CONCENTRATED PHOTOVOLTAIC SYSTEM

Conduct a Feasibility study for a prototype 10 KW Concentrated Photo Voltaic (CPV) electricity generation system. The study must include design of the receiver taking heat losses in to account & aspects of Technology & Economy for Indian situation must also be included. Compare the design with a conventional PV system. Discuss the advantages & drawbacks of implementing such a system in IITM.

Group 18

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Abstract

A feasibility study for implementing a prototype 10kW Concentrated Photo Voltaic (CPV) power plant in IIT Madras is undertaken. The individual systems of a CPV plant, such as solar cell modules, concentrators and receivers, cooling systems and solar tracking were analyzed in detail. Detailed study for a roof top CPV system in one of the hostels was done, considering the load distribution curve, advantages and challenges of implementing the same. Finally recommendations were made for each subsystem , thus optimizing the overall economics of the proposed CPV plant.

Contents

1. Introduction to solar cells

Solar cells are devices which convert the solar photonic energy into electricity. The basic principle behind this energy conversion is explained in this section.

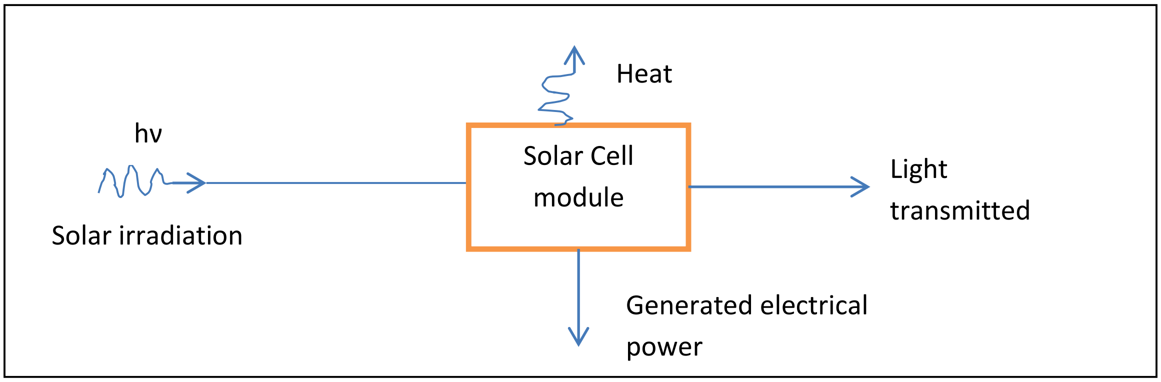


Figure 1: Schematic of solar cell energy conversion & losses

Figure 1 shows a schematic of energy conversion in a Photo-Voltaic (PV) cell. The light incident on the cell gives rise to electrical energy, along with generation of heat & some light transmission (unabsorbed light). The efficiency of the solar cell can be then defined as

$$\eta = \frac{Output\ power}{Input\ power}$$

This is generally known as Power Conversion Efficiency, or PCE. PCE for most commercial solar cells is around 10-20%, hence only about 1/5th of the incident solar energy is converted to useful electrical energy. Most of the energy is either lost in transmission losses & thermal losses. To understand these losses & power generation, we look briefly into the photo-voltaic effect of a solar cell.

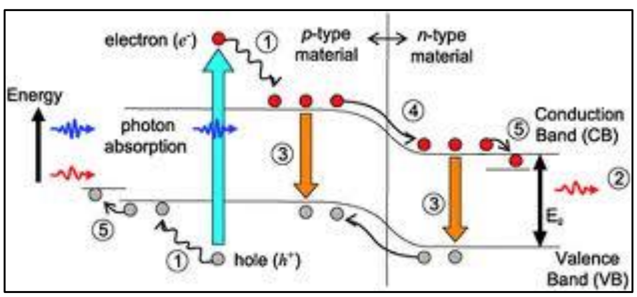


Figure 2: Energy generation & loss mechanisms in a general p-n junction solar cell

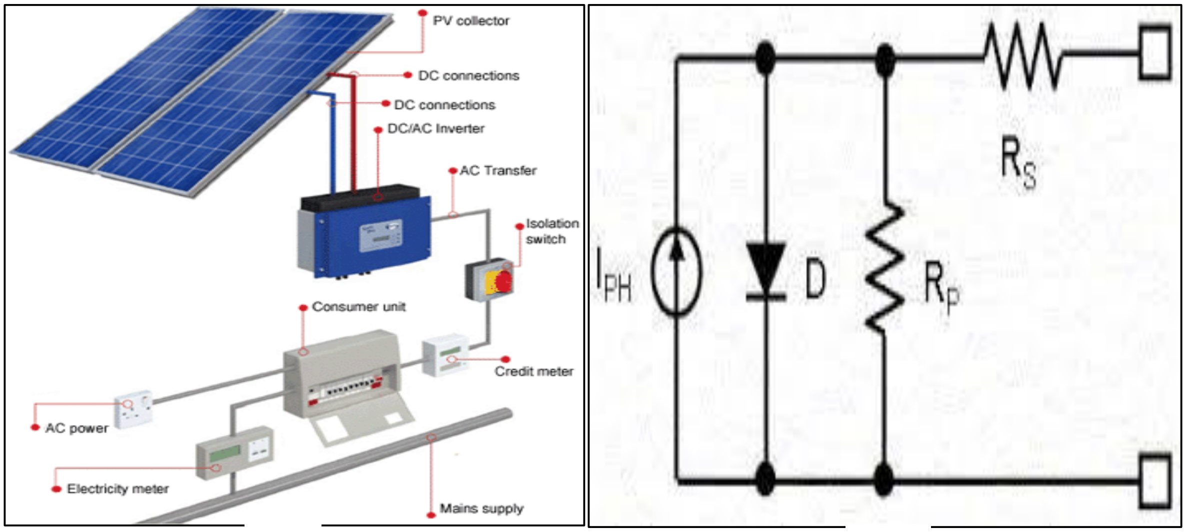
A solar cell is just a p-n junction semiconductor diode which generates current when subjected to light. The incident photons have some energy, which can be absorbed by the electrons in the valence band of the semiconductor to get promoted to the conduction band. Electrons & holes thus generated have to be now carried away quickly before they recombine & emit light.

As solar spectrum consists of a wide range of energies, we can broadly classify the photons in three categories as following:

1. **Photons with energies less than the band gap of the semiconductor**: In this case, the photons are not absorbed, as the energy of the photon is insufficient to promote an electron to conduction band. This can also be looked alternatively as the photon is absorbed, but the electron cannot reach conduction band & relaxes back to valence band with emission of the same photon. Either way, the photons with energies less than band gap of the semiconductor are simply transmitted through, & this causes the transmission losses. In addition, recombination of the carriers before collection also gives rise to photons & hence adds to the transmission losses.
2. **Photons with energy exactly equal to the band gap of the semiconductor**: These photons have the exact energy to promote an electron to the conduction band & hence give rise to charge carriers which can be carried away before recombination to generate useful current & hence electrical power. Note that not all the carriers can be carried away & some of them recombine to give rise to transmission losses as explained earlier.
3. **Photons with energies greater than the band gap energy**: In this case the photon promotes an electron to deep inside the conduction band. However, this electron relaxes quickly to the conduction band edge with the excess energy dissipated as heat. Hence we recover only a part of the photon energy as useful electrical energy. This is the cause of thermal losses in a solar cell. These losses can be huge as efficiencies of typical solar cells in production are

only about 10-20%. Hence effective cooling system has to be employed to carry away the heat which would otherwise heat up the whole module & reduce the cell efficiency. Figure 2 shows all the internal losses in a solar cell.

Apart from these losses, there are also some electrical losses in the electrical circuit. Figure 3(a) shows the electrical circuit model for a solar cell & Fig.3 (b) shows a schematic for electrical circuit of the whole power generation unit.



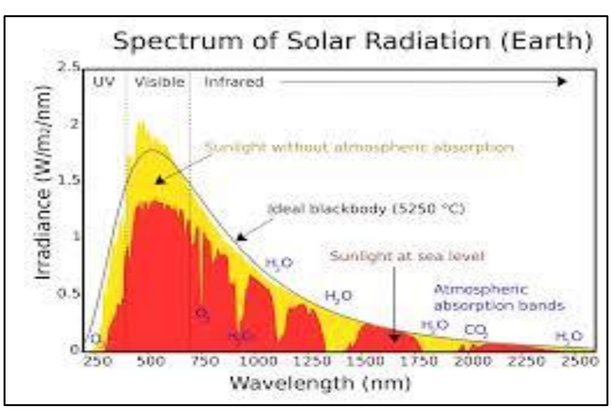
(a) (b)

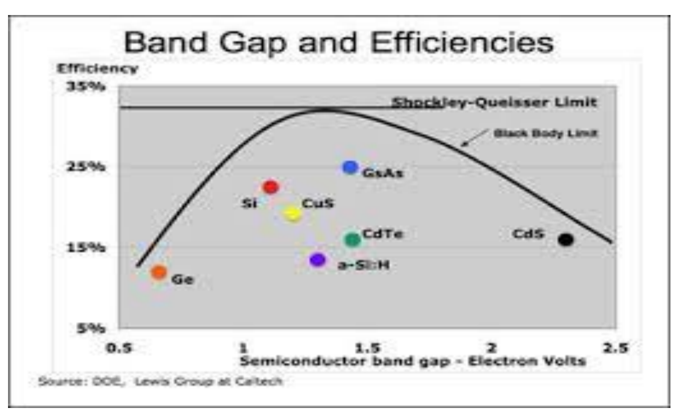
Figure 3: (a) Solar PV generation unit schematic. (b) Equivalent electrical circuit

Hence for any solar cell, the output power obtained corresponds to its band gap energy. This gives rise to a tread-off between number of photons absorbed & the useful electrical energy produced. For very low band gap semiconductors, most of the solar spectrum is absorbed, but only a small energy is converted to electrical energy & majority of it is lost as thermal losses. However, on the other hand, for very high band gaps, large portion of solar spectrum is not absorbed & transmission losses are huge. Hence there exists an optimal band gap for which maximum efficiency is obtained. Figure 4 shows the solar spectrum which gives an idea about the intensity of irradiation against the photon energy. Detailed calculation for maximum efficiency is done by Shockley (1960) & can be found in Appendix A. The analysis yields a maximum of 40% efficiency for a single junction solar cell with band gap around 1.3 eV. However, with multi-junction solar cells & concentrator technologies, this limit can be exceeded. It was shown by Brabec *et.al.* that the maximum efficiency for an infinitely stacked multi-junction solar cell is 68% & 86.8% without & with the concentrators respectively.[1]

A solar panel is an array of many such individual solar cells, which give rise to a DC current with a small voltage. To convert this into the traditional 230V AC power, the voltage needs to be stepped up using a transformer & DC power has to be converted to AC power using alternator. It is to be kept in mind that the typical lifespan of an alternator is lower than that of solar panels & this increases the maintenance cost of solar power generation unit.

Solar power plants are susceptible to temporal & seasonal variations & hence are unreliable. Further, on an average day, only about 6-8 hours of useful radiations may fall on the solar panels. To generate enough power to last throughout the day, the system has to be overdesigned for load & storage of the power has to be given special considerations. Currently, the penetration of solar energy in the main power grid is quite low, & usually these power plants are used only in the peak load hours.





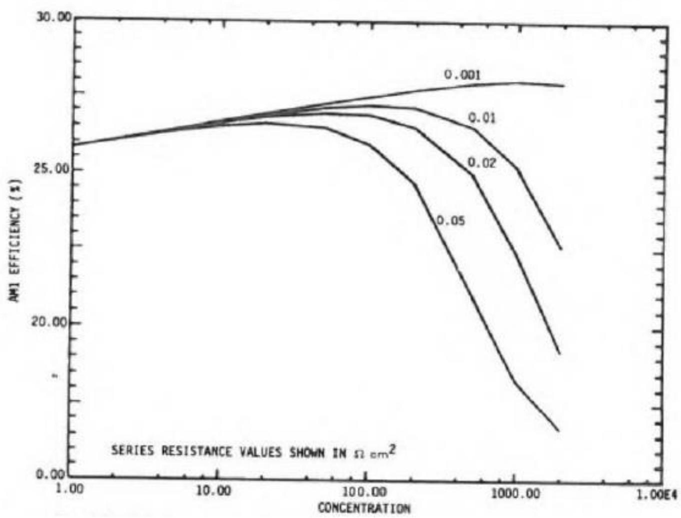
1.1 Comparison of different solar cells

In this section, we will compare a few of the commercially available solar cells used in household/ large scale power generation. Important considerations while choosing appropriate solar cell unit for a solar power plant are:

1. Cost/Power: The cost of solar panel per unit of power produced gives a general idea about the overall cost of the power generation unit & serves as a good benchmark to compare various solar cells. This includes both PCE & manufacturing costs.
2. Efficiencies: An important criterion for consideration is the cell efficiency. Usually for power plants with space constraints should use high efficiency solar cells, but a highly efficient solar cell is usually expensive. (eg Mono crystalline Si solar cell Vs. Polycrystalline Si solar cell)
3. Space constraints: With varying cell efficiencies, the amount of space required for a certain power output varies. Smaller efficiencies dictate larger areas for same power output but have less cost of manufacturing.
4. Cooling systems: As thermal losses account for about 80% of the incident energy, effective cooling systems must be employed. As the temperature of the solar cell increases, its efficiency comes down drastically.

For solar cells with high efficiencies & high cost of manufacturing (Such as GaAs cells) it may be beneficial to employ a concentrator system. With concentrator systems, the numbers of cells reduce & their efficiencies are also seen to increase up to moderate concentrations. In this report, we look at such a concentrated PV system for a 10kW power generation unit.

1.2 Concentrated solar systems (CPVs)



There are a few advantages of using a concentrator system in solar power plants such as increased cell efficiency & lesser requirement for solar cell units due to high intensity. The efficiency of a solar cell increase with concentrator up to 1000 suns (1000x magnification) & falls drastically after this owing to the increased electrical & thermal losses at high generation current & temperature respectively. A sample plot of cell efficiency against concentration is plotted in figure 4 which gives an idea of the optimum concentration for CPV systems.

Figure 4: Efficiency variation for a AlGaAs/GaAs solar cell.

1.3 Solar cells comparison

Deciding the solar cell module for a solar PV plant is of primary importance. The selection criteria not only include efficiency, cost of manufacturing, but also space considerations & overall lifetime of these cells. For example, recent developments have made manufacturing of organic & polymer solar cells which are extremely cheap & environment-friendly, but the lifetime is very low as these cells are unstable subjected to solar radiations. On the other hand, GaAs solar cells give the highest efficiencies in all the solar cell modules but manufacturing is expensive & Ga is harmful for the environment. Hence GaAs cells are mostly used with concentrators which enable to produce more power output for relatively small number of cells.

In recent years, higher solar cell efficiencies are being achieved using multi-junction solar cells. The leading manufacturers in CPV technology such as *Semprius, Soitec, ArzonSolar , CPV consortium* have progressively used multi-junction solar cells to yield efficiencies in the range of 35-45%. Such highly efficient solar cells, along with high concentration factors for concentrator systems dictate very small amounts of solar cells to be used in the solar panel, which makes this economically viable & space-efficient. A standard CPV module consists of the following modules which are shown in figure 5.

Most of the multi-junction solar cells used in CPV systems are III-IV solar cells. As the number of junctions in the multi-junction solar cells increase, the efficiency tends to go up. But, a careful spectral & electrical matching has to be done for the constituent junctions to have best efficiencies. *ArzonSolar* has commercially available triple junction solar cell (InGaP/InGaAs/Ge) which shows an efficiency of around 35% (module) & over 40% lab efficiency.

Figure 5 : Constituents of a CPV system, notice that actual size of the solar cell is very small compared to the total area.

Note that multi-junction solar cells are currently only used in CPV units as production of these cells in large quantities in highly expensive. In the CPV system, the multi-junction solar cells are only of the size of few millimeters in width.

1.3.1 Cost considerations of solar cell modules

Extra cost of a concentrator system should be justified by increased efficiency & hence power output. Inorganic semiconductors such as AlGaAs-GaAs solar cells & multi-junction solar cells are ideal to be used in tandem with concentrators as cost of manufacturing is quite high but high efficiencies drive the need of such systems. Space availability is an important factor, for example for same power output; amorphous silicon solar cells require large space due to low efficiencies even though the cost of production is quite low. Hence CPV systems are exceedingly being used in places where weight & space considerations are extremely important, such as space shuttles. However, the use of CPV systems in an ordinary solar power plant is limited due to relatively high costs.

While comparing the cost of two solar cells, generally the cost per unit power (LCOE) is calculated [2][3]. LCOE considers power plant capital cost, system operation & maintenance costs & energy yield generated over the lifetime of the plant. This normalizes the effects of efficiency & manufacturing costs & gives a platform to compare solar cells. Multi-junction solar cells by *Skyline solar* harvest solar energy at as low as \$0.095/kWh (Cost per kWh, not LCOE of the entire plant). (McDonald, 2011) The recent developments in CPV systems have made it possible to have lower levelized cost of electricity (LCOE) than non-concentrator systems. This economic advantage is expected to grow further as the cell efficiencies go up. It is estimated that just 1% increase in the efficiency (absolute) reduces the total cost by about 2.5%. (Gupta, 2013) .

The LCOE of CPV systems decreased nearly 26 percent in 2013 alone to \$2.62/W, & a 15% annual reduction is expected through 2017 to \$1.59/W. CPV's average LCOE is declining nearly 23 percent this year to \$0.14/kWh & should decline another 12 percent annually until 2017.

2. Design of Concentrators

The idea of CPV is using optical devices with cheap & suitable technology to concentrate the light on small & highly efficient photovoltaic solar cells. Hence, the cost will be reduced by means of replacing the cell surface with cheaper optical devices. Additionally the role of concentration photovoltaic systems is to collect both beam & scattered irradiation, which do not reach the photovoltaic cells.

Solar concentrators are classified by their optical characteristics such as the concentration factor, distribution of illumination, focal shape, & optical standard. Concentration factor X, which is also known as the number of suns, is the ratio of the mean radiant flux density on a receiver area G_x compared to the average normal global irradiance G:

$$X = G_x/G$$

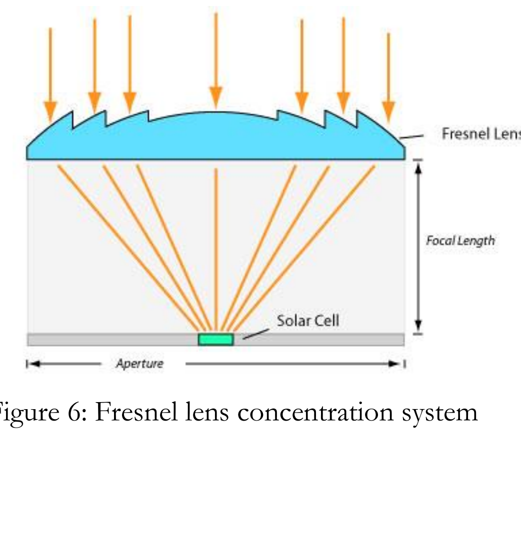


Figure 6: Fresnel lens concentration system

The classification based on the concentration factor includes the following

conditions:
(i) Low concentration (LCPV): (1–40x),
(ii) Medium concentration (MCPV): (40–300x),
(iii) High concentration (HCPV): (300–2000x).
Higher tracker tolerances, passive heat sinks, lower cost optics, reduced manufacturing costs, & reduced installation precision made LCPV more simple compared to HCPV.

Concentrators can be divided into two groups, two dimensional concentrators (2D) & three dimensional concentrators (3D). Three dimensional concentrators such as the 3D Compound Parabolic Collector change all three direction vectors, direction cosines, of the incoming rays, & will typically concentrate the incoming irradiation to a spot. Two dimensional concentrators are symmetric around one axis, only two of the direction cosines are affected by the concentrator. For example, the illumination profile from an axisymmetric concentrator is a line.
They are also classified in two other optical categories:
(1) **Imaging optical concentrators**, which means the image formed on the receiver by the optical concentrators
(2) **Non-imaging optical concentrators**: the receiver is not concerned with forming an image on it by optical concentrators.

In general, the concentrators were modeled as a black box [4] & flux was assumed to be conserved at entry & exit. The following points were concluded based on the analysis:
1. According to the laws of thermodynamics it is not possible to concentrate light infinitely; there is a theoretical upper limit for the concentration ratio. The maximum concentration ratios that can be obtained are:

$$C_{max} = n' / (n*\sin(\theta_{max})) \qquad \text{for 2D concentrator}$$

$$C_{max} = (n' / (n*\sin(\theta_{max})))\hat{}2 \qquad \text{for 3D concentrator}$$

where n' is the refractive index of the media that constitutes the concentrator, n is the refractive index of media at the entry of the concentrator & θ_{max} is the maximum extent of the beam that will still strike the exit aperture.
2. The smaller the angular interval of acceptance, the higher the concentration ratio.
3. It is important to have rays exiting at all angles up to 90° to get a high concentration ratio.
4. Use of dielectric medium with n>1 increases the concentration ratio by increasing the acceptance angle. Having an index of refraction greater than $\sqrt{2}$ gives an advantage as total internal reflection will occur in each reflection. This means a concentrator without reflectors can be constructed, something that will significantly increase the flux throughput of the system as there will be no reflection losses.

2.1 Type of Concentrators

1. **Reflector**: Upon hitting the concentrator, the sun rays will be reflected to the PV cell
Example: *Parabolic Trough, Parabolic Dish, CPC Trough, Hyperboloid Concentrator.*
2. **Refractor**: Upon hitting the concentrator, the sun rays will be refracted to the PV cell.
Example: *Fresnel lens Concentrator*
3. **Hybrid:** Upon hitting the concentrator, the rays can experience both reflection & refraction before hitting the PV cell.
Example: *DTIRC, Flat High Concentration Devices*
4. **Luminescent**: The photons will experience total internal reflection & are guided to the PV cell.
Example: *Quantum Dot Concentrator*

2.1.1 Fresnel Lens

A Fresnel lens is a flat optical component which comprises several sections with different angles that converges the light rays falling on it. Fresnel lenses recently have been one of the best choices due to their noble properties such as small volume, light weight, as well as mass production with low cost. In early Fresnel lenses, glass was replaced by polymethylmethacrylate (PMMA), discovered by Augustine Jean Fresnel, with optical characteristics almost the same as glass including good transmission & resistance to sunlight; hence it is the suitable material choice for the manufacturing of Fresnel lenses. It is possible to achieve short focal length & large aperture with a Fresnel lens in comparison to a standard lens. According to the results of an experimental & analytical method used by Harmon, the lens is an inefficient concentrator with losses that begin at 20%and rise to about 80% as the focal distance decreases.
Fresnel lens can be constructed in two ways:

- In a shape of a circle to provide a point focus with concentration ratios of around 500

- In a cylindrical shape to provide line focus with lower concentration ratios

With the high concentration ratio in a Fresnel point lens, it is possible to use a multi-junction photovoltaic cell with maximum efficiency. In a line concentrator, it is more common to use high efficiency silicon since the cost of a silicon cell is much lower compared to multi-junction PV cells.

2.1.2 Parabolic mirrors

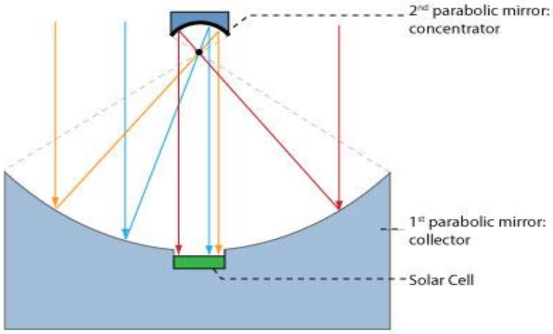


Figure 7: Parabolic concentrator

It consists of two parabolic mirrors, the primary mirror (also called the collector) converges all the incoming parallel light rays at its focal point where the secondary mirror (which is smaller in size & having the same focal length) reflects the light beams to the center of the first parabolic mirror where the solar cells are placed. Its advantage is that it does not require any optical lens. The solar parabolic trough collector is the most recognized technology due to its high dispatch ability & low unit cost. However, losses occur at the reflection points in both the mirror. A concentration ratio of up to 500 can be achieved with this combination.

2.1.3 Reflectors

These are generally used for low concentration photovoltaic applications with the concentration ratio of about 1.5-2.5. They use mirrors manufactured with silicone covered metal to concentrate sunlight onto a solar cell after a series of reflections from the side walls.

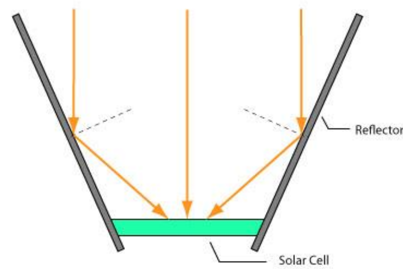


Figure 8: Reflection based concentrators

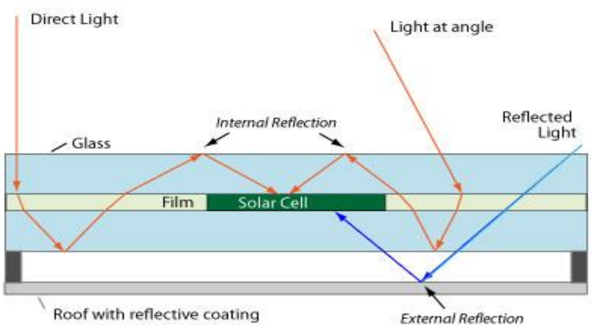


Figure 9: Luminescent concentrators

2.1.4 Luminescent concentrators

In a luminescent concentrator, light is refracted in a luminescent film, & then channeled towards the photovoltaic material. It does not require optical lenses or mirrors. It also works with diffuse light & does not require tracking. It does not require cooling as the film would be constructed such that the wavelengths that cannot be converted by the solar cell would pass through. However, the concentration ratios are quite low, around 2-3.

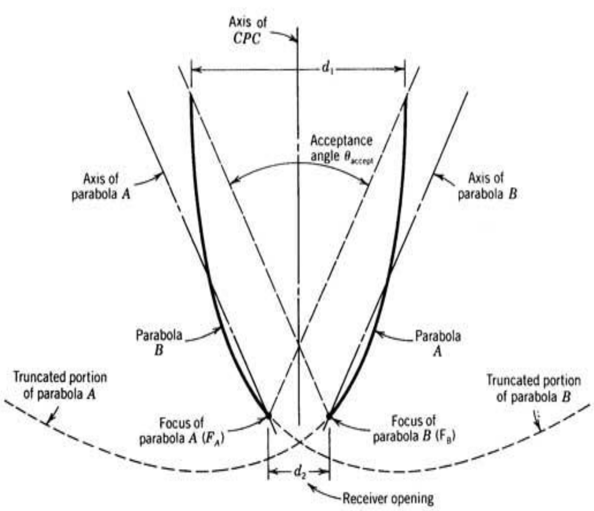


Figure 10: Compound Parabolic

2.1.5 CPC (Compound Parabolic Concentrators)

It consists of two segments of parabolas. A CPC can be divided into three parts; a planar entrance aperture, a totally internally reflecting side profile & an exit aperture. The CPC will have an acceptance angle of 2θ & will concentrate all the solar radiation at the exit aperture. The total length of a CPC depends both on the exit aperture & the acceptance angle of the concentrator. By reducing the acceptance angle, the size of the concentrator will increase. The main advantage of using a CPC is that it could offer a higher geometrical concentration gain with a narrow field of view. The disadvantages of the CPC trough concentrator will be the same as parabolic trough concentrator; it requires a good tracking system to maximize the collection of sun radiation.

The volume of a three dimensional CPC is large, & the cost of manufacturing the concentrator increases significantly when it is filled with a dielectric material in order to improve the concentration ratio. One solution to this problem is to make a small CPC & introduce it at the exit aperture of a concentrator filled with air & use the CPC as a secondary concentrator. This will increase the concentration ratio of all non-ideal concentrators, or increase the interval of acceptance of any concentrator. The small size of the secondary CPC, due to the fact that the size of the entry aperture of this CPC is the same as the exit aperture of the first concentrator, solves the problem of high manufacturing cost for the full size CPC. In theory, this two stage system makes it possible to approach the theoretical limit of $(n/\sin(\theta max))^2$. The three dimensional CPC is mostly used in solar tracking applications where a very high irradiation level at the exit aperture is desired e.g. in parabolic dish systems.

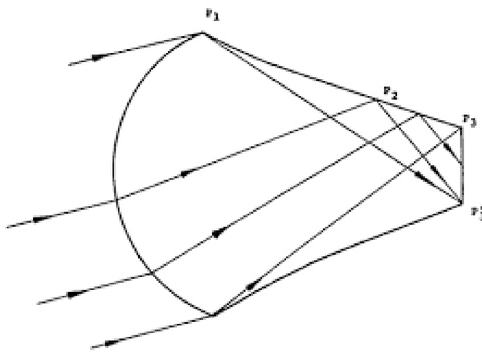


Figure 11: DTIRC

2.1.6 Dielectric Totally Internally Reflecting Concentrator (DTIRC)[5]

DTIRC consists of three parts; a curved front surface, a totally internally reflecting side profile & an exit aperture. When the rays hit the front curved surface, they are refracted & directed to the side profile. Upon hitting the sidewall, they will be totally internally reflected to the exit aperture. The front aperture can be a hemisphere, but different designs such as parabola & eclipse have been developed recently.

The geometrical concentration gain of a DTIRC depends on both acceptance angle & also the front arc angle. The advantage of DTIRC over CPC is that it offers higher geometrical concentration gain & smaller sizes. The disadvantage of a DTIRC is that it cannot efficiently transfer all of the solar energy that it collects into a lower index media. As a result, not all the sun rays are transmitted to the cell area.

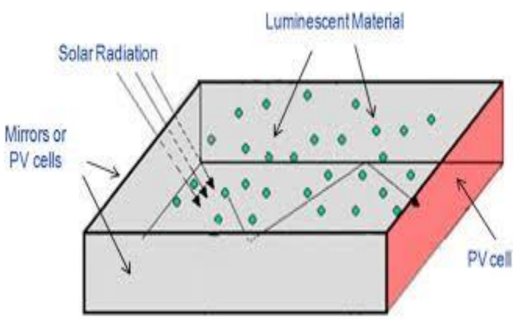


Figure 12: Quantum Dot Concentrator

2.1.7 Quantum Dot Concentrator (QDC)

Quantum dot concentrator, (QDC) is a planar device that consists of three parts; a transparent sheet of glass or plastic made doped with quantum dots (QDs), reflective mirrors mounted on the three edges & back surface, & an exit where a PV cell is attached. When the sun radiation hits the surface of a QDC, a part of the radiation will be refracted by the fluorescent material & absorbed by the QDs. Photons are then reemitted in all direction & are guided to the PV cell via total internal reflection. The total geometrical concentration will be the ratio of the large surface area of glass to the area of PV cell. QDC major advantage is that it does not requires any tracking as other conventional concentrator. It can also make full use of both direct & diffuse solar radiation. However, the drawback of the QDC is that the development of QDC is restricted to high requirements on the luminescent dyes; i.e. high quantum efficiency, suitable absorption spectra & redshifts, & stability under illumination.

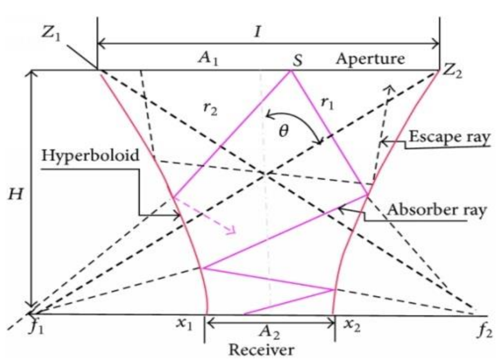


Figure 12: Hyperboloid Concentrator

2.1.8 Hyperboloid Concentrator

In this type of concentrator, incident rays on the aperture enter the hyperboloid concentrator & either reach the receiver or reflect back out of the concentrator. This kind of concentrator is also called the elliptical hyperboloid concentrator. The advantage of this concentrator is that it is very compact, since only a truncated version of the concentrator needs to be used. Because of this factor, it is mainly used as a secondary concentrator. It was found out that the one-sheet hyperbolic concentrator is an ideal 3D asymmetric concentrator as its shape does not disturb the flow lines of an elliptical disk[6]. It also does not need a tracking system where two different acceptance angles, transversal & longitudinal direction, are needed. It has been shown that the 3-D solar concentrator acquired from the hyperboloid has the ability of concentrating all the entering rays such as the trumpet concentrator, which is composed of a revolution of hyperbolic type & was considered as an ideal concentrator.

2.1.9 RR, XX, XR, RX, & RXI

These configurations represent the new concentrators which achieved the theoretical maximum acceptance angle concentration & it was concluded that they may be useful for high concentration cells. In these designs “R” denotes refraction, “X” denotes reflection, & “I” denotes internal reflection. Rays that impinge on the concentrator aperture, within the acceptance angle, are directed to the receiver by means of one refraction, one reflection, & one total internal reflection. The investigation of the performance of RX was carried out & the results indicated that when the angular spread of the input bundle is small, the performance of the rotational RX is acceptable. An analysis of the RX concentrator performed by Benitez & Minano[7] stated that when the field of view is small (less than 6 degrees full angle), even for concentrations up to 95% of the theoretical maximum, its imaging performance is similar (in MTF terms) to that of normal incidence of an f/3.7 plano-convex spherical lens with optimum defocusing. This image capability is suitable for receivers. When the acceptance angle of the concentrator is less than 5 degrees (for a source at infinity), its performance in 3D is very good.

3. Receivers

The receiver consists of solar cells arranged in the solar panel. The major criteria for selection of a concentrator are the concentration factor, the distribution of concentration, reduction in the number of the photovoltaic cells & consequently the reduction in cost. The concentration ratio depends on the size of the receiver (the photovoltaic cell modules), the receiver module efficiency & the required power output. The figure below shows the energy gained by the receiver as a function of the receiver size. The optimum size of the receiver is obtained at the point where the total receiver energy (intercepted optical energy minus heat loss) is maximized. Based on the receiver size & the available area for capturing sun rays, the required concentration ratio is determined.

3.1 Optical Energy Capture

In a concentrating photovoltaic panel, energy incident on the cell is reduced by the reflectance, ρ of the intermediate reflecting surfaces, & the fraction of reflected energy that falls on the cell, Γ. The transmittance, τ of the cover sheet used to physically protect the cell surface & to keep moisture & oxygen away from the electrical contacts, further reduces the optical energy incident on the cell.

3.1.1 Heat Loss

Heat loss from the panel follows the same three paths, convection, radiation & conduction. Optimizing those factors that *increase* heat loss without increasing cell temperature is important for well-designed photovoltaic panels. Maximizing heat loss for concentrating PV collectors is more difficult due to the reduced cell surface area resulting from concentration.

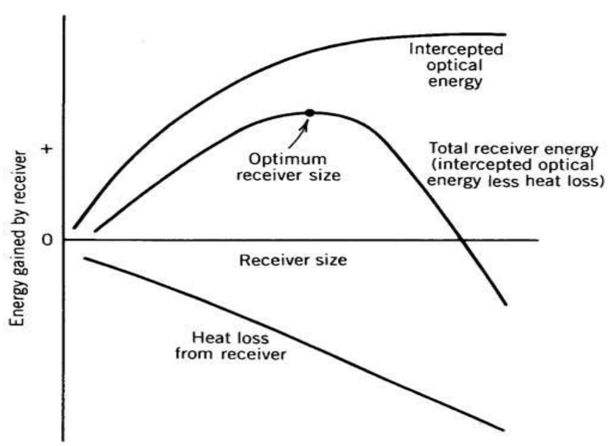


Figure 13: Variation of energy gained by receiver with respect to receiver size

3.1.2 Energy Balance

The detailed energy balance for a photovoltaic cell in a panel can be written in the following manner [8]:

$$P_{elect} = i \cdot v = \Gamma \rho \tau \alpha I_a A_a - A_r \left[h' \left(T_c - T_a \right) + \varepsilon \sigma \left(T_c^4 - T^4_{sky} \right) \right] \qquad (W)$$

Where
T_c- temperature of the cell (K)
A_c - area of the cell surface (m^2)

3.2 Solar Glass

Glass is used in photovoltaic modules as layer of protection against the elements. In thin-film technology, glass also serves as the substrate upon which the photovoltaic material & other chemicals (such as TCO) are deposited. Glass is also the basis for mirrors used to concentrate sunlight, although new technologies avoiding glass are emerging. Most commercial glasses are oxide glasses with similar chemical composition. The main component is Silicon Oxide, SiO_2, which is found in sandstone.

Thin layers of coating may be deposited on one side of the glass for anti-reflection, improved conductivity or self-cleaning. A more durable & efficient antireflective coating for solar panels & a unique, low-cost manufacturing device reduces reflection of light, increasing solar energy input.

The objectives for solar glass are:

1. Ultra-bright glass needed with high solar transmission to ensure high efficiencies in the overall pv module.
2. Mechanical strength to withstand snow & wind.
3. Depending on application, glass may need to be laminated & coated.
4. Self-cleaning characteristics would help to reduce maintenance costs.

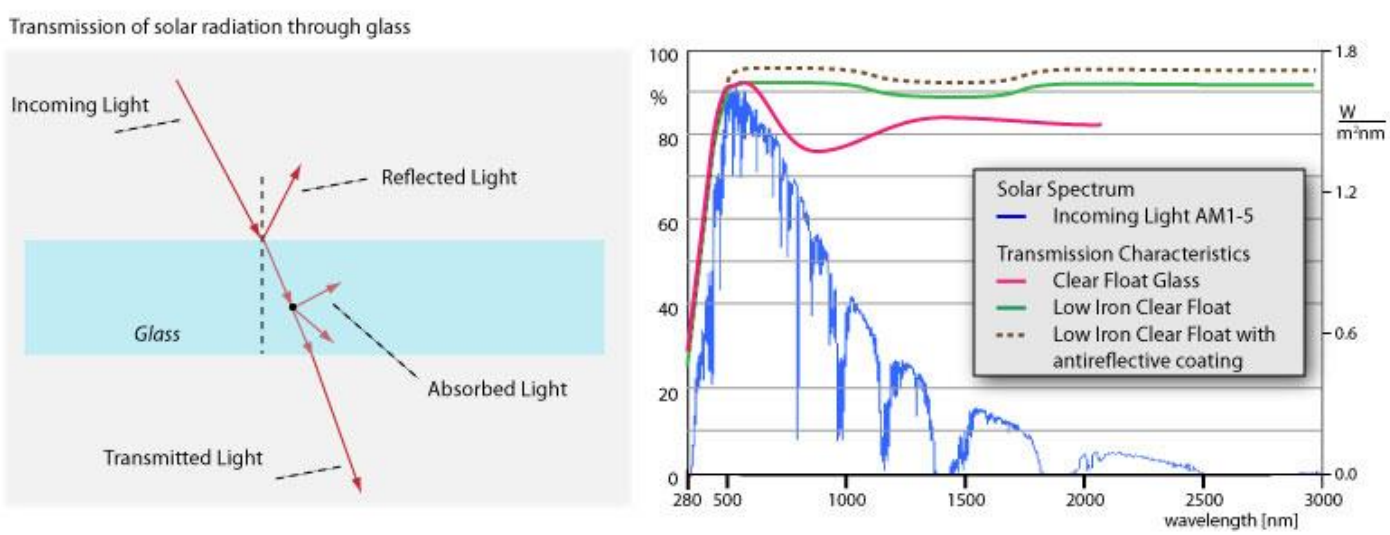


Figure 14: Transmission characteristics of solar radiation through various glass types

4. Energy Storage Systems

Solar modules generate direct current, which is converted into alternating current by an inverter before being fed into the public power grid or being used by domestic power consumers. Battery storage systems can be integrated into both the direct current & alternating current sides of the installation.

If the operator knows that a storage system is required before construction works begin, the system will normally be integrated into the direct current side of the installation. This reduces investment costs, achieves a higher efficiency, & allows module output & storage capacity to be coordinated with each other in the system design. Specific inverters with an integrated charge & discharge control directly charge the (integrated) battery with solar energy. They also convert it into alternating current if the temporarily stored solar energy is to be used by power consumers at a later point. In principal, it is possible to integrate storage systems into the direct current side even when retrofitting existing installations. If the inverter present does not have the necessary configuration, then the battery can also operate with the help of an external charge controller.

In addition to the battery, a specific battery inverter must be installed for the storage system to be integrated into the alternating current circuit. This inverter converts alternating current into direct current, which is required for charging the accumulator. The disadvantage to this solution is that further losses occur when converting back from alternating current into direct current, thus minimizing the system's efficiency. Efficiency may vary from something just over 50% when a trickle of power is being used, to something over 90% when the output is approaching the inverters rated output. An inverter will use some power from your batteries even when you are not drawing any AC power from it. This results in the low efficiencies at low power levels. On the other hand, the plant operator has significantly more choice when choosing the battery capacity, which is advantageous, for example, if module output in an existing installation is given as a set amount.

The controller regulates the amount of generated power that is fed into the public power grid, the amount used to charge the storage system & the amount that is delivered directly to domestic power consumers. Normally, the controller is programmed to maximize the on-site consumption of electricity generated in the photovoltaic installation. Storage systems can contribute significantly to this by temporarily shifting the supply. Alongside load management on the part of the consumer, stabilizing the power grids could also increasingly codetermine the storage systems' management in the future. In this case, storage system operators provide decentralized capacities, which are integrated into an intelligent power grid, & they are then remunerated as part of a capacity-dependent energy market.

Although there are many types of batteries, only two are in common use in solar energy systems; nickel-cadmium (NiCad) batteries & lead-acid batteries. By far the most commonly used type, at least for large, home or industrial photovoltaic systems is the flooded lead-acid battery.

5. Cooling Systems for CPV [9]

5.1 Cooling requirements for concentrator cells

Concentrating sunlight onto photovoltaic cells, thus replacing expensive photovoltaic area with less expensive concentrating mirrors or lenses, is seen as one method to lower the cost of solar electricity. Because of the smaller area, more costly, but higher efficiency PV cells may be used. However, only a small portion of the incoming sunlight onto the cell is converted into electrical energy (a typical efficiency value for concentrator cells is 25%). The remainder of the incoming energy will be converted into thermal energy in the cell & cause the junction temperature to rise unless the heat is efficiently dissipated to the environment. [10] stated that "this fact can be viewed as a consequence of the second principle of thermodynamics imposing a limit on the conversion efficiency of energy coming from a source at a given temperature by a converter/sink having a finite temperature" Major design considerations for cooling of photovoltaic cells are listed below:

Cell temperature: The photovoltaic cell efficiency decreases with increasing temperature [11]. Cells will also exhibit long-term degradation if the temperature exceeds a certain limit [12]. The cell manufacturer will generally specify a given temperature degradation coefficient & a maximum operating temperature for the cell.

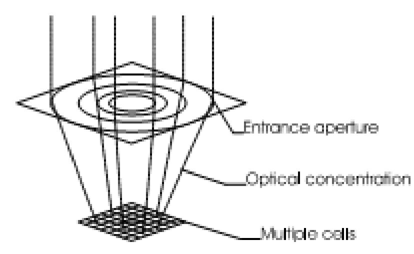


Figure 2.3: Densely packed cells. The area available for cooling is only the rear side of the cell.

Figure 15: Densely Packed Cells

Uniformity of temperature: The cell efficiency is known to decrease due to non-uniform temperatures across the cell [13]. In a photovoltaic module, a number of cells are electrically connected in series, & several of these series connections can be connected in parallel. Series connections increase the output voltage & decrease the current at a given power output, thereby reducing the Ohmic losses. However, when cells are connected in series, the cell that gives the smallest output will limit the current. This is known as the current matching problem.

Reliability & simplicity: To keep operational costs to a minimum, a simple & low maintenance solution should be sought. This also includes the avoidance of toxic materials due to health & environmental issues. Reliability is another important aspect because a failure of the cooling system could lead to the destruction of the PV cells. The cooling system should be designed to deal with "worst case scenarios" such as power outages & electrical faults within modules [13].

Use-ability of thermal energy: Use of the extracted thermal energy from cooling can lead to a significant increase in the total conversion efficiency of the receiver [14]. For this reason, subject to the constraints above, it is desirable to have a cooling system that delivers water at as high a temperature as possible. Further, to avoid heat loss through a secondary heat exchanger, an open-loop cooling circuit is an advantage.

Pumping power: Since the power required of any active component of the cooling circuit is a parasitic loss [14], it should be kept to a minimum.

Material efficiency: Materials use should be kept down for the sake of cost, weight & embodied energy considerations.

5.2 Concentrator geometries

It is sensible to distinguish between concentrators according to their method for concentrating (mirrors or lenses), concentration level or geometry. In this review, only the densely packed arrangement is considered, in accordance with the output power requirement. The issue of shading is not touched upon, as we are illuminating the cell from the top only.

5.2.1 Densely packed modules

In larger point-focus systems, such as dishes or heliostat fields, the receiver generally consists of a multitude of cells, densely packed. The receiver is usually placed slightly away from the focal plane to increase the uniformity of illumination. Secondary concentrators (kaleidoscopes) may be used to further improve flux homogeneity .Densely packed modules present greater problems for cooling than others, because, except for the edge cells, each of the cells only has its rear side available for heat sinking, as seen in **Figure 15**. This implies that, in principle, the entire heat load must be dissipated in a direction normal to the module surface. This generally implies that passive cooling cannot be used in these configurations at their typical concentration levels.

5.2.2 Heat transfer coefficients

The commonly used quantities for comparing the heat transfer characteristics of cooling systems are heat transfer coefficients *h* or thermal resistances *R*. When dealing with cooling systems, *h* is generally defined as

$$h = \frac{\dot{q}}{T_s - T_f}$$

$\dot{Q}$ - Heat input per unit area
T_s - Mean surface temperature
T_f - Mean fluid temperature/ Ambient Temperature

5.2.3 Thermal model

To examine the best cooling system for a given concentrator requires the development of a thermal model that will predict the heating & electrical output of cells. A one-dimensional model is used because this is consistent with a closely packed set of cells where heat flow is primarily directed in the normal direction. .The idealized cell & its mounting are shown schematically in **Figure 16**, where *S* is the incoming solar radiation, & t_g, t_{ad}, t_c, t_{sol} & t_{sub} denote the thicknesses of the various layer

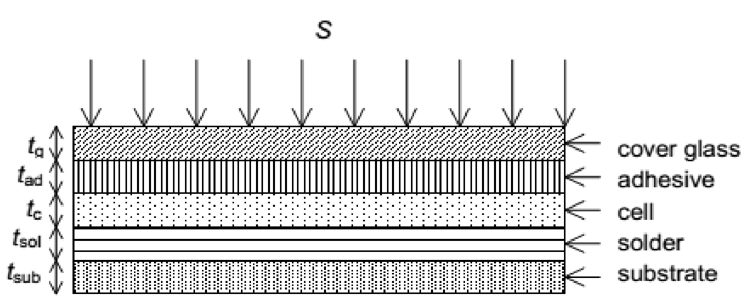


Figure 16: Cell & mounting layers with thicknesses

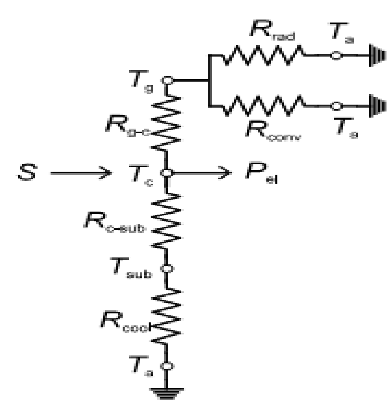


Figure 17: Equivalent Thermal Circuit of cell

This configuration can be represented by the equivalent thermal circuit shown in **Figure 17**, where R denotes a thermal resistance. As this model is one dimensional, all relevant values are per unit area. T_g, T_s & T_a are the temperatures of the top surface of the cover glass, the bottom surface of the substrate & the ambient, respectively. $R_{g\text{-}c}$, $R_{c\text{-}sub}$ & R_{cool} denote the thermal resistances from cover glass to the cell junction, from cell junction to substrate bottom, & from substrate, through cooling system, to the ambient. T_c denotes the temperature of the cell junction, which is assumed to be in the middle of the cell. This temperature determines the efficiency of the cell. The simple model assumes that all incoming radiation, S, is transmitted through the encapsulants & absorbed in the cell junction, where a percentage determined by the cell temperature is converted to electricity, & the remainder is converted to heat. It is also assumed that some heat is lost through radiation & convection from the cover glass surface, & that the remainder of the heat is removed by the cooling system on the substrate surface.

5.2.4 Electrical power output

The cell efficiency varies with both temperature & concentration. There are various models for temperature & concentration dependency found in literature [15]. As shown in Figure 18, most of the models predict quite similar slopes in the lower temperature range. The different values predicted arise from the fact that different cells have different peak efficiencies. Therefore, a simple approach is used in this article by assuming a linear decrease in efficiency with temperature, & no dependency on concentration, as in [15]. This gives the following model:

$$\eta = a(1 - bT_c)$$

,where *a & b* are parameters from [15] ,& h is the cell efficiency at a given cell temperature Tc. The electrical output per unit area is given by

$$P_{el} = \eta S$$

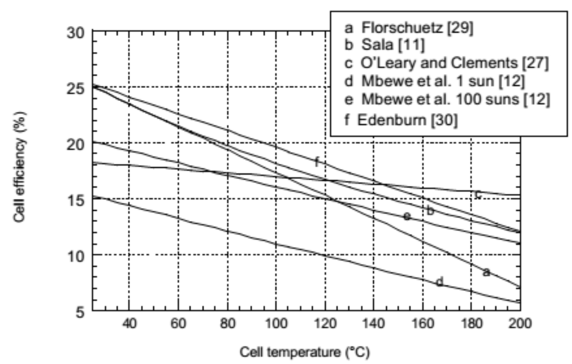


Figure 18: Comparison of different models

5.2.4 Energy balance

If S denotes the incoming solar irradiation, & $\dot{Q}_{cool}$ is the thermal energy removed by the cooling system, the following relation must be satisfied to achieve thermal equilibrium:

$$\dot{q}_{cool} = \frac{T_s - T_a}{R_{cool}}$$

$$S - \dot{q}_{rad} - \dot{q}_{conv} - P_{el} - \dot{q}_{cool} = 0$$

Solving all the above equations gives the value for T_c at any given illumination value. It should be noted that $\dot{Q}_{cool}$ is very large compared to $\dot{Q}_{rad}$ & $\dot{Q}_{conv}$ in most cases of concentration, & so the significance of the model & parameters chosen for these aspects of the actual cells becomes less important.

Figure 19 shows the electrical power output that would result from various illumination levels using this model & the values given in the appendix. The different curves correspond to different values of R_{cool}.

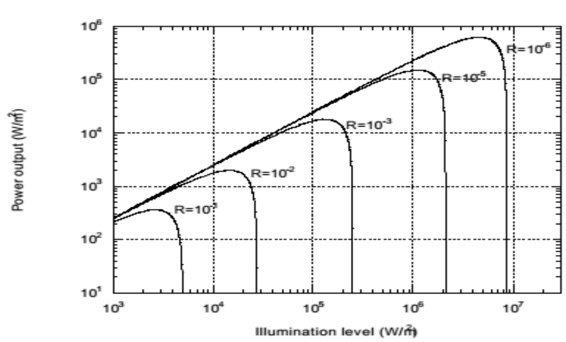


Figure 19: Electrical output per are versus illumination, for various thermal resistances

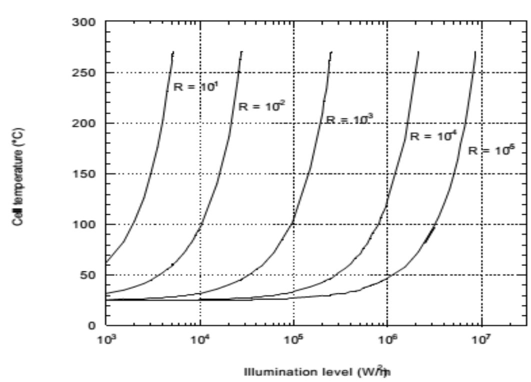


Figure 20: Cell Temperatures versus illumination levels for various resistances

There is clearly a definitive maximum power output for all curves. However, these curves must be seen together with Figure 20, which shows the cell temperature rise with increasing concentration. It shows that the maximum power points correspond with very high cell temperatures. The actual power output will be limited by the bounds on the cell operating temperature.

This implies temperature is always the limiting factor for concentrator cells. A low thermal resistance in the cooling system is crucial, & becomes even more important with increasing concentration level.

5.3 Existing Cooling Options for Densely Packed Cells

The existing cooling options for a CPV plant are reviewed here.

5.3.1 Passive Cooling systems

Passive cooling does not require input of mechanical or electrical power as it acts through the exploitation of natural laws, whereas active cooling requires external energy to cool the solar cells. These are not really effective for high loads like a CPV plant, & hence no reports of passive cooling under high concentration have been found.

5.3.2 Active cooling systems

Existing options available in active cooling are plentiful, & have been summarized here, along with the **Table 1**.

A **monolithic silicon concentrator module with a fully integrated water cooled cold plate** as described by Verlinden *et al.* [16] can be used. The module consists of 10 cells & is supposed to act as a "tile" in a larger array. With an optimized coolant flow rate of 0.0127 kg s-1 on an area of 3600 mm2, the total thermal resistance from cell to water (including all layers in between) is measured to be 2.3 x 10-4 K m2 W-1.

A water cooling circuit for densely packed solar cells under high concentration, patented by John Lasich [17] is also considered. Its heat extraction rate can touch 500 kW m-2 from the photovoltaic cells & to keep the cell temperature at around 40 °C for normal operating conditions. The concept is based on water flow through small, parallel channels in thermal contact with the cells. The cooling circuit also forms part of the supporting structure of the photovoltaic receiver. Solar Systems Pty. Ltd. has reported some significant results, working with a concentration of about 340 suns, & using the above mentioned patent [17]. This demonstrates the benefits of active cooling if one can find uses for the waste heat.

Figure 21: Manifold Micro Channels

Vincenzi *et al.* [18] at the University of Ferrara have suggested using **micro machined silicon heat sinks** .By using a silicon wafer with micro channels circulating water directly underneath the cells, the cooling function is integrated in the cell manufacturing process.. The reported thermal resistance is 4 x 10-5 K m2 W-1.

5.4 Other Cooling Options Considered

Cooling problems are not exclusive to photovoltaic. Recently, extensive research has been performed on the issue of cooling of electronic devices & for the nuclear energy & gas turbine industries, where strict temperature limitations due to material property exist. The following section presents some studies that might be relevant for PV cooling, especially for the most demanding case of densely packed cells under high concentration.

5.4.1 Passive systems

There is a wide variety of passive cooling options available, such as fins, two phase flows & natural circulation methods. However, it should be noted that passive cooling is just a means of transporting heat from where it is generated (in the PV cells) to where it can be dissipated (the ambient) Hence, if the area available for heat spreading is small & shading is an issue, no complex solutions will help avoid the use of active cooling. One way of passively enhancing heat conduction is the use of heat pipes. It seems that the use of heat pipes is probably not feasible for very high concentrations because heat pipe performance is limited by the working fluid saturation temperature & the point at which all liquid evaporates (burnout). For water, a heat flux of 250-1000 kW m_{-2} can be accommodated but only at temperatures above 140 °C. Anderson et al showed that heat pipes can be successfully applied for CPV passive cooling, from 200-approx 1000 suns.

5.4.2 Forced air cooling

The thermal properties of air make it far less efficient as a coolant medium than water. Thus, more parasitic power (to power fans) will be needed to achieve the same cooling performance. Hence, air cooling is not considered as a viable option.

5.4.3 Liquid single-phase forced convection cooling: Micro-channel heat sinks

The micro channel heat sink is a concept well suited for many electronic applications because of its ability to remove a large amount of heat from a small area. Chronologically speaking, [19] were the pioneers who first suggested the micro channel heat sink. Later studies have showed two major drawbacks to the micro channel heat sink. These are a large temperature gradient in the stream-wise direction, & a significant pressure drop that leads to high pumping power requirements. An experimental study of by [20] concludes that heat transfer performance depends on the Re number. Developing laminar flow is found to perform better than turbulent flow due to the larger pressure drop associated with turbulent flow. Alternating flow directions is one way of reducing the stream wise temperature gradient in the micro channel heat sink. A two-layered micro channel heat sink with counter flow, called the manifold micro channel heat sink, is also designed to lower the temperature gradient & pressure drop ,modeled & optimized by Ryu et al. [21] (Figure 21). Muller et al. [22] investigated the micro channels performances in a 1500 CPV. They showed that the system remained fully functional up to 4930 suns & registered a decrease of 1% in the photovoltaic efficiency for every 100 suns concentration increase.

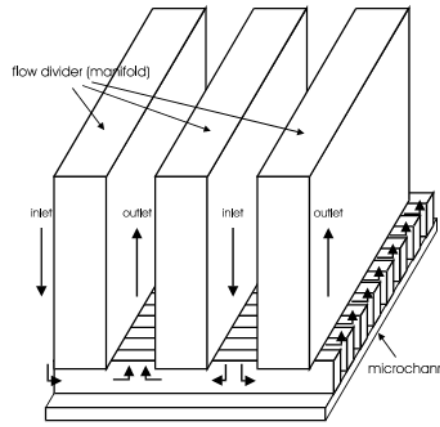


Figure 2.14: Manifold microchannels as suggested by Ryu [48].

5.4.4 Impinging jets

Very low thermal resistances (generally 10^{-5} - 10^{-6} K m^2 W^{-1}) can be achieved through the use of impinging liquid jets. When high velocity liquid is forced through a narrow orifice (axisymmetric jet) or slot (planar jet), into the surrounding air, a free surface forms. The impinging jets are capable of extracting a large amount of heat because of the very thin thermal boundary layer However, the heat transfer coefficient decreases rapidly with distance from the jet. To cool larger surfaces, it is therefore desirable to use an array of jets. A problem arises when water from one jet meets the water from the neighbouring jet. Disturbances arise which are very hard to model but have been shown to decrease the overall heat transfer drastically. If measures are taken to deal with this "spent flow" (through drainage openings), impinging jets have been predicted to be a superior alternative to micro-channel cooling [23] for target dimensions larger than the order of 0.07 m x 0.07 m.

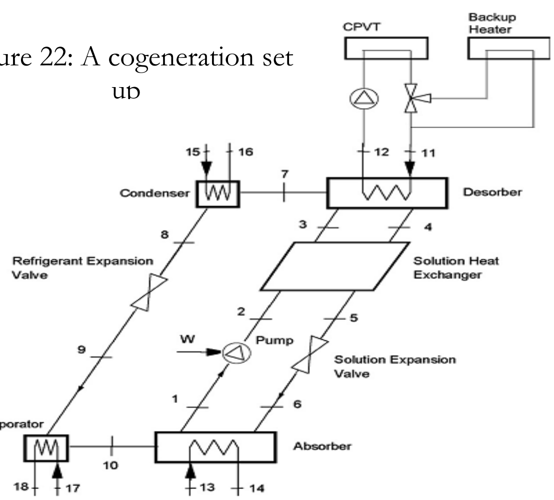
5.4.5 Two-phase forced convection cooling

By allowing the coolant fluid to boil, the latent heat capacity of the fluid is used to allow for a significantly larger heat flux & an almost isothermal surface. When the bulk liquid is below saturation temperature, but the heat flux is high enough that liquid at the surface can reach saturation temperature, sub cooled boiling occurs. Under sub cooling, bubbles will collapse as they are released from the wall & travel into the surrounding liquid. Sub cooled forced convection boiling in small channels is among the most efficient heat transfer methods available. This is often used in applications with extremely large heat fluxes such as fusion reactors first walls & plasma limiters. The most important parameter in this case is the critical heat flux (CHF). A number of studies are devoted to the detailed analysis of bubble formation, onset of different boiling regimes, & CHF for sub cooled boiling. Ghia assiaan [24] presents a very good literature review on sub cooled boiling. Hestroni [25] describes a micro channel heat sink that keeps the electronic device of a temperature of 50-60 °C, a temperature highly suited for photovoltaic purposes.

5.4.6 Cogeneration Cooling System

More than half of the solar radiation, collected with considerable effort & investment, is converted to thermal energy & then rejected to the environment. A well-known way to achieve a better overall efficiency is cogeneration: capturing the waste heat as well & using it as an additional energy product. This can be achieved with photovoltaic/thermal (PV/T) collectors that contain a heat exchanger behind the PV cells to collect the heat rejected from the cells. Concentrating photovoltaic (CPV) systems can operate at higher temperatures than flat plate collectors. Collecting the rejected heat from a CPV system leads to a CPV/thermal (CPVT) system, providing both electricity & heat at medium rather than low temperatures. Poly generation with CPV collectors may offer a significant advantage not only in overall efficiency but also in economic feasibility. A study by Gur Mittelman et al [26] shows that using the waste heat of CPV systems for cooling can lead to higher overall efficiency than trying to generate additional

Figure 22: A cogeneration set up



electricity. In systems having coupled concentrating thermal collectors, the thermal energy is coming from dedicated solar collectors, & therefore, the cost of the thermal energy is high. In the CPVT system, the thermal energy is a low cost byproduct and, therefore, could lead to a much more competitive solar cooling solution.

5.4.7 Recent developments

In particular, during the last years, several investigations were reported on liquid immersed solar cells .This is an active cooling solution: solar cells are immersed in a circulating dielectric liquid. According to [27], the convective heat transfer coefficient could be higher than 3000 W/m^2K for concentrations higher than 200 suns

5.5 Comparison of Cooling Options

Depending on the application, one may want to compare parameters such as pumping power, weight, materials use, ease of manufacturing & maintenance, maximum heat removal, temperature uniformity, shading etc. In order to enable a comparison of pumping powers, which is an important parameter when it comes to power generating systems, the pumping power has been calculated as *P* = *m* & ´ D*p* in cases where only mass flow rate & pressure drops are given.

Extra care should be taken when comparing different systems such as jets versus passive cooling or two-phase versus single-phase flows. Thermal resistances, flow rates & pumping powers are all given per unit area below for easier comparison. All precautions taken, Figure 23, still provide a comparison between options. The letters in the graphs mark where they are taken from in Table 1. What seems to do best in all comparisons is the category **"improved micro channels"** which includes various forms of alternating flows. This method provides the clearly lowest thermal resistance along with low power requirements. In all micro channel studies, laminar flow seems to outperform turbulent. Etching micro channels into the silicon substrate as a part of the manufacturing process of photovoltaic modules may prove a very good option for photovoltaic cell cooling.

Table 1

Work	Configuration	Heated area m^2	Pump power Wm^{-2}	Pressure drop kPa	Mass Flow Rate $kg\ m^{-2}s^{-1}$	Thermal Resistance $K\ m^2\ W^{-1}$	Code
Sala	Air cooling, plane surface,					2.0×10^{0}	a
	Water cooling, plane surface: laminar mode					2.6×10^{-3}	b
	Water cooling, plane surface :turbulent mode					2.7×10^{-4}	c
Florshuetz	No extruded surface, calm air					3.3×10^{-2} *	d
	Finned strip, calm air					1.1×10^{-2} *	e
	Forced air through multiple passages	1.52×10^{-1}			3.95×10^{-1}	2.6×10^{-3}	f
	Water cooling	1.52×10^{-1}			3.03×10^{0}	4.3×10^{-4}	g
	Impinging jet, nozzle-plate distance = 0.16 cm	2.58×10^{-3}			7.75×10^{0}	5.1×10^{-5}	h
Feldman et al.	Finned heat pipe, calm air	6.10×10^{-1}				9.8×10^{-3} *	i
Luque et al.	Finned strip, calm air					2.2×10^{-3}	j
Chenlo & Cid	Water flow through rectangular steel pipe					8.7×10^{-4}	k
Coventry	Water flow through internally extruded channel	1.15×10^{-1}			3.48×10^{-1} - 3.74×10^{1} - 1.21×10^{2}	1.3 x 10-3	l
Verlinden	Water cooled cold plate	3.60×10^{-3}			3.51×10^{0}	2.3 x 10-4	m
Vincenzi et al	Microchannels	3.40×10^{-5}	8.82×10^{2}		1.82×10^{1}	4.0 x 10-5	n
Kraus & BarCohen	Parallel fin heat sink, calm air	1.68×10^{-2}				4.7 x 10-3 *	o
Harms et al	Microchannels	3.93×10^{-3}	6.32×10^{3}	1.69×10^{2}	3.74 x 10	1.3 x 10-4	r
Owhaib & Palm	Circular microchannels, laminar					4.0 x 10-4	s

	flow						
	Circular microchannels, turbulent flow					1.0 x 10-4	t
Missaggia and Walpole	Microchannels, single layer counter flow	2.30×10^{-4}	3.00×10^{4}	2.48×10^{2}	1.21×10^{2}	1.1 x 10-5	u
Chong et al.	Microchannels, single layer counter flow, laminar	1.00×10^{-4}	7.70×10^{0} +	1.18×10^{2}	6.53×10^{-2}	6.9×10^{-6}	v
	Microchannels, single layer counter flow, turbulent		5.04×10^{1} +	1.12×10^{2}	4.50×10^{-1}	4.8×10^{-6}	w
	Microchannels, double layer counter flow, laminar		5.25×10^{1} +	5.64×10^{2}	9.31×10^{-2}	6.6×10^{-6}	x
	Microchannels, double layer counter flow, turbulent		1.48×10^{2} +	5.64×10^{2}	2.62×10^{-1}	5.8×10^{-6}	y
Ryu et al	Manifold microchannels	1.00×10^{-4}	1.50×10^{4}		1.40×10^{-1}	3.1×10^{-6}	z
Rohsenow et al	Impinging jets					1.0×10^{-6}	A
Hetsroni et al	Two-phase microchannels	1.00×10^{-4}	8.70×10^{2}	3.00×10^{0}	2.90×10^{2}	9.5×10^{-5}	B

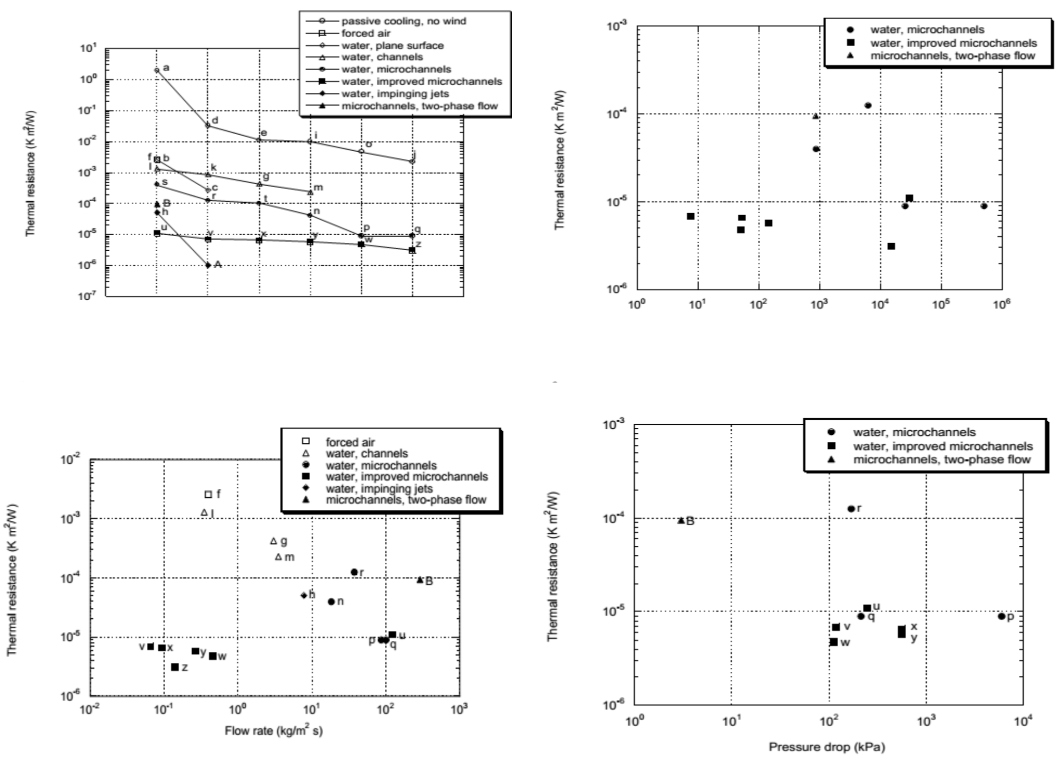


Figure 23: Comparison of cooling options

6. Solar trackers [30]

A **solar tracker** is a device that orients a payload toward the sun. Payloads can be photovoltaic panels, reflectors, lenses or other optical devices.

In concentrated photovoltaic (CPV) & concentrated solar thermal (CSP) applications, trackers are used to enable the optical components in the CPV & CSP systems. The optics in concentrated solar applications accepts the direct component of sunlight light & therefore must be oriented appropriately to collect energy. Tracking systems are found in all concentrator applications because such systems do not produce energy unless pointed at the sun.

Sunlight has two components, the "direct beam" that carries about 90% of the solar energy, & the "diffuse sunlight" that carries the remainder. As the majority of the energy is in the direct beam, maximizing collection requires the sun to be visible to the panels as long as possible. The energy contributed by the direct beam drops off with the cosine of the angle between the incoming light & the panel. In addition, the reflectance (averaged across all polarizations) is approximately constant for angles of incidence up to around 50°, beyond which reflectance degrades rapidly. For example trackers that have accuracies of ± 5° can deliver greater than 99.6% of the energy delivered by the direct beam plus 100% of the diffuse light.

The sun travels through 360 degrees east to west per day, but from the perspective of any fixed location the visible portion is 180 degrees during an average 1/2 day period. Local horizon effects reduce this making the effective motion about 150 degrees. A solar panel in a fixed orientation between the dawn & sunset extremes will see a motion of 75 degrees to either side, & thus, will lose 75% of the energy in the morning & evening. Rotating the panels to the east & west can help recapture those losses. A tracker rotating in the east-west direction is known as a single-axis tracker.

The sun also moves through 46 degrees north & south during a year. The same set of panels set at the midpoint between the two local extremes will thus see the sun move 23 degrees on either side, causing losses of 8.3% A tracker that accounts for both the daily & seasonal motions is known as a dual-axis tracker. Generally, the losses due to seasonal angle changes are complicated by changes in the length of the day, increasing collection in the summer in northern or southern latitudes. This biases collection toward the summer, so if the panels are tilted closer to the average, the total yearly losses are reduced

There is considerable argument whether the small difference in yearly collection between single & dual-axis trackers makes the added complexity of a two-axis tracker worthwhile. Actual production statistics suggested the difference was about 4% in total, which was far less than the added costs of the dual-axis systems. This compares unfavorably with the 24-32% improvement between a fixed-array & single-axis tracker. This is also reflected in our decision.

6.1 Types of solar collector for Concentrating Photo Voltaic Units

Different types of solar collector & their location (latitude) require different types of tracking mechanism. Tracking systems may be configured as: **Fixed collector / moving mirror** - i.e. *Heliostat* & **Moving collector**

Trackers: Even though a fixed flat-panel can be set to collect a high proportion of available noon-time energy, significant power is also available in the early mornings & late afternoons when the misalignment with a fixed panel becomes excessive to collect a reasonable proportion of the available energy. Thus the primary benefit of a tracking system is to collect solar energy for the longest period of the day, & with the most accurate alignment as the Sun's position shifts with the seasons.
The greater the level of concentration employed, the more important accurate tracking becomes, because the proportion of energy derived from direct radiation is higher, & the region where that concentrated energy is focused becomes smaller.
Fixed collector / moving mirror: Many collectors cannot be moved, for example high-temperature collectors where the energy is recovered as hot liquid or gas (e.g. steam). In such cases it is necessary to employ a moving mirror so that, regardless of where the Sun is positioned in the sky, the Sun's rays are redirected onto the collector. Due to the complicated motion of the Sun across the sky, & the level of precision required to correctly aim the Sun's rays onto the target; this generally employs a dual axis tracking system.
Moving collector: Trackers can be grouped into classes by the number & orientation of the tracker's axes. Compared to a fixed mount, a single axis tracker increases annual output by approximately 30% & a dual axis tracker an additional 6%. [31]

Photovoltaic trackers can be classified into two types: standard photovoltaic (PV) trackers & concentrated photovoltaic (CPV) trackers. Each of these tracker types can be further categorized by the number & orientation of their axes, their actuation architecture & drive type, their intended applications, their vertical supports & foundation.

6.2 Concentrated photovoltaic (CPV) trackers

The optics in CPV modules accept the direct component of the incoming light & therefore must be oriented appropriately to maximize the energy collected. The tracking functionality in CPV modules is used to orient the optics such that the incoming light is focused to the collector. CPV modules that concentrate in one dimension must be tracked normal to the sun in one axis. CPV modules that concentrate in two dimensions must be tracked normal to the sun in two axes.

Accuracy requirements: The physics behind CPV optics requires that tracking accuracy increase as the systems concentration ratio increases. However, for a given concentration, non-imaging optics provides the widest possible acceptance angles, which may be used to reduce tracking accuracy. In typical high concentration systems tracking accuracy must be in the ± 0.1° range to deliver approximately 90% of the rated power output. As a result, high accuracy tracking systems are typical.
Technologies supported: Concentrated photovoltaic trackers are used with refractive & reflective based concentrator systems. There are a range of emerging photovoltaic cell technologies used in these systems. These range from crystalline silicon based photovoltaic receivers to germanium based triple junction receivers.

6.2.1 Single axis trackers

Single axis trackers have one degree of freedom - an axis of rotation. The axis of rotation of single axis trackers is typically aligned along a true North meridian. It is possible to align them in any cardinal direction with advanced tracking algorithms. There are several common implementations of single axis trackers. Some of these are:

Horizontal single axis tracker (HSAT): The axis of rotation for horizontal single axis tracker is horizontal with respect to the ground. Field layouts with horizontal single axis trackers are very flexible. Appropriate spacing can maximize the ratio of energy production to cost. Backtracking is one means of computing the disposition of panels. Horizontal trackers typically have the face of the module oriented parallel to the axis of rotation. As a module tracks, it sweeps a cylinder that is rotationally symmetric around the axis of rotation. Panels are mounted upon the tube, which rotates on its axis to track the motion of the sun through the day.

Horizontal single axis tracker with tilted modules (HTSAT): In HSAT, the modules are mounted flat at 0 degrees, while in HTSAT, the modules are installed at a certain tilt. It works on same principle as HSAT. These trackers are usually suitable in high latitude locations but do not take as much land space as consumed by Vertical single axis tracker (VSAT). Therefore it brings the advantages of VSAT in a horizontal tracker & minimizes the overall cost of solar project.

Vertical single axis tracker (VSAT): The axis of rotation for vertical single axis trackers is vertical with respect to the ground. These trackers rotate from East to West over the course of the day. Such trackers are more effective at high latitudes than are horizontal axis trackers. Vertical single axis trackers typically have the face of the module oriented at an angle with respect to the axis of rotation. As a module tracks, it sweeps a cone that is rotationally symmetric around the axis of rotation.

Tilted single axis tracker (TSAT): All trackers with axes of rotation between horizontal & vertical are considered tilted single axis trackers. Tracker tilt angles are often limited to reduce the wind profile & decrease the elevated end height.

Polar aligned single axis trackers (PASAT): This method is scientifically well known as the standard method of mounting a telescope support structure. The tilted single axis is aligned to the polar star. It is therefore called a polar aligned single axis tracker (PASAT). The tilt angle is equal to the latitude. This aligns the tracker axis of rotation with the earth's axis of rotation.

6.2.2 Dual axis trackers

Dual axis trackers have two degrees of freedom that act as axes of rotation. These axes are typically normal to one another. The axis that is fixed with respect to the ground can be considered a primary axis. The axis that is referenced to the primary axis can be considered a secondary axis. There are several common implementations of dual axis trackers. They are classified by the orientation of their primary axes with respect to the ground.

Dual axis trackers allow for optimum solar energy levels due to their ability to follow the sun vertically & horizontally. No matter where the sun is in the sky, dual axis trackers are able to angle themselves to be in direct contact with the sun.

Tip–tilt dual axis tracker (TTDAT): A tip–tilt dual axis tracker is so-named because the panel array is mounted on the top of a pole. Normally the east-west movement is driven by rotating the array around the top of the pole. On top of the rotating bearing is a T- or H-shaped mechanism that provides vertical rotation of the panels & provides the main mounting points for the array. The posts at either end of the primary axis of rotation of a tip–tilt dual axis tracker can be shared between trackers. Other such TTDAT trackers have a horizontal primary axis & a dependent orthogonal axis. The vertical azimuthal axis is fixed. This allows for great flexibility of the payload connection to the ground mounted equipment because there is no twisting of the cabling around the pole.
Normally the trackers would have to be positioned at fairly low density in order to avoid one tracker casting a shadow on others when the sun is low in the sky. Tip-tilt trackers can make up for this by tilting closer to horizontal to minimize up-sun shading. The axes of rotation of many tip–tilt dual axis trackers are typically aligned either along a true north meridian or an east west line of latitude. Given the unique capabilities of the Tip-Tilt configuration & the appropriated controller totally automatic tracking is possible for use on portable platforms. The orientation of the tracker is of no importance & can be placed as needed.[32]

Azimuth-altitude dual axis tracker (AADAT): An azimuth–altitude dual axis tracker has its primary axis (the azimuth axis) vertical to the ground. The secondary axis (often called elevation axis) is then typically normal to the primary axis. They are similar to tip-tilt systems in operation, but they differ in the way the array is rotated for daily tracking. Instead of rotating the array around the top of the pole, AADAT systems can use a large ring mounted on the ground with the array mounted on a series of rollers. The main advantage of this arrangement is the weight of the array is distributed over a portion of the ring, as opposed to the single loading point of the pole in the TTDAT. This allows AADAT to support much larger arrays. Unlike the TTDAT, however, the AADAT system cannot be placed closer together than the diameter of the ring, which may reduce the system density, especially considering inter-tracker shading.

6.3 Control Systems [33]

Closed Loop: For the closed-loop sun-tracking approach, various active sensor devices, such as CCD sensor or photodiode sensor are utilized to sense the position of the solar image on the receiver. A feedback signal is then generated to the controller if the solar image moves away from the receiver. Sun-tracking systems that employ active sensor devices are known as closed-loop sun trackers. Although the performance of the closed-loop tracking system is easily affected by weather conditions & environmental factors, it has allowed savings in terms of cost, time & effort by omitting more precise sun tracker alignment work. The closed-loop tracking approach has been traditionally used in the active sun-tracking scheme over the past 20 years. However, this method is rather expensive & complicated because it requires four CCD cameras & four radiometers to be placed on the target. Then the solar images captured by CCD cameras must be analyzed by a computer to generate the control correction feedback for correcting tracking errors. However, the criterion is that this tracking system requires full clear sky days to operate, as the incident sunlight has to be above a certain threshold to ensure that the minimum required resolution is met.

Open Loop: Although closed-loop sun-tracking system can produce a much better tracking accuracy, this type of system will lose its feedback signal & subsequently its track to the sun position when the sensor is shaded or when the sun is blocked by clouds. As an alternative method to overcome the limitation of closed-loop sun trackers, open-loop sun trackers were introduced by using open-loop sensors that do not require any solar image as feedback. The open-loop sensor such as encoder will ensure that the solar collector is positioned at pre-calculated angles, which are obtained from a special formula or algorithm. The sun's azimuth & elevation angles can be determined by the sun position formula or algorithm at the given date, time & geographical information. This tracking approach has the ability to achieve tracking error within ±0.2° when the mechanical structure is precisely made as well as the alignment work is perfectly done. Generally, these algorithms are integrated into the microprocessor based or computer based controller.

Hybrid Tracker: Both sun-tracking approaches mentioned above have both strengths & drawbacks, so some hybrid sun-tracking systems have been developed to include both the open & closed-loop sensors for the sake of high tracking accuracy.

6.4 Drive types

Active tracker: Active trackers use motors & gear trains to direct the tracker as commanded by a controller responding to the solar direction. In order to control & manage the movement of these massive structures special slewing drives are designed & rigorously tested. The technologies used to direct the tracker are constantly evolving. Counter rotating slewing drives sandwiching a fixed angle support can be applied to create a "multi-axis" tracking method which eliminates rotation relative to longitudinal alignment.

Active two-axis trackers are also used to orient heliostats - movable mirrors that reflect sunlight toward the absorber of a central power station. Light-sensing trackers typically have two or more photo sensors, such as photodiodes, configured differentially so that they output a null when receiving the same light flux. Mechanically, they should be omnidirectional (i.e. flat) & are aimed 90 degrees apart. This will cause the steepest part of their cosine transfer functions to balance at the steepest part, which translates into maximum sensitivity. Since the motors consume energy, one wants to use them only as necessary. So instead of a continuous motion, the heliostat is moved in discrete steps. Also, if the light is below some threshold there would not be enough power generated to warrant reorientation. This is also true when there is not enough difference in light level from one direction to another, such as when clouds are passing overhead.

Passive tracker : The most common passive trackers use a low boiling point compressed gas fluid that is driven to one side or the other (by solar heat creating gas pressure) to cause the tracker to move in response to an imbalance. As this is a non-precision orientation it is unsuitable for certain types of concentrating photovoltaic collectors but works fine for common PV panel types.

Chronological tracker: A chronological tracker counteracts the Earth's rotation by turning at the same speed as the Earth relative to the Sun. around an axis parallel to the Earth's, but in the direction opposite to the Earth's rotation. To do this, a simple rotation mechanism, turning at a constant speed of one revolution per day or 15 degrees per hour, is adequate for many purposes, such as keeping a photovoltaic panel pointing within a few degrees of the Sun, but for accurate tracking, such as may be needed to keep a telescope aimed at the Sun, the *equation of time* must be taken into account, so the tracker moves according to *apparent solar time*, often called "sundial time". The tracker contains a mechanism that takes account of the equation of time & makes the tracker move according to sundial time. So the tracker's movement is governed by sundial time, which in turn is governed by the movement of the Sun in the sky. This makes the tracker accurately keep pace with the Sun. In addition to following the daily East-West apparent motion of the Sun in the sky, the tracker must follow the Sun's seasonal apparent movements in the North-South direction. A simple mechanism that produces a sinusoidal movement can be used in a tracker that will work well enough for many purposes. However, accurate tracking must take into account the fact that the peaks & troughs of the sun's movement graph are more sharply "pointed" than those of a sine wave. A mechanism that contains a cam, rotating once a year & shaped according to the correct waveform, provides one way of achieving accurate tracking.

6.5 Tracker type selection

The selection of tracker type is dependent on many factors including installation size, electric rates, government incentives, land constraints, latitude, & local weather. Horizontal single axis trackers are typically used for large distributed generation projects & utility scale projects. The combination of energy improvement & lower product cost & lower installation complexity results in compelling economics in large deployments. The robustness & the simplicity of the mechanism also result in high reliability.

A vertical axis tracker pivots only about a vertical axle, with the panels either vertical, at a fixed, adjustable, or tracked elevation angle. Such trackers with fixed or (seasonally) adjustable angles are suitable for high latitudes, where the apparent solar path is not especially high, but which leads to long days in summer – which is not relevant in this case. Dual axis trackers are typically used in smaller residential installations & locations with very high government feed in tariffs.

Table 2

S No	Work	Configuration	Control System	Cost (Comparative)	Area per tracker module (in m^2)	Energy consumption per day	Precision (Worst) (in ^{o})
1	Koel Keong Chong et al[33]	Dual Axis	Hybrid (More Open)	Low	-	1.26 kWh/day	0.12
2	Prinsloo et al[34]	Dual Axis	Closed	-		1.82 kWh/day	1
3	Seung Jin Oh et al[35]	Dual Axis	Closed	Low	0.725		0.7
4	Semprius *	Dual Axis	Hybrid	High	-	-	-
5	Sener*	Dual Axis	Closed	High	85		0.1
6	Exotrack*	Dual Axis	Hybrid	Medium	28	0.109 kWh/day*	0.1
7	MorganSolar*	Dual Axis	Closed	-	-	0.09 kWh/day*	1
8	Titan *	Dual Axis	Hybrid	-	55	1.08 kWh/day	

* - Brochures consulted

We choose the model suggested by [33] for further considerations.

7. Comparison between CPV & PV systems

Concentrated Photovoltaic (CPV) technology is gaining popularity in recent decades & is expected to be the major part of solar PV technology by 2017. In this section, we compare the concentrated PV systems with the conventional PV systems & try to understand the advantages of CPV over conventional PV which will explain the increasing demand for these systems.

- **Start-up cost & ease of installation:** The conventional PV plants have an advantage over CPV in both the start-up cost & ease of installation of the plants. Due to additional systems such as cooling, tracking & concentrators, CPV systems are often bulkier & costlier than the conventional PV systems.
- **Space requirement:** As the concentrated PV systems tend to have much higher efficiencies than the conventional PV systems, the space needed for CPV plant is much lower than that for a conventional PV plant of the same capacity. This is owing to the fact that the CPV systems can use highly efficient multi-junction solar cells due to less solar cell area required. Multi-junction solar cells cannot be used in conventional PV systems due to their high manufacturing cost.

- **Maintenance:** PV systems tend to have low maintenance due to absence of supplementary systems such as cooling & tracking system. The concentrators in CPV tend to have a lot more weight than solar panels itself, & this requires high power motors for tracking which in turn increases the maintenance cost.
- **Efficiency:** CPV systems have more than twice the efficiency of the conventional solar panels due to highly efficient solar modules which have even higher efficiencies as the concentration ratio goes up. Also, co-generation plants can be used in tandem with CPV plants such as CSP (Concentrated Solar Power) systems which further increases the overall efficiency.
- **Life & Levelized Cost of Electricity (LCOE):** Life of the solar cells used in both the systems is approximately same (around 20 years), but the LCOE shows large differences due to high setup & maintenance costs in CPV systems. LCOE of CPV systems is expected to come down by this decade & even lower than conventional power plants.
- **Overall performance:** Due to the concentrator design, CPV systems are unable to capture the diffused part of the solar insolation. To capture the direct solar radiation effectively, often a tracking system is required. However, CPV systems capture more amount of solar radiation than PV systems due to their higher performance in late afternoon & early morning.

All these factors are to be taken into account for selection of a photovoltaic system. For places where space constraint is not a major factor, conventional solar panels are generally used. But applications requiring high space efficiency & high performance, CPV systems are preferred over conventional PV systems, such as space crafts & satellites.

8. Implementation of a CPV system in IITM

CPV systems have gained widespread popularity all over the globe & large scale power plants are being setup across the globe using CPV systems especially in the remote areas with high solar insolation. In this section, we discuss the advantages & drawbacks of implementing a CPV system in IIT Madras, & draw conclusions about feasibility of such a power plant.

8.1 Feasibility study

Feasibility of implementing a 10kW CPV power plant in IITM is discussed in this subsection. First, a basic calculation of the power need & size of the power plant is made & is followed with some advantages & key issues of implementing CPV system in the campus are discussed.

8.1.1 Load calculations

Let us consider a 10kW power plant on the rooftop of one of the hostels in IIT Madras. An estimate of the amount of load throughout the day in a hostel with approximately 400 residents must be made to comment on the effectiveness of such a rooftop power plant.

We consider power consumption of an average room & multiply it by the number of residents in the hostel to get an approximate estimate of the overall consumption. The major sources of power consumption for a student in IIT madras are tube-light, ceiling fan & laptop. The average power ratings of these were obtained from the internet[36]. The maximum power usage of these appliances is about 150W for laptop, 50W for ceiling fan & 40W for tube light. The load vs time curve can now be approximately plotted for a week day using these values as following (Figure 24):

The approximations used while calculating this graph were:

1. For all the calculations, the maximum load is taken for an appliance when it is in use & zero when it is expected to be not in use.
2. The load during class hours 8AM-2PM is assumed to be a lowly, say 20W (To take into account the common hostel power consumptions & few residents not having classes)
3. During 2PM-6PM, ceiling fan & computer are switched on. Additionally, lights are switched on after 6PM.
4. Student sleeps at 11 PM & only ceiling fan is on from 11PM to 8AM.
5. Seasonal variations & weekend loads are not taken into consideration.

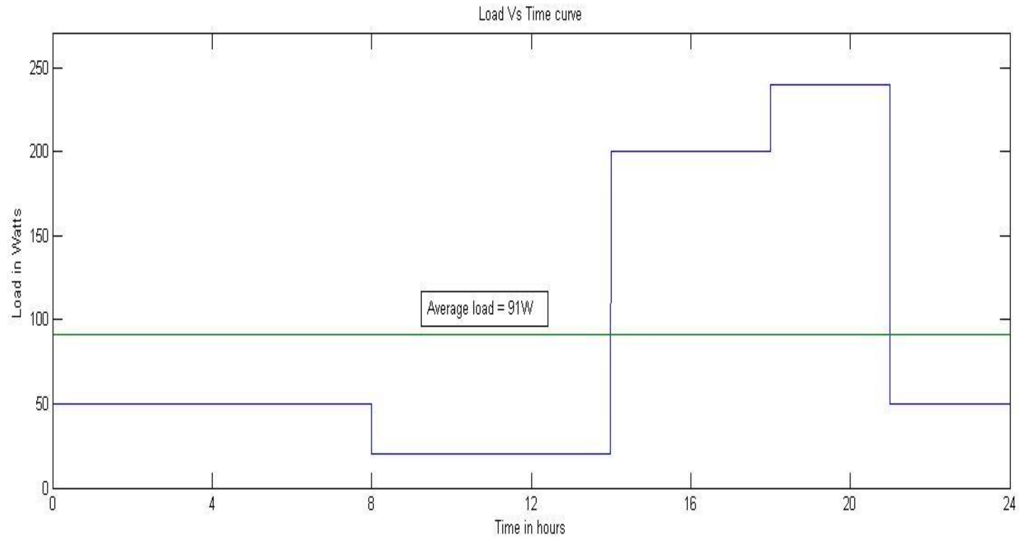


Figure 24: Load distribution curve

This gives an approximate estimate of the power consumption for a week day of a typical resident. The average load due to one such room is then around 91 W. We multiply this with a factor of 1.4 to take into consideration the seasonal variations & significantly higher loads on weekends. Hence we get an approximately average power of 130W.

We calculate the power consumption based on this number as follows:

An average consumption of 130W * 24 hours gives the daily energy consumption of 3.12kWh. This consumption is for an approximate area of $6m^2$ (3m x 2m room) & considering a four storied building, the average consumption per unit area comes down to 2.08 kWh/m^2 & power required is around 90 W/m^2.

Now we must look into the power output of a CPV system per unit area. If the requirements of the hostel are thus met by a completely occupied rooftop solar power plant, the hostel can be thus powered independently using only a solar power plant.

In Chennai, the average solar insolation throughout the year is around $800W/m^2$. [37] (For 6 hours of good sunlight per day).As power requirement is throughout the day, we must harvest enough solar energy in 6 hours to cater to requirements of the whole day.

Assuming a solar cell efficiency of 35% (for a multi-junction solar cell), concentrator efficiency of 85%, battery efficiency of 90% we get the overall power conversion efficiency of 26.7%. Considering this & the time factor (24hrs/6hrs) of 4 we can get the area requirement for a 10kW (average) power plant capacity as around 200 m^2. Hence we get the converted power density around $50W/m^2$. Thus, it is clearly evident that the 10kW rooftop power plant cannot meet out the requirements of the hostel on both the total consumption & power density basis (Inadequate space). However, such a power plant can greatly reduce the electricity requirement from the external grid & hence can cause large savings over the lifetime of the plant. It is estimated that such a CPV system can cover all its startup costs within 10 years & hence produces low cost electricity for approximately half its lifetime. It is obvious that such rooftop power plants can greatly reduce the external power needs of IITM hostel zone.

8.1.2 Advantages of CPV system in IITM

We will now briefly discuss the advantages of implementing a CPV system in IIT Madras. As shown in the preceding subsection, such a plant can cut down the power requirements in hostel zones by 50% just by installing rooftop CPV systems which will cover for their startup costs in about 10 years through the savings.

1. **Clean energy:** A major supporting argument for the solar power plants, clean & environmental friendly energy obtained through these systems will make the institute energy self-sufficient. A conventional coal power plant can also be used for this cause, but a solar power plant will have near-zero carbon foot print & will help preserve the wildlife. Also as the proposed plants will be installed on the rooftops, extra space need not be allocated for construction.

2. **Longer life:** A CPV system has an average lifetime of 20 years, & as per calculation shown in the preceding section, it can produce clean, low cost for half its lifetime.
3. **High energy density in Chennai:** As Chennai receives large amount of solar insolation constantly throughout the year (Chennai being near the equator), we can effectively harvest solar energy with only small seasonal variations compared to USA, Canada & Australia.
4. **Self-sufficient hostel zones:** As mentioned earlier, rooftop installations can reduce the external power requirements for the hostel zone.

There are some key issues with such installations, local to IIT Madras, which have to be taken into considerations while implementing CPV system. Some of the issues are listed below:

1. **Reliability:** One of the key issues with any solar power plant is the fluctuations in the incident radiations. Solar influx varies with the time of the day & also seasonal variations cause large fluctuations in the plant capacity. Chennai weather being unpredictable, may cause fluctuations in the solar power generation which is already experienced with the case of solar water heaters already installed in most of the hostels.
2. **Wildlife interference:** The campus is filled with variety of wildlife & it can be a measure headache for any installation in the campus. Adequate protection from monkeys should be provided especially for the rooftop installations, & special care must be taken to keep the impact on natural habitat to a minimum.
3. **Unpredictable weather variations:** As the campus is near to the sea, we experience a rather unpredictable weather. Hurricanes similar to the one experienced in 2012 can destroy such a rooftop power plant, hence adequate protection must be provided considering all the environmental factors. This will in turn increase the setup & maintenance cost.
4. **Tracking problems:** An active solar tracking mechanism is sensitive to large wind velocities. Also, frequent cloudy days will produce extremely low power output & hence will give rise to large variations in power output.

After considering all the advantages & disadvantages of a CPV plant in IIT Madras, we are now in position to discuss the feasibility of such an installation in the campus. The setup cost of CPV system can be back-calculated from the LCOE values of CPV plants currently installed across the globe. For a $3/W of LCOE, the setup cost comes out to be around 20 Lakhs. Including the costs of concentrator & cooling system, this can go up to 25-30 Lakhs. Further, the power output is not reliable & is sensitive to ever changing Chennai's weather. On the other hand, installing a CPV system is quite beneficial for wildlife preservation compared to the other alternatives. A CPV plant can reduce energy requirement in the campus as shown in the earlier calculations. Large rooftop space available in the campus is ideal for CPV installations & can make the institute partially energy-sufficient.

8.2 Selection of Receiver

The area requirement for the 10kW concentrated photovoltaic power generation system as calculated in the previous section is 200 m^2. This means that, in case of no concentration system, the solar panels consisting of solar cells have to cover the entire area. In that case, using multi junction cells would not be cost effective. The solar cells that can be used will be low efficiency silicon cells which would require even more area (Around 2.5 times more assuming the overall nominal efficiency to be around 10%) which is more than the rooftop area of a hostel/building. Therefore, the need for concentrator arises which would greatly reduce the area of the receiver panel & help in reducing the cost.

The multi junction solar cell that can be used InGaP/InGaAs/Ge which gives an efficiency of 35%. To determine the optimum receiver size, information about the intercepted optical energy & heat loss have to be computed first. As the receiver size increases, the amount of intercepted energy increases. However, all else remaining constant, as the receiver size increases, the heat loss from the receiver increases. The sum of the energy intercepted by the receiver & the heat loss from the receiver will show a maximum at some optimum receiver size. This will be the design point for sizing the receiver.

8.3 Selection of Concentrator

Based on the receiver size & the required solar power, the amount of concentration needed can be determined. In general, for rooftop applications, the concentration ratios required are of the order of 100-500X. So for application in hostels, we take a concentration ratio of 200X & decide the type of concentrator based on that. Such a concentrator system falls in the category of high concentration systems.

Table 3

S.No.	Type of Concentrator	Advantages	Disadvantages
1.	Fresnel lens	Small volume, Light weight, Mass production	Imperfection on the edges of the facets, causing the rays to be improperly focused at the receiver, Possibility of lost light due to incidence on the draft face. If these have to be overcome, the Luminance is necessarily reduced.
2.	Quantum dot concentrator	Non tracking concentrator. Have less problems of heat dissipation. Sheets are inexpensive & are suitable architectural components	Developing QDCs was restricted by stringent requirements of the luminescent dyes
3.	Parabolic trough	Make efficient use of direct solar radiation	Use only direct radiation, high cost, low optical & quantum efficiencies
4.	Compound parabolic concentrator	Most of radiation within the acceptance angle can transmit through the output aperture into receivers.	Needs good tracking system in order to get maximum efficiency
5.	Dielectric totally internally reflecting concentrator	Higher efficiency & concentration ratio than CPC, Work without any needs of cooling features	Cannot efficiently pass all of the solar energy that it accepts into a lower index media.
6.	Hyperboloid concentrator	Very compact	Need to introduce lens at the entrance aperture to work effectively
7.	RR, XX, XR, RX, & RXI	Achieving the theoretical maximum acceptance angle concentration, High concentration, Lighter weight, Less expensive tracking system	The size of the cell must be kept to minimum to reduce shadowing effect.

The concentrators that can be used are point-focus Fresnel lens, parabolic mirrors, compound parabolic concentrators or a two stage concentration system consisting of a parabolic trough & a secondary CPC for high concentration purpose (Quantum dot concentrators & RR,RX type concentrators give very high concentration ratios but they are not commercially produced). The best choice for a concentration factor of 200 is Fresnel lens since they are cost effective & can give the required concentration.

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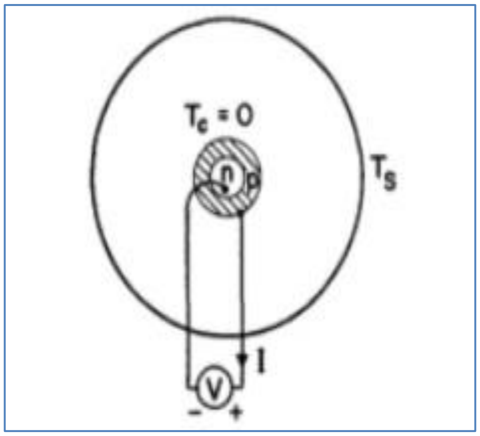
Appendix A: Shockley limit on solar cell efficiency

Shockley – Queisser limit, alternatively also known as detailed balance limit, models a solar cell under illumination as a simple model of a p-n solar cell kept in a spherical cavity (source) which is at a temperature T_s ,and the solar cell being at a temperature T_c lower than that of the source.

Now, consider that the band gap of the semiconductor is $E_g = qV_0 = h\nu_0$. As discussed in the introduction part of this report, any radiation with $\nu < \nu_0$is not absorbed, & all the radiation with $\nu \geq \nu_0$ gives rise to output energy of $h\nu_0$.

Keeping this in mind, we calculate total input & output powers & hence maximize the efficiency.



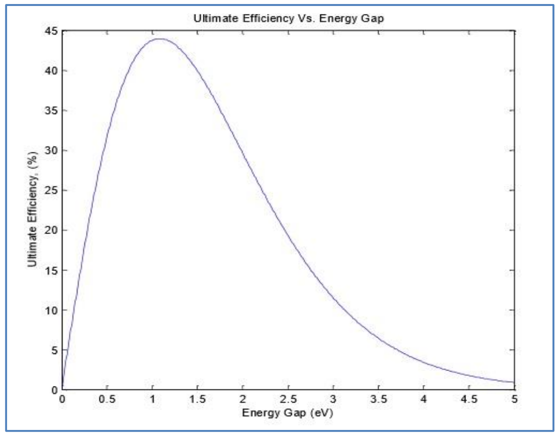


Figure A1: (a) Shockley model of solar cell under illumination (b) Efficiency vs Band gap

Assume that the no. of quanta of energy corresponding to a certain frequency is $Q_v = Q_v(T_s , v)$ & hence Qs be the quanta of photons incident which have energy greater than E_g. Then the power conversion efficiency can be expressed as

$$\eta = \frac{Output\ power}{Solar\ irradiation} = \frac{h\nu_0 Q_s}{P_s}$$

Where $P_s = \int_0^\infty h\nu Q_v$. From Plank's distribution of blackbody radiation, we can write $Q_v = Q_v(T_s , v) = \frac{2\pi}{c^2} \cdot \frac{\nu^2}{e^{\frac{h\nu}{kT_s}} - 1}$

Integrating this with change of variable as $x = \frac{h\nu}{kT_s}$, the problem reduces to maximize the integral

$$\eta(x) = \frac{x_0 \int_{x_0}^{\infty} \frac{x^2}{e^x - 1} dx}{\int_0^\infty \frac{x^3}{e^x - 1} dx}$$

This gives the distribution as shown in Figure A1 (b). Hence we get a maximum efficiency of around 44%, which occurs at a band gap of about 1.2-1.3 eV.

Appendix B: Contributions

The following are the contributions to this project by the various team members:

1) Solar Cells : Tejas Kulkarni, ME12B068
2) Receivers and Concentrators : Varun N Gupta, ME12B070 and Hemanth Vegi, ME12B071
3) Cooling Systems and Solar Tracking : Tejaswin P, ME12B069
4) Feasibility and Institute Implementation : Tejas Kulkarni, ME12B068 ; Varun N Gupta, ME12B070 and Tejaswin P, ME12B069