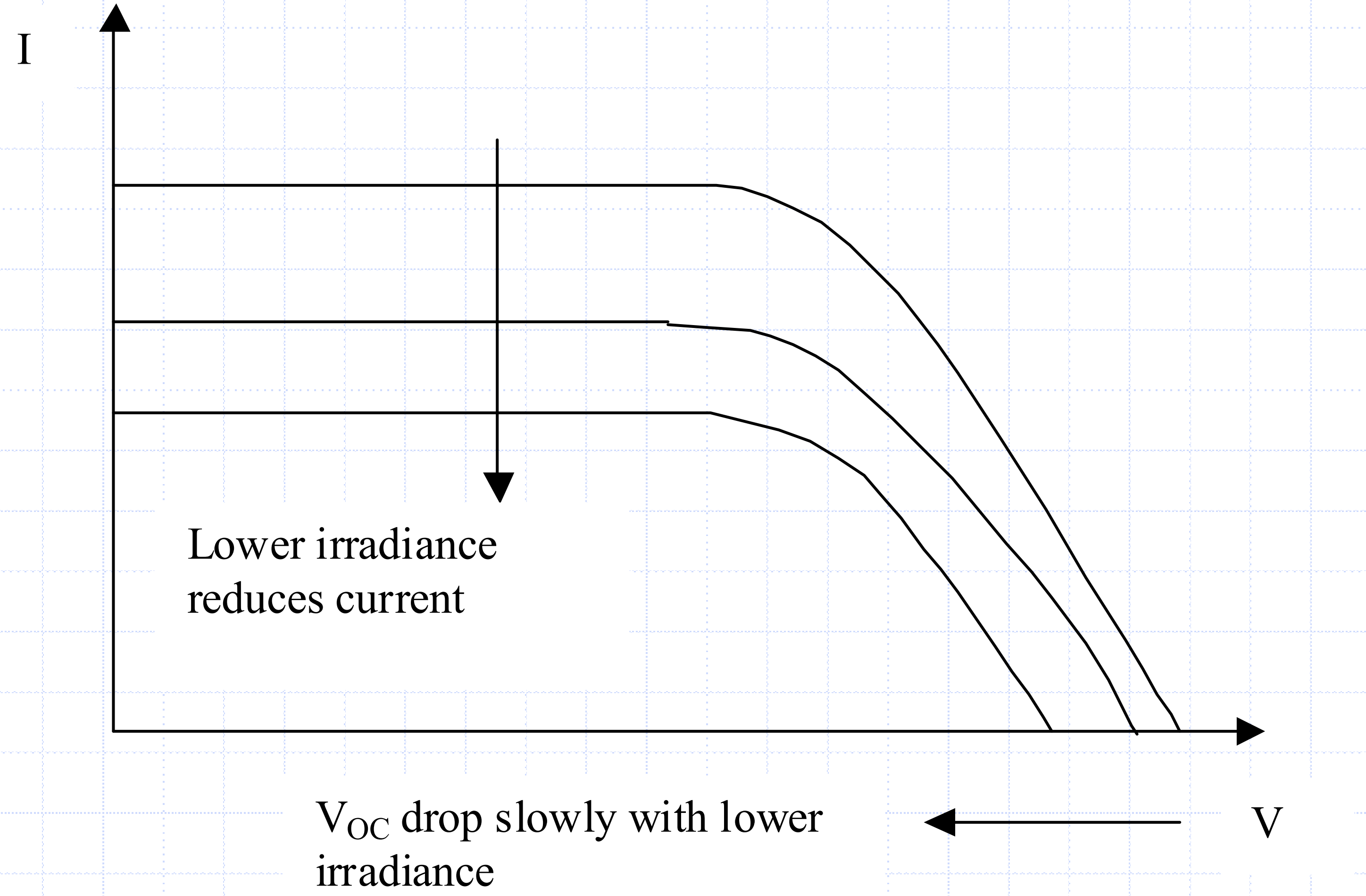
$$I_{SC} = I_{ph} - I_o \cdot \left[\exp\left(\frac{I_{SC} \cdot R_s}{V_T} \right) - 1 \right] - \left[\frac{I_{SC} \cdot R_s}{R_p} \right]$$

$I_{SC} \ \alpha \ I_{ph}$

Open circuit voltage

$$V_{OC} = V_T \cdot \ln\left[\frac{I_{ph}}{I_o} - \frac{V_{OC}}{I_o \cdot R_p} + 1\right]$$

Open circuit voltage



Quality of cell

- As time progresses, the quality of cell deteriorates
- quality of the cell is in terms of Fill Factor (FF)

Fill Factor

$$FF = \frac{V_{mp} \cdot I_{mp}}{V_{OC} \cdot I_{SC}}$$

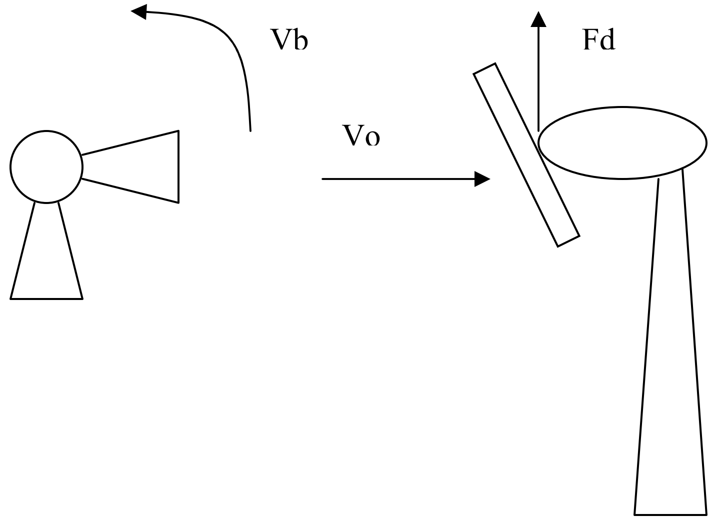
- Ideally, the fill factor should be 1 or 100%
- The actual value of FF is about 0.8 or 80%
- A graph of the FF vs the insolation gives a measure of the quality of the PV cell

Efficiency of the cell

$$\eta = \frac{V_{mp} \cdot I_{mp}}{I(kW/m^2) \cdot A(m^2)}$$

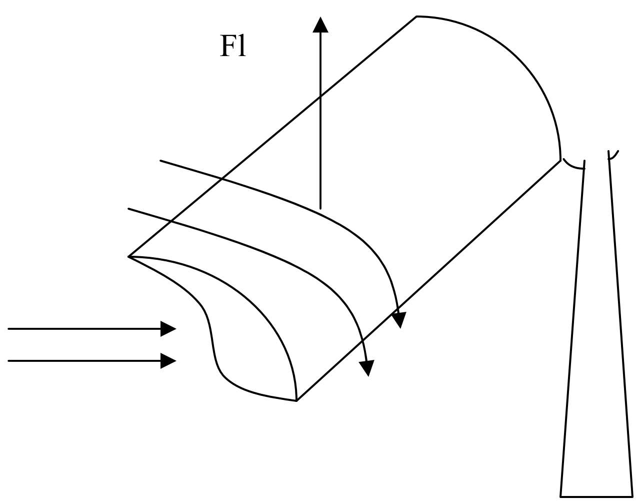
where A is the area of the cell and I is the Insolation

Student slide 5-03
Horizontal axis wind mill
Drag type:



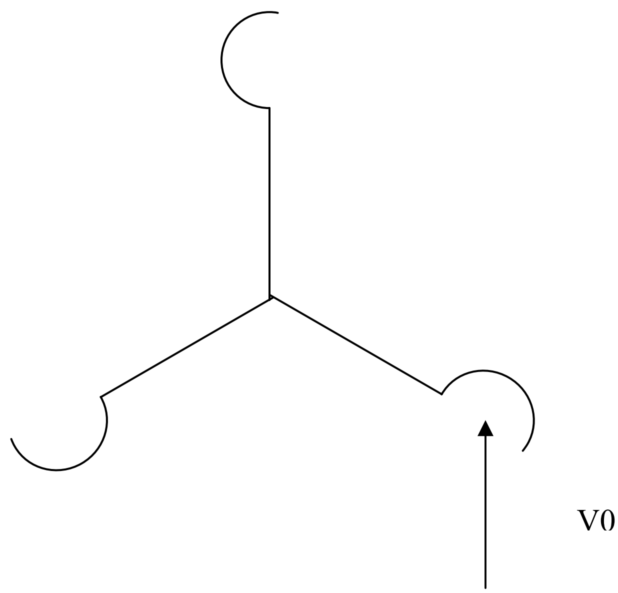
Tip speed ratio=vb/vo

Blade speed vb=ω*r
Nb=blade speed in rpm
ω=(2*π*Nb)/60
Tip speed ratio=(2*π*Nb*r/vo)

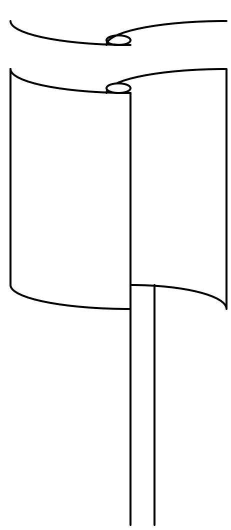


The velocity of air above the blade is higher compared to below it. because of the high velocity the pressure is less and a force Fl is applied as shown in figure, which rotates the blades.

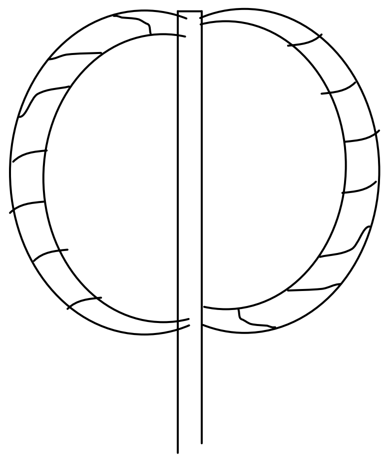
Cup anemometer:



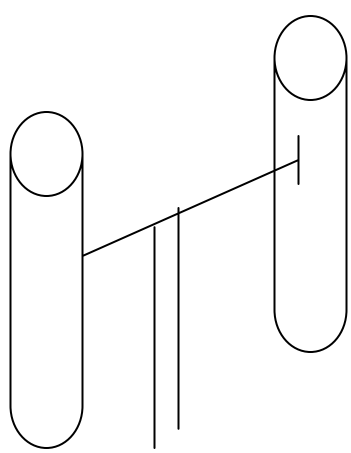
Tip speed ratio gives the quality of the turbine.
Savenius:



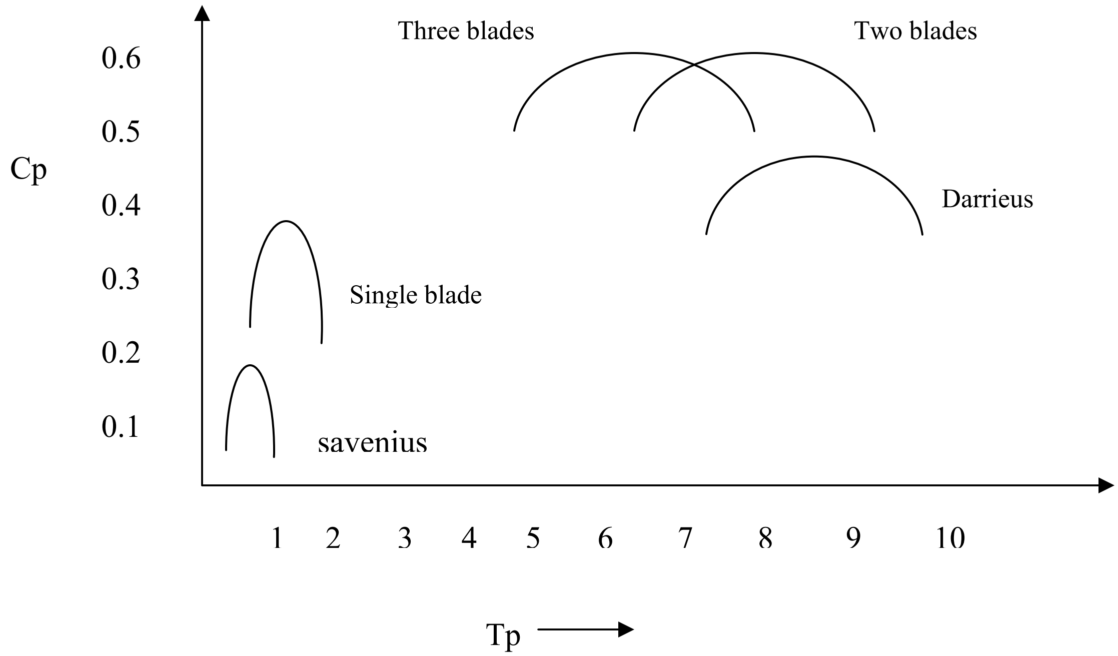
Darrieus:

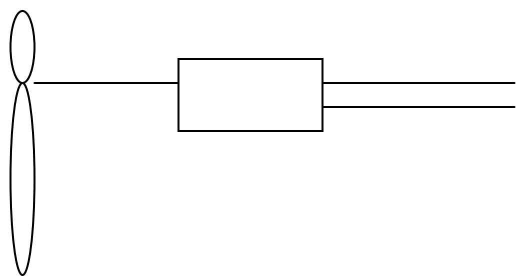


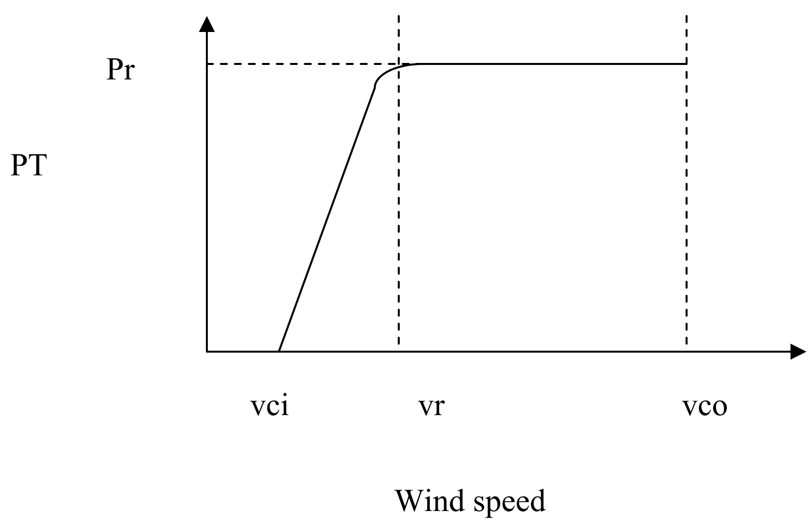
Evans:



Tip ratio of 10 is possible when darrieus and evans blades are used.







(Vci) cutin speed: it is of order 5m/s. there is no power out up to this speed. Below this speed the power obtained is used to supply losses.
Vco(cutout speed): it is of order 30m/s. when the speed of wind is beyond 30m/s the turbine is not operated.

Student slide 5-02

Energy content in windmill:

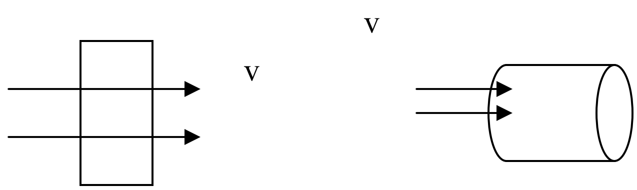
$E=(1/2)mv^2$

$P=(1/2)*(dm/dt)*v^2$

$=(1/2)*\rho(dQ/dt)*v^2$

$=(1/2)*\rho*A*v^3$

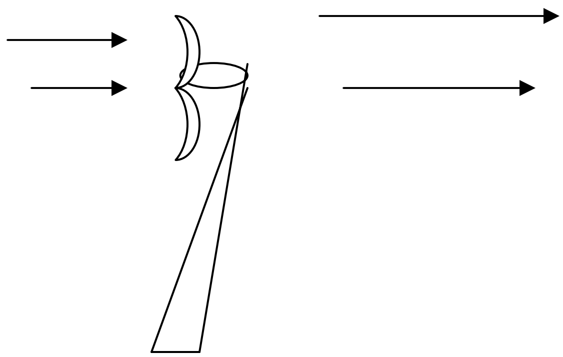
ρ is density of air = 1.2Kg/m^3 at sea level



$P=0.6Av^3$

$Pw=0.6Av^3$ watt/m^2

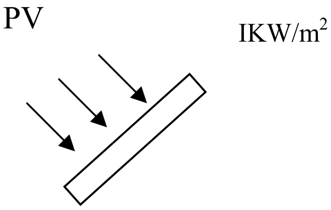
Anemometer is used to measure the wind velocity



Cp=Pturbine/Pinput =0.59

Cp is in the range of 35%-40%

PV



Output = 120 W/m^2

Panel efficency =12%

wind

Pin =120/0.3

=400w/m^2

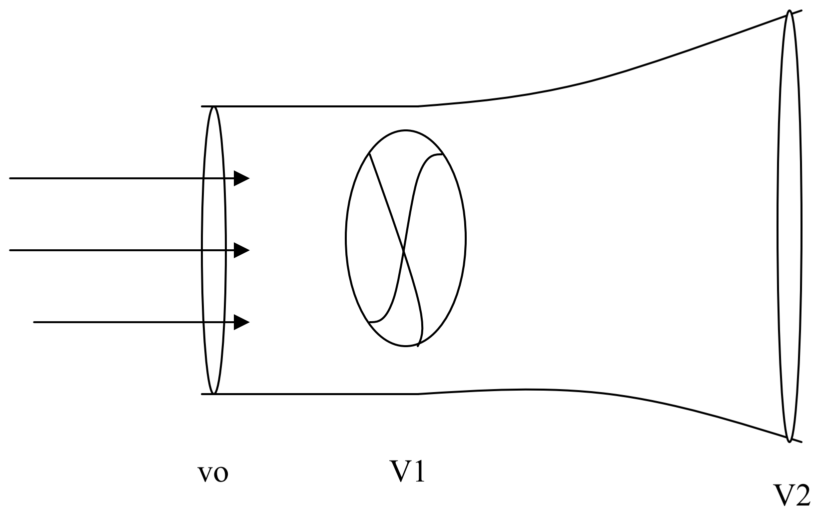
$400=0.6v^3$

v=8.73m/sec

=31.5Km/hr

Wind speed KmpH	Wind speed m/sec	P w/m^2	Pt w/m^2	
1	0.278	.013	.004	
10	2.778	12.86	3.858	
25	6.944	200.9	60.282	
50	13.889	1607.5	482.25	
75	*20.833*	*5425.35*	*1627.6*	→ Gale Storm
100	27.78	12860	-----	
125	34.722	25117.3	-----	

Betz model:



$$F=(dm/dt)vo-(dm/dt)v2$$

$$(dm/dt)*(v0-v2)*v1=(1/2)*(dm/dt)(vo^2-v2^2)$$

$$v1=(v0+v2)/2$$

$$P=(1/2)*\rho1*A1*v1^3$$

$$=(dm/dt)*(v0-v2)*v1$$

$$=\rho Av1^2(v0-v2)$$

$$=2\rho Av1^2(v0-V1)$$

$$a=(v0-v1)/v0$$

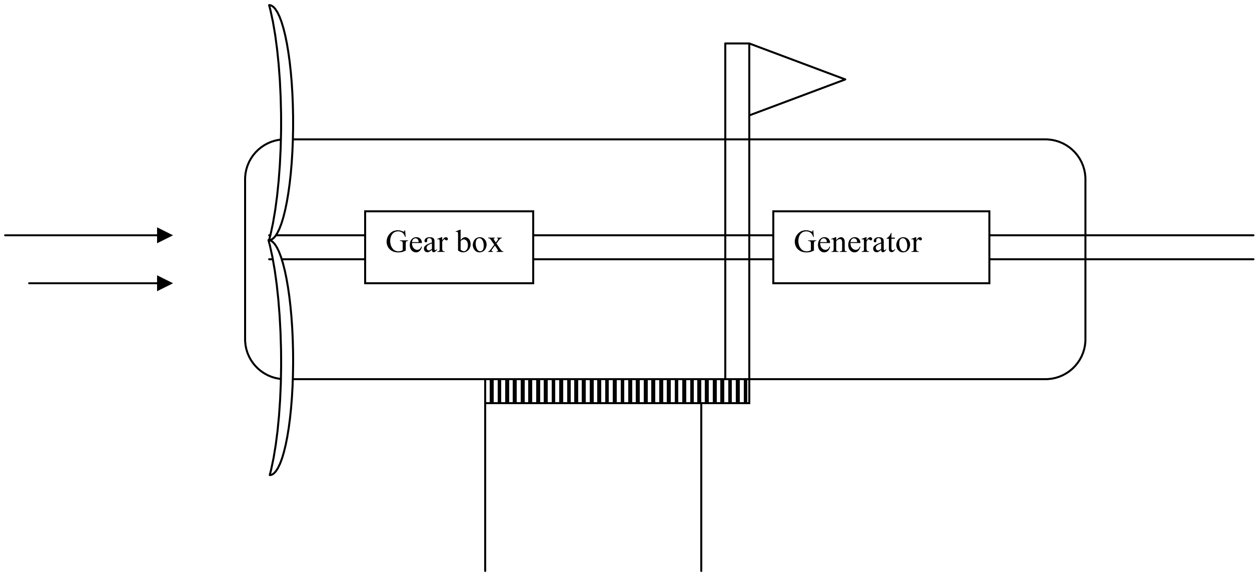
$$P=2\rho A(1-a)^2 avo^3$$

$$Pt=4(1-a)^2 a(1/2)(\rho avo^3)$$

$$dCp/dt=0$$

$$a=1/3$$

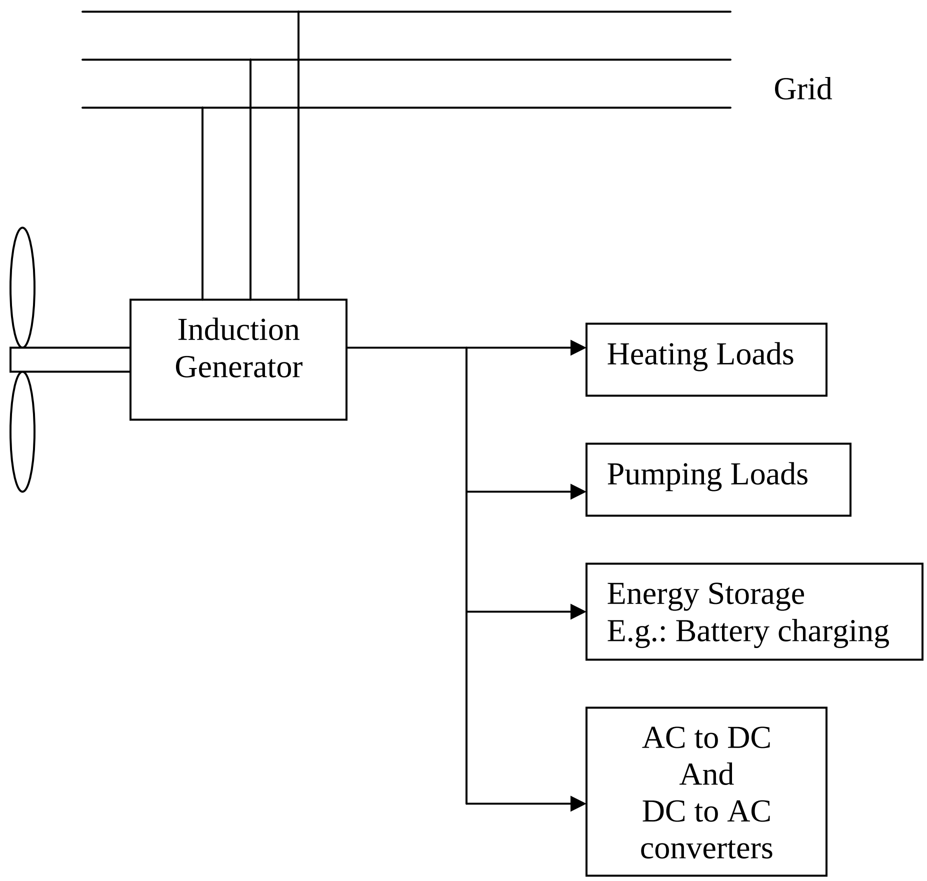
Cp=0.59 Betz number



Vertical axis is axis perpendicular to ground.
Horizontal axis is axis parallel to the ground.

Student slide 5-04

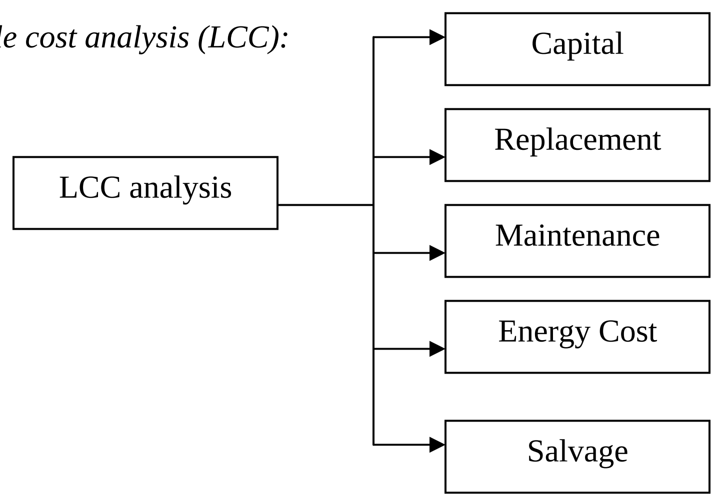
<u>Applications</u>:



When the induction generator is connected to the grid, the operating frequency of the induction generator becomes the grid frequency. When a generator is connected directly to a load, the generator starts up because of the presence of the residual magnetism in it.

Cost analysis:

Life cycle cost analysis (LCC):



The money on capital, replacement, maintenance, energy costs, salvage are spent at different times. We need to express them on single time instant.

Simple interest:

Interest rate -----------l
Principal amount-----P
Period time ----------n
$S=P(1+ni)$

Compound interest:

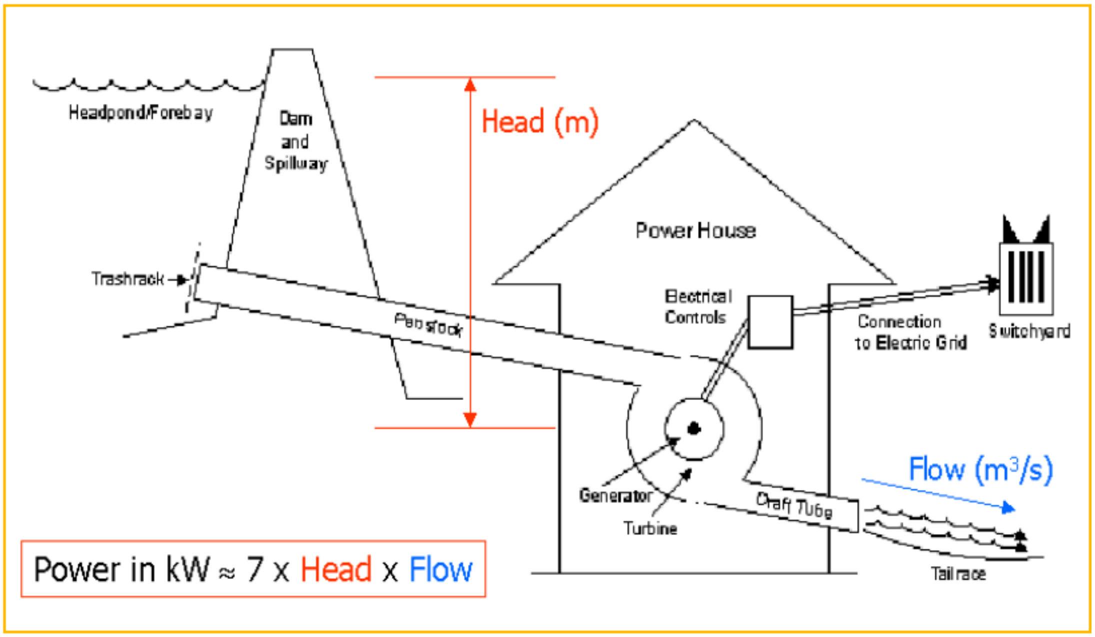
$S1= P(1+i)$
$S2= P(1+i)^2$

$Sn= P(1+i)^n$
$Sn= P(1+i/m)^{nm}$
$Sn = Lt\ (m \rightarrow \propto)\ P(1+i/m)^{nm} = Pe^{in}$
Present worth$=s/(1+i)^n$

Non conventional energy systems

Hydro Electric Power (Hydel Power)

Hydro-electric power is generated by the flow of water through turbine, turning the blades of the turbine. A generator shaft connected to this turbine also turns and hence generates electricity. Following figure shows how hydro-electric power is generated:



The main components of a hydel power plant are:

1. Dam/Reservoir/Large buffer tank
2. Penstock
3. Power House
    a. Turbines
    b. Generators
    c. Step-up Transformers

Depending on the capacity, hydel power plants are divided into the following categories:

Category	Capacity	Application
Large Hydel Plant	50 MW to 1000 MW	Large Cities
Small Hydel Plant	1 MW to 50 MW	Small cities to Towns
Mini Hydel Plant	100 kW to 1000 kW	Towns
Micro Hydel Plant	< 100 kW	Rural community
Pico Hydel Plant	< 5 kW	Individual home

Hydel plants have an efficiency of 75%. The power delivered is given by the following expression:

$$Power\_Delivered = 7.H.\frac{dQ}{dt}$$ kilo watts, where H = Head in meters

dQ/dt = Rate of discharge in m3/s.

In the figure we see that the turbine is coupled to a generator for generating electrical power. The generator can be of any of the following types:

- Permanent magnet DC generator (PMDC)
- Alternator (Synchronous Generator)
- Induction Generator
- Synchronous reluctance Generator

To select the best among the listed options, we need to know the requirement of a generator. Following list gives the requirement:

1. Rugged and easy to maintain
2. Simple to fabricate
3. High efficiency
4. Fail safe or "should not fail at all"
5. Sinusoidal output
6. Good voltage regulation
7. Cost effective for given power
8. Ease of servicing/operation
9. Safety
10. Reliability

When we try to match the requirements to the types of generators, Induction generator fits the bill better than others and hence, this is the type normally used for power generation. The only drawback with induction generators is its poor voltage regulation. To improve the voltage regulation, normally load governors are used in parallel to the actual load.

Non conventional energy systems

History of Wind-Mills:

The wind is a by-product of solar energy. Approximately 2% of the sun's energy reaching the earth is converted into wind energy. The surface of the earth heats and cools unevenly, creating atmospheric pressure zones that make air flow from high- to low-pressure areas.

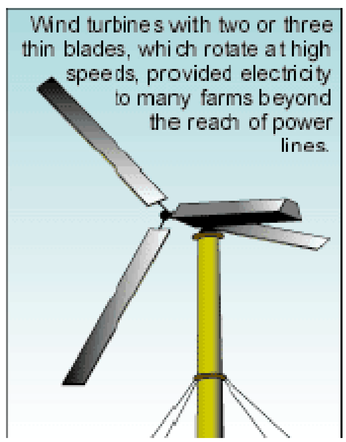
The wind has played an important role in the history of human civilization. The first known use of wind dates back 5,000 years to Egypt, where boats used sails to travel from shore to shore. The first true windmill, a machine with vanes attached to an axis to produce circular motion, may have been built as early as 2000 B.C. in ancient Babylon. By the 10th century A.D., windmills with wind-catching surfaces having 16 feet length and 30 feet height were grinding grain in the areas in eastern Iran and Afghanistan.

The earliest written references to working wind machines in western world date from the 12th century. These too were used for milling grain. It was not until a few hundred years later that windmills were modified to pump water and reclaim much of Holland from the sea.

The multi-vane "farm windmill" of the American Midwest and West was invented in the United States during the latter half of the l9th century. In 1889 there were 77 windmill factories in the United States, and by the turn of the century, windmills had become a major American export. Until the diesel engine came along, many transcontinental rail routes in the U.S. depended on large multi-vane windmills to pump water for steam locomotives.

Farm windmills are still being produced and used, though in reduced numbers. They are best suited for pumping ground water in small quantities to livestock water tanks. In the 1930s and 1940s, hundreds of thousands of electricity producing wind turbines were built in the U.S. They had two or three thin blades which rotated at high speeds to drive electrical generators. These wind turbines provided electricity to farms beyond the reach of power lines and were typically used to charge storage batteries, operate radio receivers and power a light bulb. By the early 1950s, however, the extension of the central power grid to nearly every American household, via the Rural Electrification Administration, eliminated the market for these machines. Wind turbine development lay nearly dormant for the next 20 years.

A typical modern windmill looks as shown in the following figure. The wind-mill contains three blades about a horizontal axis installed on a tower. A turbine connected to a generator is fixed about the horizontal axis.



Like the weather in general, the wind can be unpredictable. It varies from place to place, and from moment to moment. Because it is invisible, it is not easily measured without special instruments. Wind velocity is affected by the trees, buildings, hills and valleys around us. Wind is a diffuse energy source that cannot be contained or stored for use elsewhere or at another time.

Classification of Wind-mills:

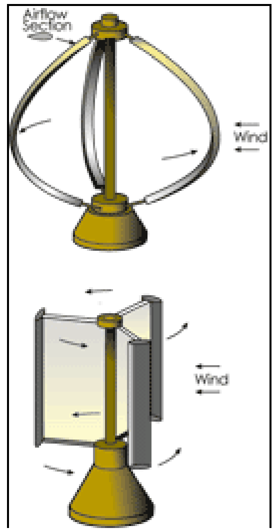
Wind turbines are classified into two general types: Horizontal axis and Vertical axis. A horizontal axis machine has its blades rotating on an axis parallel to the ground as shown in the above figure. A vertical axis machine has its blades rotating on an axis perpendicular to the ground. There are a number of available designs for both and each type has certain advantages and disadvantages. However, compared with the horizontal axis type, very few vertical axis machines are available commercially.

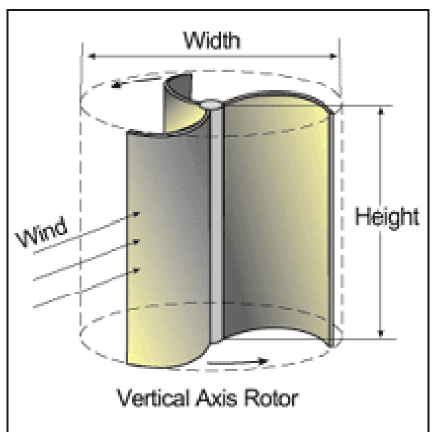
Horizontal Axis:

This is the most common wind turbine design. In addition to being parallel to the ground, the axis of blade rotation is parallel to the wind flow. Some machines are designed to operate in an upwind mode, with the blades upwind of the tower. In this case, a tail vane is usually used to keep the blades facing into the wind. Other designs operate in a downwind mode so that the wind passes the tower before striking the blades. Without a tail vane, the machine rotor naturally tracks the wind in a downwind mode. Some very large wind turbines use a motor-driven mechanism that turns the machine in response to a wind direction sensor mounted on the tower. Commonly found horizontal axis wind mills are aero-turbine mill with 35% efficiency and farm mills with 15% efficiency.

Vertical Axis:

Although vertical axis wind turbines have existed for centuries, they are not as common as their horizontal counterparts. The main reason for this is that they do not take advantage of the higher wind speeds at higher elevations above the ground as well as horizontal axis turbines. The basic vertical axis designs are the Darrieus, which has curved blades and efficiency of 35%, the Giromill, which has straight blades, and efficiency of 35%, and the Savonius, which uses scoops to catch the wind and the efficiency of 30%. A vertical axis machine need not be oriented with respect to wind direction. Because the shaft is vertical, the transmission and generator can be mounted at ground level allowing easier servicing and a lighter weight, lower cost tower. Although vertical axis wind turbines have these advantages, their designs are not as efficient at collecting energy from the wind as are the horizontal machine designs. The following figures show all the above mentioned mills.

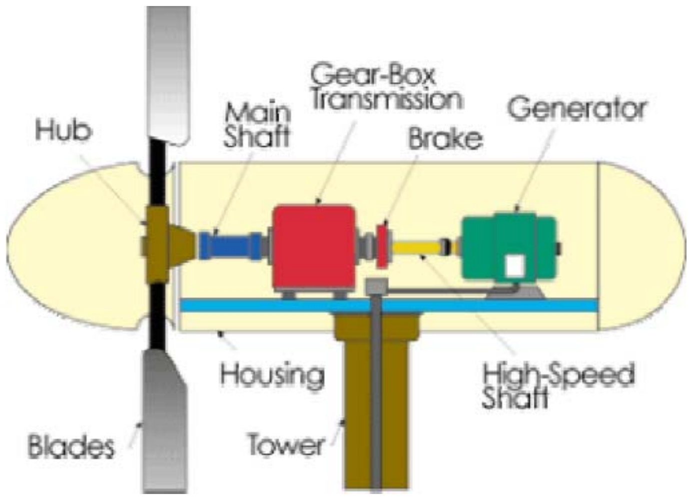




There is one more type of wind-mill called Cyclo-gyro wind-mill with very high efficiency of about 60%. However, it is not very stable and is very sensitive to wind direction. It is also very complex to build.

Main Components of a wind-mill :

Following figure shows typical components of a horizontal axis wind mill.



Rotor:

The portion of the wind turbine that collects energy from the wind is called the rotor. The rotor usually consists of two or more wooden, fiberglass or metal blades which rotate about an axis (horizontal or vertical) at a rate determined by the wind speed and the shape of the blades. The blades are attached to the hub, which in turn is attached to the main shaft.

Drag Design:

Blade designs operate on either the principle of drag or lift. For the drag design, the wind literally pushes the blades out of the way. Drag powered wind turbines are characterized by slower rotational speeds and high torque capabilities. They are useful for the pumping, sawing or grinding work. For example, a farm-type windmill must develop high torque at start-up in order to pump, or lift, water from a deep well.

Lift Design:

The lift blade design employs the same principle that enables airplanes, kites and birds to fly. The blade is essentially an airfoil, or wing. When air flows past the blade, a wind speed and pressure differential is created between the upper and lower blade surfaces. The pressure at the lower surface is greater and thus acts to "lift" the blade. When blades are attached to a central axis, like a wind turbine rotor, the lift is translated into rotational motion. Lift-powered wind turbines have much higher rotational speeds than drag types and therefore well suited for electricity generation.

Following figure gives an idea about the drag and lift principle.

Tip Speed Ratio:

The tip-speed is the ratio of the rotational speed of the blade to the wind speed. The larger this ratio, the faster the rotation of the wind turbine rotor at a given wind speed. Electricity generation requires high rotational speeds. Lift-type wind turbines have maximum tip-speed ratios of around 10, while drag-type ratios are approximately 1. Given the high rotational speed requirements of electrical generators, it is clear that the lift-type wind turbine is most practical for this application.

The number of blades that make up a rotor and the total area they cover affect wind turbine performance. For a lift-type rotor to function effectively, the wind must flow smoothly over the blades. To avoid turbulence, spacing between blades should be great enough so that one blade will not encounter the disturbed, weaker air flow caused by the blade which passed before it. It is because of this requirement that most wind turbines have only two or three blades on their rotors.

Generator:

The generator is what converts the turning motion of a wind turbine's blades into electricity. Inside this component, coils of wire are rotated in a magnetic field to produce electricity. Different generator designs produce either alternating current (AC) or direct current (DC), and they are available in a large range of output power ratings. The generator's rating, or size, is dependent on the length of the wind turbine's blades because more energy is captured by longer blades.

It is important to select the right type of generator to match intended use. Most home and office appliances operate on 240 volt, 50 cycles AC. Some appliances can operate on either AC or DC, such as light bulbs and resistance heaters, and many others can be adapted to run on DC. Storage systems using batteries store DC and usually are configured at voltages of between 12 volts and 120 volts.

Generators that produce AC are generally equipped with features to produce the correct voltage of 240 V and constant frequency 50 cycles of electricity, even when the wind speed is fluctuating.

DC generators are normally used in battery charging applications and for operating DC appliances and machinery. They also can be used to produce AC electricity with the use of an inverter, which converts DC to AC.

Transmission:

The number of revolutions per minute (rpm) of a wind turbine rotor can range between 40 rpm and 400 rpm, depending on the model and the wind speed. Generators typically require rpm's of 1,200 to 1,800. As a result, most wind turbines require a gear-box transmission to increase the rotation of the generator to the speeds necessary for efficient electricity production. Some DC-type wind turbines do not use transmissions. Instead, they have a direct link between the rotor and generator. These are known as direct drive systems. Without a transmission, wind turbine complexity and maintenance requirements are reduced, but a much larger generator is required to deliver the same power output as the AC-type wind turbines.

Tower:

The tower on which a wind turbine is mounted is not just a support structure. It also raises the wind turbine so that its blades safely clear the ground and so it can reach the stronger winds at higher elevations. Maximum tower height is optional in most cases, except where zoning restrictions apply. The decision of what height tower to use will be based on the cost of taller towers versus the value of the increase in energy production resulting from their use. Studies have shown that the added cost of increasing tower height is often justified by the added power generated from the stronger winds. Larger wind turbines are usually mounted on towers ranging from 40 to 70 meters tall.

Towers for small wind systems are generally "guyed" designs. This means that there are guy wires anchored to the ground on three or four sides of the tower to hold it erect. These towers cost less than freestanding towers, but require more land area to anchor the guy wires. Some of these guyed towers are erected by tilting them up. This operation can be quickly accomplished using only a winch, with the turbine already mounted to the tower top. This simplifies not only installation, but maintenance as well. Towers can be constructed of a simple tube, a wooden pole or a lattice of tubes, rods, and angle iron. Large wind turbines may be mounted on lattice towers, tube towers or guyed tilt-up towers.

Towers must be strong enough to support the wind turbine and to sustain vibration, wind loading and the overall weather elements for the lifetime of the wind turbine. Their costs will vary widely as a function of design and height.

Operating Characteristics of wind mills:

All wind machines share certain operating characteristics, such as cut-in, rated and cut-out wind speeds.

Cut-in Speed:

Cut-in speed is the minimum wind speed at which the blades will turn and generate usable power. This wind speed is typically between 10 and 16 kmph.

Rated Speed:

The rated speed is the minimum wind speed at which the wind turbine will generate its designated rated power. For example, a "10 kilowatt" wind turbine may not generate 10 kilowatts until wind speeds reach 40 kmph. Rated speed for most machines is in the range of 40 to 55 kmph. At wind speeds between cut-in and rated, the power output from a wind turbine increases as the wind increases. The output of most machines levels off above the rated speed. Most manufacturers provide graphs, called "power curves," showing how their wind turbine output varies with wind speed.

Cut-out Speed:

At very high wind speeds, typically between 72 and 128 kmph, most wind turbines cease power generation and shut down. The wind speed at which shut down occurs is called the cut-out speed. Having a cut-out speed is a safety feature which protects the wind turbine from damage. Shut down may occur in one of several ways. In some machines an automatic brake is activated by a wind speed sensor. Some machines twist or "pitch" the blades to spill the wind. Still others use "spoilers," drag flaps mounted on the blades or the hub which are automatically activated by high rotor rpm's, or mechanically activated by a spring loaded device which turns the machine sideways to the wind stream. Normal wind turbine operation usually resumes when the wind drops back to a safe level.

Betz Limit:

It is the flow of air over the blades and through the rotor area that makes a wind turbine function. The wind turbine extracts energy by slowing the wind down. The theoretical maximum amount of energy in the wind that can be collected by a wind turbine's rotor is approximately 59%. This value is known as the Betz limit. If the blades were 100%

efficient, a wind turbine would not work because the air, having given up all its energy, would entirely stop. In practice, the collection efficiency of a rotor is not as high as 59%. A more typical efficiency is 35% to 45%. A complete wind energy system, including rotor, transmission, generator, storage and other devices, which all have less than perfect efficiencies, will deliver between 10% and 30% of the original energy available in the wind.

Non conventional energy systems

Mathematical Expression Governing Wind Power

The wind power is generated due to the movement of wind. The energy associated with such movement is the kinetic energy and is given by the following expression:

$Energy = KE = 1/2.m.v^2$ Where

m = Air mass in Kg = Volume (m^3) x Density (Kg/m^3) = Q x ρ

Q = Discharge

v = Velocity of air mass in m/s

Hence, the expression for power can be derived as follows:

$$Power = dE/dt$$

$$= \frac{1}{2} \cdot \frac{d}{dt} \left\{ m.v^2 \right\}$$

$$= \frac{1}{2} \cdot \frac{d}{dt} \left\{ \rho.Q.v^2 \right\}$$

$$= \frac{1}{2} \cdot \rho \cdot \frac{dQ}{dt} \cdot v^2$$

Here, $\frac{dQ}{dt}$ = Rate of discharge (m^3/s) = A (m^2) • v (m/s)

Where, A = Area of cross section of blade movement.

$$Power = \frac{1}{2} \cdot \rho \cdot A \cdot v^3$$

We know that for given length of blades, A is constant and so is the air mass density ρ.

Hence we can say that wind power is directly proportional to (wind speed)^3.

At sea level, ρ = 1.2 Kg/m^3. Therefore,

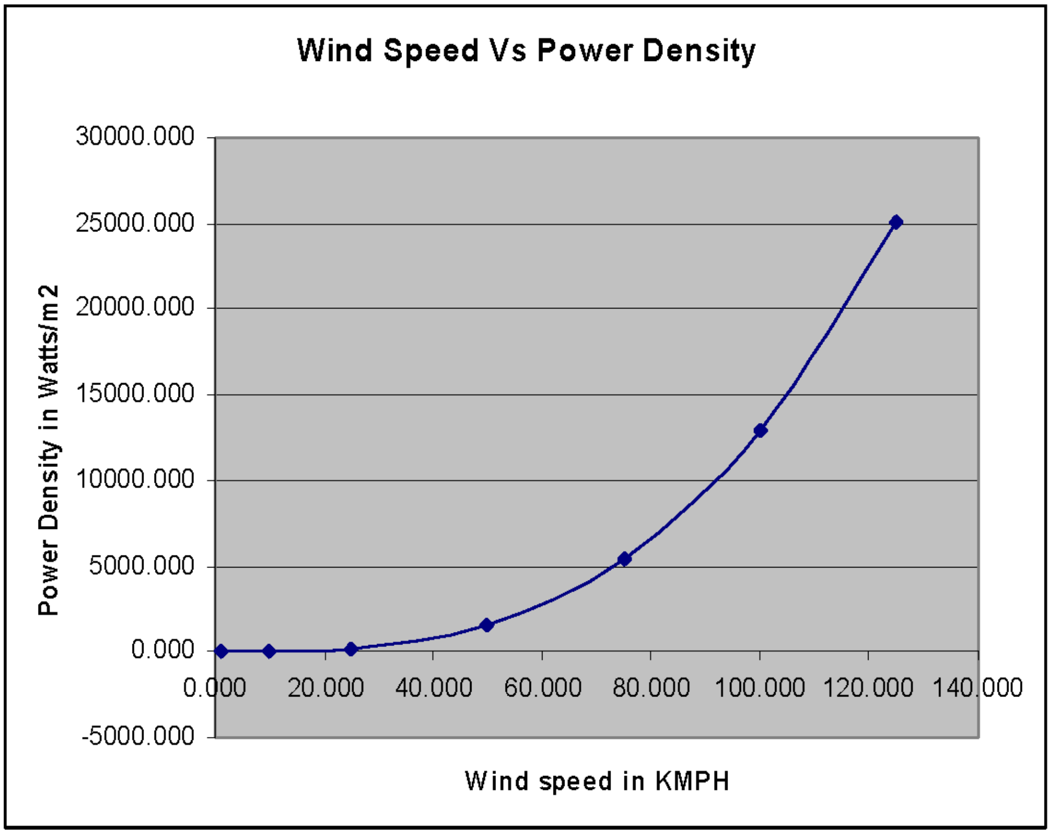
$$Power = \frac{1}{2}\cdot(1\cdot 2)\cdot A\cdot v^3$$

$$\frac{Power}{Area} = (0\cdot 6)\cdot v^3 \quad = \text{Power Density in watts/m}^2$$

Let us construct a chart relating the wind speed to the power density and the output of the wind turbine assuming 30% efficiency of the turbine as shown in the following table.

Wind Speed kmph	Wind speed m/s	Power Density Watts/m^2	Turbine Output 30% efficiency
1	0.278	0.013	0.004
Wind Speed kmph	Wind speed m/s	Power Density Watts/m^2	Turbine Output 30% efficiency
10	2.778	12.860	3.858
25	6.944	200.939	60.282
50	13.889	1607.510	482.253
75	20.833	5425.347	1627.604
100	27.778	12860.082	3858.025
125	34.722	25117.348	7535.204

The following plot gives the relationship between wind speed in KMPH and the power density.



In the last column of the table, we have calculated the output of the turbine assuming that the efficiency of the turbine is 30%. However, we need to remember that the efficiency of the turbine is a function of wind speed. *It varies with wind speed*.

Now, let us try to calculate the wind speed required to generate power equivalent to 1 square meter PV panel with 12% efficiency. We know that solar insolation available at the PV panel is 1000 watts/m^2 at standard condition. Hence the output of the PV panel with 12% efficiency would be 120 watts. Now the speed required to generate this power by the turbine with 30% efficiency can be calculated as follows:

Turbine output required = 120 Watts/m^2

Power Density at the blades = 120/ (0.3) = 400 watts/m^2

Therefore, the wind speed required to generate equivalent power in m/s = $\left(\frac{400}{0.6}\right)^{1/3}$ = 8.73 5805 m/s = 31.4489 kmph.

We have seen that the theoretical power is given by the following expression: $P_{theoretical} = \frac{1}{2} \cdot \rho \cdot A \cdot v^3$

However, there would be losses due to friction and hence, the actual power generated would be smaller. The co-efficient of power is defined as the ratio of actual power to the theoretical power. That is,

$$C_p = \frac{P_{actual}}{P_{theoretical}}$$

Another important ratio we need to know is the tip speed ratio. It is defined as the ratio of tip speed of blade to wind speed. That is,

$$T_R = \frac{T_{ip} - Speed\_of\_Blade}{Wind\_Speed} = \frac{\omega \cdot radius}{Velocity} = \frac{(radians/\sec ond) \cdot meters}{(meters/\sec ond)}$$

In general, C_p is of the order of 0.4 to 0.6 and T_R is of the order of 0.8. Performance measure of a wind mill is given by a plot of T_R Vs C_p as shown in the following figure:

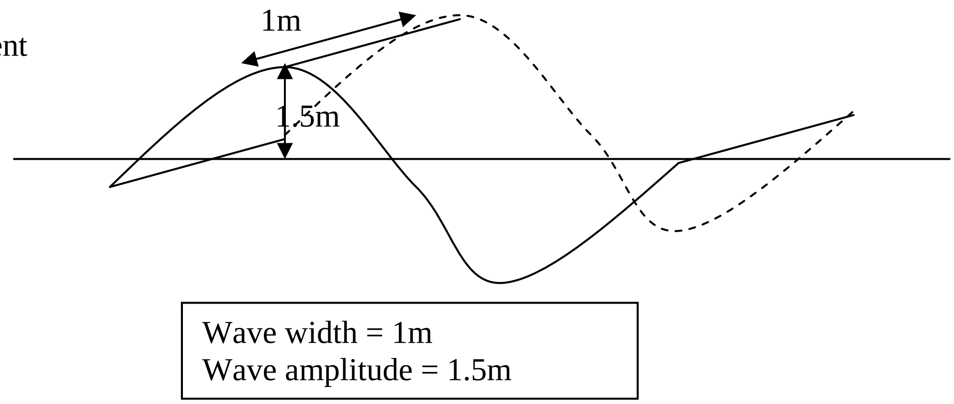
Student slide 7-02

Wave Energy:

Advantages:

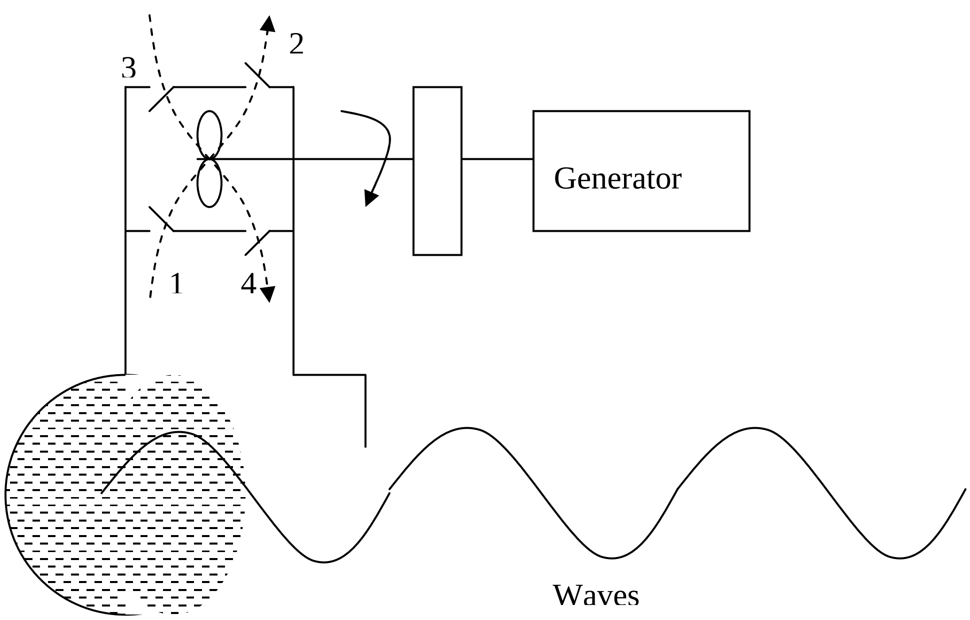
1. It is always available (24/7/365) 24hrs a day/ all 7days/ through out the year.
2. Consistent energy source.
3. Power density is very high.

Power of the wave shown adjacent
= 75 KW/m of wave width



Generation of electric power from the Wave Energy:

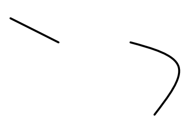
Schematic Diagram:



Working:

The schematic of the electric power generation from the wave energy is shown in the above fig. When the wave enters the chamber, the air inside the chamber is compressed and hence the valves 1 and 2 open up and hence the air moves from left to right and bottom to top as shown by the dotted line. When the water moves away from the chamber the air from the atmosphere enters the chamber through the valves 3 and 4 and hence the air moves from left to right and from top to bottom as shown. The turbine rotates as indicated. The turbine is mechanically coupled to a generator.

Energy content in the wave is dependent upon the wavelength and the amplitude of the wave. It can be seen that the energy content of the wave whose wavelength is greater is greater.



Student slide 7-03

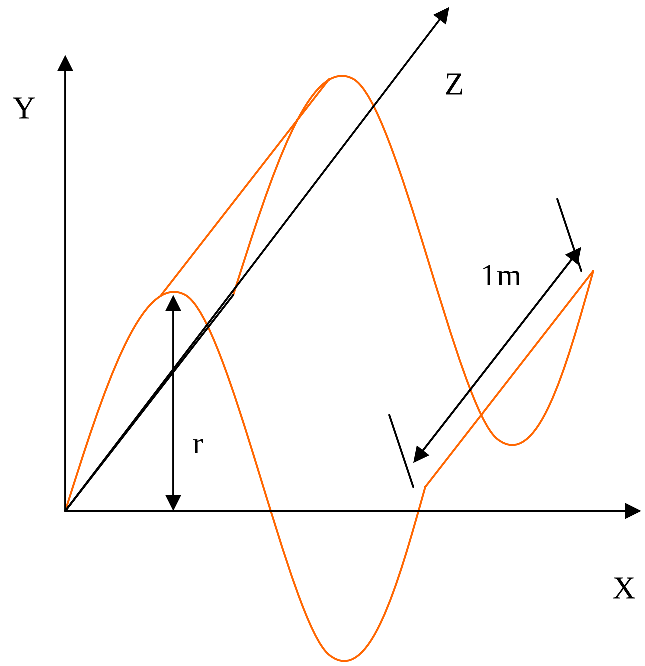


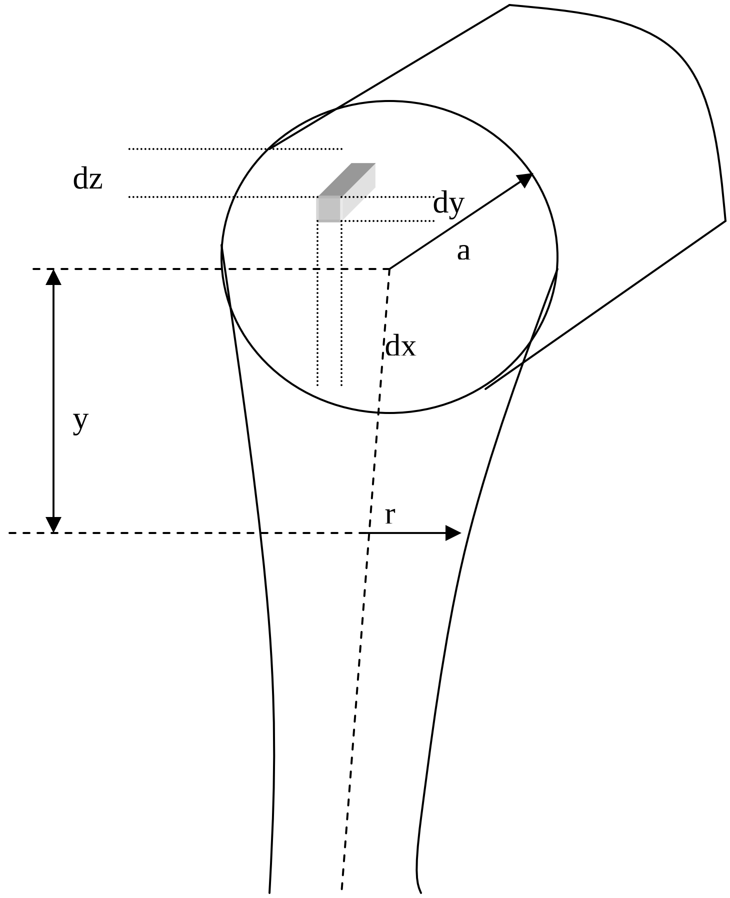
Fig: A Wave of unit Width and amplitude r moving along x-direction

Ocean Surface

Let the ampitude of the wave at the surface of the wave be ‘a’.

Wave is traveling in the x-direction.
Wave amplitude is in Y direction.
$r = ae^{ky}$
Where r is amplitude of wave at distance y in the negative direction.

It means that the amplitude of oscillations of particles decreases as we move in to the depth of the sea.



dv=dx.dy.dz
dx*dy is the volume per unit width of the wave.
Ek = kinetic energy per unit length in X direction.
dEk*dx= K.E of particle of width dx

$$=(1/2)mv^2$$
$$=(1/2).dx.dy.\rho.v^2$$
$$=(1/2).dx.dy.\rho.(\omega.r)^2$$

$$dEk=(1/2).dy.\rho.(\omega.r)^2$$
$$=(1/2).\ \rho.\omega^2.a^2.e^{2y}.dy$$

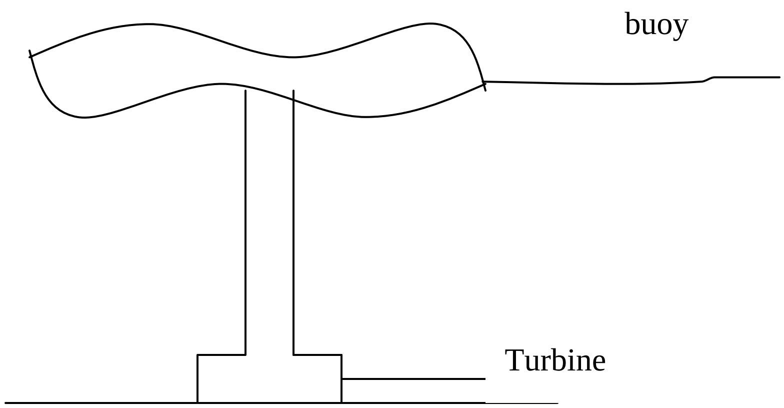
$$\int_{-\infty}^{0} dEk = (1/2).\ \rho.\omega^2.a^2.\int_{-\infty}^{0} e^{2y}\cdot dy$$
$$= \rho*\omega^2*a^2/(4*K)$$
$$K=2\pi/\lambda$$
$$\lambda=2\pi g/\omega^2$$

$$Ek=(1/4).\rho.a^2.g$$
$$Ep=(1/4).\ \rho.a^2.g$$

Total wave energy$=(1/2)*.\rho.a^2.g$
$E\lambda=(1/4)*\ \rho.a^2.g.\lambda$

$=(1/4\pi).\ \rho.a^2.T^2$

Power associated with the wave per unit width, P/unit width $=(1/8\pi)\ \rho a^2 g^2 T$



Non conventional energy systems

Wave energy

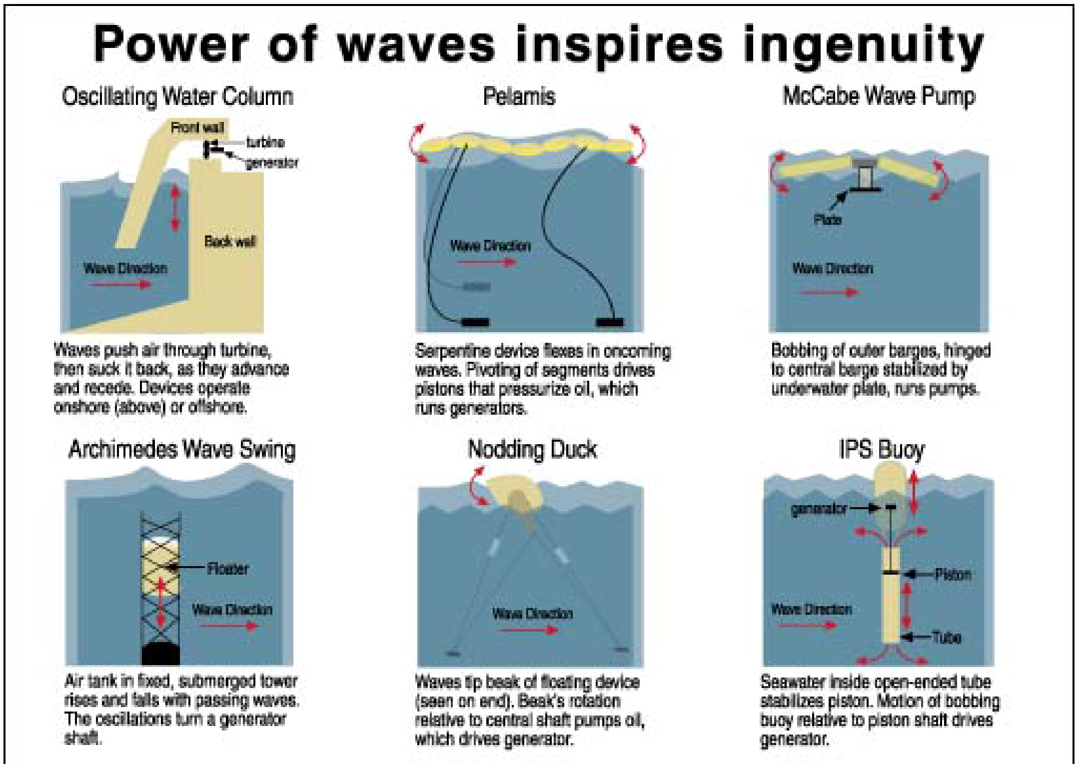
Wave energy is an irregular and oscillating low frequency energy source that can be converted to a 50 Hertz frequency and can then be added to the electric utility grid. Waves get their energy from the wind, which comes from solar energy. Waves gather, store, and transmit this energy thousands of kilometers with very little loss. Though it varies in intensity, it is available twenty four hours a day all round the year. Wave power is renewable, pollution free and environment friendly. Its net potential is better than wind, solar, small hydro or biomass power.

Wave energy technologies rely on the up-and-down motion of waves to generate electricity. There are three basic methods for converting wave energy to electricity.

1. **Float or buoy systems** that use the rise and fall of ocean swells to drive hydraulic pumps. The object can be mounted to a floating raft or to a device fixed on the ocean bed. A series of anchored buoys rise and fall with the wave. The movement is used to run an electrical generator to produce electricity which is then transmitted ashore by underwater power cables.

2. **Oscillating water column devices** in which the in-and-out motion of waves at the shore enters a column and force air to turn a turbine. The column fills with water as the wave rises and empties as it descends. In the process, air inside the column is compressed and heats up, creating energy. This energy is harnessed and sent to shore by electrical cable.

3. **Tapered channel** rely on a shore mounted structure to channel and concentrate the waves driving them into an elevated reservoir. Water flow out of this reservoir is used to generate electricity using standard hydropower technologies.



The advantages of wave energy are as follows:

1. Because waves originate from storms far out to sea and can travel long distances without significant energy loss, power produced from them is much steadier and more predictable day to day and season to season.

2. Wave energy contains about 1000 times the kinetic energy of wind.

3. Unlike wind and solar energy, energy from ocean waves continues to be produced round the clock.

4. Wave power production is much smoother and more consistent than wind or solar resulting in higher overall capacity factors.

5. Wave energy varies as the square of wave height whereas wind power varies with the cube of air speed. Water being 850 times as dense as air, this result in much higher power production from waves averaged over time.

6. Because wave energy needs only 1/200 the land area of wind and requires no access roads, infrastructure costs are less.

Student slide 8-02
Life Cost Analysis:

f is the rate of inflation
i is the rate of interest
If C is the present cost after n years it would cost $C(1+f)^n$
Present worth=$C(1+f)^n/(1+i)^n$

Present Worth = $1/(1+i) + 1/(1+i)^2 + \ldots\ldots + 1/(1+i)^n$

$=(1/i)*(1-(1/(1+i))^n)$

$=(1+f)/(i-f)* (1-(1/(1+i))^n)$ $i \neq f$
$= n$ $i=f$

Sample example:
Data:

	Cost	Life
PV Array	Rs 200/Wp	15 years
Motor + Pump	Rs 80/W	7.5 years
Transportation	Rs 50/W	
Pipe cost	Rs 10/m	5 years
Cost of well	Rs500/m	
Maintenance	Rs 1000/year	

PV Array 500W peak watts
Piping length 30m
Water depth 2m
i=10%

Capital (C):

Array cost	Rs 200*500
Motor+Pump	Rs 80*500
Transportation	Rs 50*500
Pipe cost	Rs 10*30
Cost of well	Rs 500*2
	Rs 1,66,300

Replacement (R):

Motor + Pump:
$80*500/(1+0.1)^{7.5}$ =Rs 19571.08

Pipes:
$300/(1+0.1)^{5} + 300/(1+0.1)^{10}$
=Rs 301.939

Maintenance:

$M=(1000/0.1)*(1-(1/1.1)^{15})$= Rs 7606

Life Cycle Cost = C+R+M
=Rs 193779

Student slide 8-03

Annual Life Cycle cost (ALCC) is the amount of installment to be paid (to the bank for eg.) every year.

$$LCC = ALCC \left\{ 1/i(1-1/(1+i)^n \right\}$$

$$ALCC = \frac{LCC}{\left\{ 1/i(1-1/(1+i)^n \right\}}$$

Example Problem:

A community of 500 people with a per capita consumption of 40litres/day. The cost of building of a bore well pump system is as follows:

Cost of the bore well	250/year
Bore well of depth	20m
Hand pump cost	5000/pump
Life of pump	10years
Maintenance cost	Rs.1250/pump/year
Period of analysis	20 years
Interest	10%

6 units are built what is the water charge in Rs/litre of Rs/m^3

Solution:

Life Cycle Cost:

Capital Cost:

Cost of borewell = 6*250*20 = 30000
Cost of handpumps = 6*5000 =30000

Replacement:

Hand pump replacement $=6*\{5000*1/(1+I)^{20}\} = 11566.3$

Maintenance:

Maintenance cost of the pumps = 6*1250*

Total Life Cycle cost = 30000+30000+11566.3+63851.7 = 1,35,418

$$\text{ALCC} = \frac{\text{LCC}}{\left\{ 1/i(1-1/(1+i)^n \right\}}$$

$$= \frac{1135418}{\frac{1}{0.1}\left\{ 1- \frac{1}{(1+0.1)^{20}} \right\}} = \text{Rs. } 15406$$

Annual Water requirement = 500*40*365 = 84,68,000

Water Cost = LCC/84,68,000
= Rs 16 /m^3

Hydel:

Example:

Month	**Lt/day**	**Static head**	**Dynamic head**	**Total head**	**Hydraulic energy required**	**Ht KWh/m^2/day**	**P_{req}**
Jan	42	2	0.2	2.2	0.025	6.26	
Feb	83	2	0.2	2.2	0.497	6.75	
Mar	88	2	0.2	2.2	0.527	6.40	
Apr	73	2	0.2	2.2	0.457	5.681	
May	100	2	0.2	2.2	0.598	4.394	
Jun	93	2	0.2	2.2	0.577	3.985	
Jul	63	2	0.2	2.2	0.557	4.463	
Aug	33	2	0.2	2.2	0.377	4.901	
Sep	32	2	0.2	2.2	0.197	5.17	
Oct	37	2	0.2	2.2	0.210	5.55	
Nov	40	2	0.2	2.2	0.310	5.663	
Dec	35	2	0.2	2.2	0.255	5.77	

Design Month

Design Month is ***June***

E_h = 0.557 KWh/day

H= 2.2m

H_t = 3.985 KWh/m^2/day

Efficiency of the system can be considered to be a maximum of 40%

PV array size = 0.577/0.4 KWh = 1.4425 KWh

Peak Watt, W_p = 1.4425*10^{-3}/3.985 = 392 W

Wattage of the motor required ≤ 350 W = ½ hp

Non conventional energy systems

Life Cycle Costing

Engineering economy is the application of economic factors and criteria to evaluate alternatives, considering the time value of money. The engineering economy study involves computing a specific economic measure of worth for estimated cash flows over a specific period of time.

The terms interest, interest period and interest rate are useful in calculating equivalent sums of money for an interest period. Interest is the manifestation of the time value of money. It is the difference between an ending amount of money and the beginning amount over an interest period. For more than one interest period, the terms simple interest and compound interest become important.

Simple Interest:

Simple interest is calculated using the principal only, ignoring any interest accrued in preceding interest periods. The total simple interest over several periods is computed as:

Simple Interest = (Principal) x (Number of Periods) x (Interest Rate)

Here the interest rate is expressed in decimal form. The total sum accrued at the end of n interest periods is given by:

$$S = P(1 + n \cdot i) \quad \ldots\ldots \quad (1)$$

S = Sum accrued at the end of interest periods (also called Future Worth)

P = Principal (also called Present Worth)

n = Number of interest periods (normally one year is taken as one interest period)

i = Interest rate (normally annual interest rate)

Compound Interest:

For compound interest, the interest accrued for each interest period is calculated on the principal plus the total amount of interest accumulated in all previous periods. Compound interest reflects the effect of the time value of money on the interest also. The interest for one period is calculated as:

Compound Interest = (Principal + All accrued Interest) x (Interest Rate)

The total sum accrued after a number of interest periods can be calculated from the following expression:

$$S_n = P(1 + i)^n \quad \ldots\ldots \quad (2)$$

S_n = Sum accrued at the end of n interest periods

P = Principal

i = Interest rate expressed in decimal form (annual interest rate)

n = Number of interest periods (number of years)

We can see from the above two expressions that the sum accrued at the end of first year would be same for both simple interest and compound interest calculations. However, for interest periods greater than one year, the sum accrued for compound interest would be larger.

What happens if the interest is compounded more than once in a year?

We need to modify equation (2) and is given by:

$$S_n = P\left(1+\frac{i}{m}\right)^{nm} \quad \text{…….……………………………………………………..………. (3)}$$

m = Number of periods the interest is compounded in one year

i = Annual interest rate in decimal form

n = Number of years

We can extend equation (3) to calculate the sum accrued if the interest is compounded continuously. Here m tends to ∞. Taking the limits such that m goes to infinity, we get the following expression:

$$S = P \cdot e^{in} \quad \text{…………………………………………………………..……………….... (4)}$$

For all practical purposes, equation (2) is used for interest calculations and repeated here for convenience:

$$S_n = P(1+i)^n$$

Here,

Sn = Future Worth of money

P = Present Worth of the money

$(1+i)^n$ = Future Worth Factor.

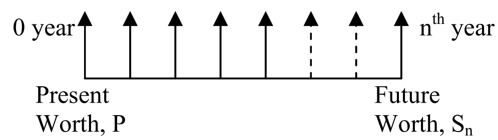
Given the present worth, annual interest rate and number of years, we can calculate the future worth. There may be situations when the future worth of money is given and we need to find the present worth of the money. The above equation can be re-arranged to calculate the present worth, given by:

$$P = \frac{S_n}{(1+i)^n} \quad \text{………………………………………………………………………..….(5)}$$

Here,

$\frac{1}{(1+i)^n}$ = Present Worth Factor.

To carry out calculations, it is convenient to draw what is called as cash flow diagram. The following figure gives one such cash flow diagram:



The cash flow diagram helps in analyzing the problem better.

Equations (2) and (5) are used in problems concerning single payment. In today's world we deal with problems that involve annual/monthly equal payments such as home mortgage payments, vehicle loans or loans for consumer electronic goods. The following relationships hold good for problems involving such uniform series:

$$P = A\left(\frac{(1+i)^n - 1}{i(1+i)^n}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

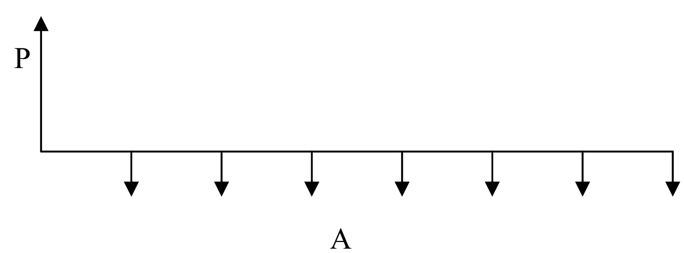
P = Present worth

A = Uniform Annual amount (installments)

$$S_n = A\left(\frac{\left((1+i)^n - 1\right)}{i}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(7)$$

S_n = Future worth

From these equations, we can calculate present worth or future worth given uniform annual amounts. We can also calculate the uniform annual amounts given either present worth or the future worth. A typical example would be person borrowing money from a financial institute for buying a vehicle. Knowing the interest rate and number of installments, the person can calculate the uniform equal amounts he or she has to pay depending on the amount borrowed. A typical cash flow diagram would look as follows:



The up-arrow indicates the amount 'coming in' such as borrowing and the down arrow indicates the amount 'going out' such re-payments towards the borrowing.

Inflation:

In all the above equations, we had assumed that there is no inflation. Inflation is an increase in the amount of money necessary to obtain the same amount of product before the inflated price was present. Inflation occurs due to downward change in the value of the currency. If 'C' is the cash in hand today for buying a product, f is the inflation rate, then the amount we need to pay for the same product after n years would be $C(1 + f)^n$, assuming uniform inflation over the years. The present worth of such money with interest component added is given by:

$$P_f = C \cdot \frac{(1+f)^n}{(1+i)^n} \quad \text{......(8)}$$

P_f = Present worth with inflation taken into account.

If i = f, no change in worth, year after year.

If i > f, save and do not buy the product now.

If i < f, buy the product now and do not save.

An important relationship between the present worth and the uniform annual amount taking inflation into account is given by the following equation:

$$P = A \cdot \left(\frac{1+f}{i-f}\right) \cdot \left[1 - \left(\frac{1+f}{1+i}\right)^n\right] \quad \text{......(9)}$$

for $i \neq f$. If i = f, then we get the following relationship:

$$P = A \cdot n \quad \text{......(10)}$$

Life Cycle Cost:

Life cycle costing or LCC is an important factor for comparing the alternatives and deciding on a particular process for completing a project. The different components taken into account for calculating LCC are:

LCC = Capital + Replacement cost + Maintenance cost + Energy cost – Salvage

Here, Capital is the present worth. Replacement cost that may occur at a later years need to converted to present worth. Maintenance cost is annual maintenance cost and needs to be converted to present worth and so is the energy cost. Salvage is the money that is obtained while disposing the machinery at the end of life cycle period. Even this amount has to be converted to present worth for calculating LCC. Once we have the LCC value, we can easily find the Annual Life Cycle Costing using the following equation:

$$ALCC = \frac{LCC}{\left(\frac{1+f)}{i-f}\right) \cdot \left[1 - \left(\frac{1+f}{1+i}\right)^n\right]} \quad \text{......(11)}$$

These equations would be clearer once we do some problems.

Non conventional energy systems

Example 1:

A community has 500 people. The source of water to the community is from the bore-wells and the supply of water from the bore-wells is by hand-pumps. Six hand-pumps are installed to meet the water requirement of the community. Per-capita water consumption of the community is 40 liters/day. Bore-well depth is 20 meters. The cost of each hand-pump is Rs.5,000.00. Cost of digging of each bore-well is at the rate of Rs.250.00 per meter. Life of the hand-pump is 10 years. Annual maintenance cost per pump is Rs.1250.00. If the rate of interest is 10%, what is the unit water cost for the life cycle period of 20 years?

Solution:

Step 1: Calculate capital cost (K):

For digging 6 bore-wells = (Rs.250.00 x 20) x 6 ……………….. = Rs.30,000.00

Cost of 6 hand-pumps = Rs.5,000.00 x 6 ………………………. = Rs.30,000.00

Total capital cost ………………………………………………. = Rs.60,000.00

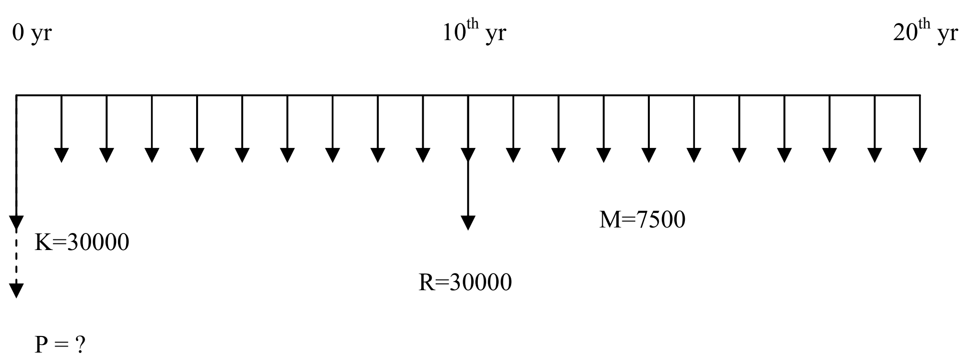
Step 2: Calculate replacement cost (R):

Cost for replacing 6 hand-pumps after 10 years ……………. = Rs.30,000.00

Step 3: Calculate annual maintenance cost (M):

Annual maintenance cost for 6 hand-pumps = Rs.1250.00 x 6 = Rs.7,500.00

Now let us draw the cash-flow diagram for the above data:



From figure, K is the capital at 0^{th} year. Let us call it **P1 = Rs.30000.00**

R is the replacement cost for hand-pumps occurring in 10^{th} year. We need to find the Present worth of this replacement cost. Let P2 be the present worth.

Hence, the value of

$$\textbf{P2} = \frac{R}{(1+i)^n} = \frac{30000}{(1+0.1)^{10}} = \textbf{Rs.11566.30}$$

M is the annual maintenance cost for 6 hand-pumps occurring at the end of each year. The present worth of the uniform series needs to be found. Let P3 be the present worth.

Hence, the value of

$$\textbf{P3} = M \cdot \frac{1}{i} \cdot \left[1 - \frac{1}{(1+i)^n}\right] = 7500 \cdot \frac{1}{0.1} \cdot \left[1 - \frac{1}{(1+0.1)^{20}}\right] = \textbf{Rs.63851.73}.$$

Step 4: Find the total present worth or LCC

Now the total present worth showed by dotted line in the cash flow diagram is the sum of all the present worth. That is: P = P1 + P2 + P3.

Hence, Life Cycle Cost or **LCC** = Rs.60000.00 + Rs.11566.30 + Rs.63851.73 = **Rs.135418.03**.

Step 5: Find annual life cycle cost or ALCC.

From LCC value, we can calculate Annual Life Cycle Cost or ALCC by using the following expression:

$$ALCC = \frac{LCC}{\left(\frac{1}{i}\right) \cdot \left[1 - \left(\frac{1}{1+i}\right)^n\right]} = \frac{135418.03}{\left(\frac{1}{0.1}\right) \cdot \left[1 - \left(\frac{1}{1+0.1}\right)^{20}\right]} = \textbf{Rs.15906.15}$$

Step 6: Find unit water cost.

Annual water requirement = 500 people x 40 liters/day x 365 days = 7300000 liters.

$$\textbf{Cost of water} = \frac{ALCC}{Annual Water\ Requirement} = \frac{15906.15}{7300000} = \textbf{Rs.0.00218/liter}.$$

Example 2:

A PV array of 500 watts has been installed to pump water from a bore-well of 2 meters deep using a submergible motor and pump system to an over-head tank. The length of pipe required to pump the water is 30 meters. Following are the costs involved for the sub-systems and their life spans:

PV Array : $8/peak watt; Life span – 15 years

Motor and pump: $2/watt; Life span – 7.5 years

Pipe cost: $8/meter; Life span – 5 years

Cost of digging the bore-well: $20/meter

Maintenance cost: $80/year

Miscellaneous cost: $3.5/watt

If the interest rate is 10%, calculate the Life Cycle Cost of the water for a period of 15 years and also water cost per year (ALCC).

Solution:

Step 1: Calculate the Capital cost (K)

Cost of PV array = $8/watt x 500 watts = $4000

Cost of motor and pump = $2/watt x 500 watts = $1000

Cost of pipe = $8/meter x 30 meters = $240

Cost of digging the bore-well = $20/meter x 2 meters = $40

Miscellaneous cost = $3.5/watt x 500 watts = $1750

Total capital cost = $4000 + $1000 + $240 + $40 + $1750 = **$7030**

Step 2: Calculate Replacement cost (R)

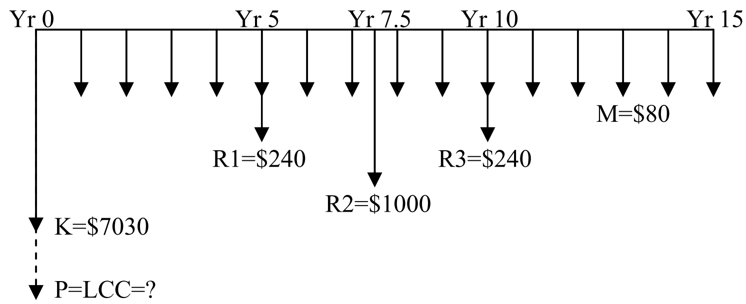
Replacement cost of motor and pump after 7.5 years = $1000

Replacement cost of pipe at the end of 5th year and at the end of 10th year = $240 each

Step 3: Calculate maintenance cost (M)

The annual maintenance cost is given as $80.

Let us draw the cash-flow diagram for the above data.



From the figure, K is the capital cost at year 0. Let us call it **P1 = $7030**.

R1 is the replacement cost of pipe in year 5. Let us call the present worth of R1 as P2.

This can be calculated as follows: P2 = $\frac{R1}{(1+i)^n} = \frac{240}{(1+0.1)^5}$ = **$149.02**

R2 is the replacement cost of motor and pump in year 7.5. Let us call the present worth of R2 as P3. Hence, **P3** = $\frac{R2}{(1+i)^n} = \frac{1000}{(1+0.1)^{7.5}}$ = **$489.28**

R3 is the replacement cost of pipe in year 10. Let us call the present worth of R3 as P4.

Hence, **P4** = $\frac{R3}{(1+i)^n} = \frac{240}{(1+0.1)^{10}}$ = **$92.53**

M is the annual maintenance cost starting at the end of year 1 till the end of year 15. Let us call the present worth of this uniform series is **P5**. Hence P5 = $M \cdot \frac{1}{i} \cdot \left[1 - \frac{1}{(1+i)^n}\right] =$

$80 \cdot \frac{1}{0.1} \cdot \left[1 - \frac{1}{(1+0.1)^{15}}\right]$ = **$608.49**

Step 4: Calculate LCC

The total present worth = LCC = P = P1 + P2 + P3 + P4 + P5

LCC = $7030 + $149.02 + $489.28 + $92.53 + $608.49 = **$8369.32**

Step 5: Calculate ALCC. This gives water cost per year.

$$ALCC = \frac{LCC}{\left(\frac{1}{i}\right)\cdot\left[1-\left(\frac{1}{1+i}\right)^{n}\right]} = \frac{8369.32}{\left(\frac{1}{0.1}\right)\cdot\left[1-\left(\frac{1}{1+0.1}\right)^{15}\right]} = \mathbf{\$1100.35}$$

Hence the water cost per year is $1100.35.

Example 3:

A micro-hydel plant of 1kW power capacity has been installed. Following are the cost involved in installation of the whole system:

Installation cost of the plant = Rs.16000

Cost of mains transmission = Rs.16000

Cost of distribution transformer = Rs.2500

Cost of 11 kV line per Kilometer = Rs.4000

Life span of the plant is 25 years. If the rate of interest is 12%, find the unit cost per Kilometer.

Solution:

Step 1: Calculate the capital cost (K)

The problem involves only the initial cost incurred at year 0. There is no replacement cost or maintenance cost involved. Hence, we can calculate the total capital cost just by adding the given quantities. Let K be the capital cost. It is calculated as follows:

K = Rs.16000 + Rs.16000 + Rs.2500 + Rs.4000 x d

Here d is the distance to which 11 kV line runs.

Step 2: Calculate LCC

Since no other costs except capital cost is involved, LCC can be directly calculated. Therefore K= **LCC** = Rs.(**34500 + 4000d**)

Step 3: Calculate ALCC

Annual cost (ALCC) can be calculated from the above data.

$$ALCC = \frac{LCC}{\left(\frac{1}{i}\right)\cdot\left[1-\left(\frac{1}{1+i}\right)^{n}\right]} = \frac{34500+4000d}{\left(\frac{1}{0.12}\right)\cdot\left[1-\left(\frac{1}{1+0.12}\right)^{25}\right]} = \frac{34500+4000d}{7.84314}$$

ALCC = 4398.75 + 510d

Step 4: Calculate energy generated per year

Energy generated per year = 24 hours x 365 days x 1 kW = 8760 kWHr

Transmission efficiency η = 30%

Hence, energy available = 8760 x 0.3 = 2628 kWHr

Step 5: Calculate cost per unit (1 unit = 1 kWHr)

Cost per unit = $\frac{ALCC}{EnergyAvailable} = \frac{4398.75+510d}{2628}$ = **1.674 + 0.1941d**

We can see that cost per unit depends on the value of d, the distance to which 11 kV line runs. As example, let us calculate cost per unit for d = 5 KM and d = 100 KM

Cost per unit for d = 5 KM : 1.674 + 0.1941 x 5 = Rs.2.64

Cost per unit for d = 100 KM : 1.674 + 0.1941 x 100 = Rs.21.08.

We can see how adverse effect the distance has on the cost per unit. Hence, care must be taken that we do not run such 11 kV lines for long distances.