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Performance Evaluation of a Concentrator Photovoltaic/Thermal Hybrid Prototype

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Abstract

Concentrator photovoltaic/thermal (PV/T) hybrid systems produce both electricity and thermal energy; this increases the overall efficiency of the system and reduces the cost of solar electricity. These systems use concentrators which are optical devices that concentrate sunlight on to solar cells and reduce expensive solar cell area. This work deals with the performance evaluation of a concentrator PV/T hybrid system prototype with a single-axis tracking single-mirror two-stage (SMTS) concentrator and a mono-crystalline solar cell string bonded to a thermal receiver. The concentration ratio of system is between 11 and 5.6, and was measured by a customized circuit added to a micrologger instrument. The optical efficiency of the concentrator is 33% and was measured using short-circuit current method. This value is less compared to a SMTS system which has a theoretical maximum optical efficiency of 90%. The average thermal efficiency is 15% and the electrical efficiency is 4.6% under corrected solar concentration ratio of 17.1. The overall energy efficiency of the system is 19.6%. The low efficiency is mainly explained by improper reflector geometry. The prototype’s concentrator was built using geometrical ray tracing which is generally used for drawing conic sections. However, for surfaces other than conic, like SMTS, the surface interaction of the incident rays at two or more points makes ray tracing a computationally intensive process and often the surfaces are far away from ideal surface. This work includes a review of current concentrator PV/T hybrid activities which shows that a variety of systems are in use and the combined thermal and electrical efficiency one such system has approached up to 70%. A wide range of concentrator reflector material are available for solar energy use, but long term performance and durability of low cost materials for application in high concentration systems which operates at high temperature need to be studied thoroughly.

Keywords: PV/T, co-generation, efficiency, concentration ratio, ray tracing, reflector material
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1. Introduction

Renewable energy has to play an ever-increasing role in contributing to the energy demand of the 21st century and beyond, since the production of electricity from non-renewable fossil fuels such as coal, oil, natural gas and nuclear fuel is not a sustainable practice, due both to adverse environmental impacts and limited amounts of these fuels. There has been a growing concern for global warming and the drive to limit greenhouse gas emissions. To some extent it can be reduced by making better use of our renewable energy resources.

Virtually all renewable energy resources are derived one way or the other from sunlight. The sun releases an enormous amount of radiant energy into the solar system. Only a tiny fraction of that energy is intercepted by the earth, but if the sun’s ray reaching the surface of the earth just for one hour could all be converted into electricity it would be enough to meet the energy needs for the entire world’s population for a year [22]. Estimates are that a typical photovoltaic system in a house roof could prevent over 34 tonnes of green house gas emissions during its lifetime [23].

The major application of solar energy includes solar thermal and solar photovoltaic (PV) systems. Photovoltaics is a technology that converts sunlight directly into electricity using solar cells. The solar cell is a solid-state device that has no moving parts to breakdown and is rugged in design and requires little maintenance and no supervision. PV technology does not consume fuel resources or produce green house gases. However we do not find it in all roof tops. The reason is solar cells are expensive. Therefore, the overall goal of PV research and manufacturing has been to produce a low cost system, for which the need is a low-cost-efficient solar cells and a low cost efficient PV system.

The prototype for this work is a concentrator PV/Thermal (PV/T) hybrid system that deals with two of the cost reducing options, which are, concentration of sunlight onto solar cells and electrical/thermal co-generation. The primary aim of a concentrator is to significantly reduce the cost of electricity by replacing expensive solar cell area with less expensive optical materials such as plastic refractors or metal reflectors. Available literatures show that the research and development of PV/T system have been promising, but the overall system’s cost reduction still has been a formidable challenge. Installed PV systems provide electricity now at a cost in the range of US$ 0.30 to 0.50 per kWh [24].
This thesis deals with a prototype built by Solar20 of Härnösand, Sweden. Their mission statement is “to produce solar power at an investment of 1 US$ / W_{peak}”. The prototype has a 20x sun concentrator aluminium reflector a string of high performance solar cells. The structural hardware is made of aluminium. The cumbersome feature of finding and tracking the sun is replaced by a simple tracking mechanism consisting of an electronic sensor circuit connected to and electric motor coupled to a worm gear arrangement. The solar cell string is bonded to a heat sink and the cooling is done by water circulation, thereby preventing an efficiency reduction due to heat. Further development is envisioned for the utilization of thermal energy by producing hot water. The hybrid energy system generating electrical and thermal energies aims to increase the system’s total energy output which eventually will help them achieve their perceived goal.

1.1 Objective of this thesis work

The main objective of this thesis work is to evaluate performance of a prototype which is a Single-Mirror Two-Stage (SMTS) concentrator PV/T hybrid system. In order to achieve the objective the following aims were defined

- To understand trough shaped concentrator optics and PV/T hybrid systems.
- Literature study of PV/Thermal hybrid systems and solar reflector materials.
- Describe the profile of the concentrator.
- Evaluation of optical, electrical and thermal efficiency.

1.2 Motivation for this thesis work

This work is done by a student from Nepal, where 83% of the total area is covered by hills, mountains and valleys in between. Electricity is accessible to only 18% of the total population. In remote hills and mountains, houses are dotted and the population density is very low, therefore the cost of electrical transmission lines from local or national grid, reaching each household has not been economical. The government of Nepal with help from donor countries has initiated programs to install standalone PV system and it is gaining momentum.
In the hills and mountains winters are cold and hot water is always in demand. These areas are frequented by western tourists (for whom hot water is a must) where firewood is being used for heating water, due to which, large scale deforestation has been happening and the impact to the local ecology has been massive. Standalone PV and thermo-siphon systems are ubiquitous in lodge and motel tops. If a PV/T hybrid system could be used in such areas, both the electricity and the thermal energy demand can be met by a single system. The usefulness of PV/T hybrid and its prospects for its application in such areas has motivated me to do this thesis work.

1.3 Current photovoltaic market

Photovoltaic cell, modules, and systems have undergone intensive development in the last 20 to 30 years. The photovoltaics industry is growing rapidly as concern for global warming is increasing and as a result of falling prices due to technological breakthroughs. There has been a considerable gain in cell and module efficiency along with the reduction in cost of solar cells.

The world photovoltaic market installation has soared to 574 Megawatts in 2003, with a growth rate of 34% over 2002 [25]. Figure 1.1 shows costs, US$ per peak watt (US$/W_p), and production in MW_p over the last 25 years [12]. As of May 2004, many manufacturers are selling PV modules for prices below US$4.5 /W_p and one company, Kyocera is selling it for the lowest price at US$ 3.25/W_p. A solar energy website, Solarbuzz’s price index, based on a residential standard 2 kilowatt peak system, shows that, as of May 2004, at sunny climates the solar energy price is 39.44 US cents per kilowatt hour [25].

The cost per peak watt ($/W_p) of the PV system depends on the cost per peak watt ($/W_p) of the PV module and the balance of system (components other than photovoltaic cells). At present, the PV system prices are high since the volume production is low, so the research and start-up costs are spread over the relatively few units sold. Contrary to this, if the volume of the product increases, costs fall due to the economies of scale. Once the cost becomes closer to conventional electricity, its environmental friendly merit will influence, and a massive new market will open up and will attract investors.
Moreover, concentration of sunlight onto solar cells could be an option for achieving further cost reduction in photovoltaic energy generation. Concentrator systems, generally using tracking mechanisms, have proved to be of higher efficiency, but it requires more research. Static concentrators concentrate sunlight without tracking the sun, thus avoiding the increase in cost, but they are less efficient.

Above figure shows that prices of PV modules are continuously decreasing. Therefore, a concentration PV/T hybrid could make PV systems cost-effective by increasing the overall efficiency of the system. Thus Solar20’s mission of 1 US$/W_p at 6 to 8 US cents per kWh does not seem to be unrealistic and will turn into reality in near future.
2. Solar radiation and theoretical limits of concentration

The sun has an effective black body temperature close to 5800 K. The resulting average energy flux incident on a unit area perpendicular to the beam outside of earth’s atmosphere is the solar constant, \( G_{sc} \). The World Radiation Centre has adopted solar constant value as 1367 W/m\(^2\), with an uncertainty of 1%.

Irradiance is the amount of electromagnetic energy incident on a surface per unit time per unit area. This quantity is often referred to as ‘flux’. Insolation is the incident solar radiation received at the earth’s surface. This is the rate at which solar radiation is incident upon a unit horizontal surface at any point on or above the surface of the earth.

Solar radiation reaching the earth surface consists of direct, diffuse and reflected radiation. About 30% of sunlight is attenuated by the earth’s atmosphere before reaching the earth surface. The reasons are molecules of air, water and dust particles in the atmosphere scatter sunlight. Where as, Ozone, water particles and carbon dioxide absorb sunlight. In a clear sky day, after scattering and absorption followed by partial re-radiation into the space, solar irradiance value of approximately 1000 W/m\(^2\) reaches the earth surface at sea level at noon.

![Figure 2.1: The solar spectrum for a black body at 5800 k, an AM0 spectrum and an AM1.5 global spectrum; and the absorption bands of different gases [11].](image)
Solar spectrum is short for spectral distribution of electromagnetic radiation coming from the sun and its wavelength extends from 200 nm to 3000 nm. The effect of atmosphere on solar spectrum is expressed by air mass and is defined as the relative length of the direct beam path through to sea. At just above the earth’s atmosphere the spectral distribution is referred to as an air mass zero, AM0, solar spectrum. At sea level, when the sun is at zenith, the spectral distribution is referred to as air mass one, AM1. The general expression for air mass is \( AM_m \), where \( m \) is given by \( \frac{1}{\cos \theta_z} \) and \( \theta_z \) is the solar zenith angle. Figure 2.1 shows the solar spectrum for a black body at 5800 K, an AM0 spectrum and AM1.5 spectrum along with important bands of different atmospheric gases.

### 2.1 Angular distribution of sunlight

Since long, sunlight has been concentrated using optical devices for different applications. In concentrating devices, the angular distribution of a light source decides the maximum concentration that can be achieved. A very high level of concentration can be obtained from a point source while a much lower level of concentration can be obtained from broadly diffused light. The concentrating receivers have a small acceptance angle and do not use diffuse sunlight. Since concentration ratio is inversely proportional to half-acceptance angle. In these devices, much higher level of concentration can be obtained from sunlight using a tracking mechanism that follows the path of the sun across the sky.

### 2.2 Theoretical limits of concentration

Concentration ratio is defined in terms of optical concentration and geometric concentration. Optical concentration ratio \((CR_o)\) is the ratio of averaged irradiance, \( I_r \), integrated over the receiver area \( A_r \) and the incident solar radiation, \( I_a \), on the concentrator aperture. Optical concentrator is dependent on the quality of the reflector surface.

\[
CR_o = \frac{1}{A_r} \int I_r dA_r
\]

Geometric concentration ratio \((CR_g)\) is the ratio of the area of the collector aperture, \( A_a \), and the surface area of the receiver, \( A_r \).
The two concentration terms are related by $I$, which is the fraction of total power incident entering the concentrator and that reaches the receiver. For a concentrator without loss the value of $I$ is 1.

$$CR_o = I \cdot CR_g$$  \hspace{1cm} (2.3) \\

Concentration of light can be achieved using both imaging and non-imaging optics. Imaging optical systems like lenses in microscopes and cameras redistribute light so that an entire pencil of rays originating from one point of the source meets again in one image of the target. Non-imaging optics deals with optimal transfer of light between source distribution and target distribution. For an illuminating source, all points of the source are homogenous where all radiation coming from the source and intercepted by the concentrator surface will finally transfer to the target.

Non-imaging optics is used for transferring radiation flux from one area to another area where the path of light ray is of less importance. There exists a relationship between concentration ratio and acceptance angle in non-imaging optical systems and is determined using phase space concentration, and through radiation heat transfer theory and the second law of thermodynamics. In a simple concentrator, where the light source is homogenous and all light within the acceptance angle reaches the receiver the geometric and optical concentrations are equal.

The geometrical concentration can be expressed by applying law of thermodynamics. The following derivation for the maximum concentration ratio is based on the second law of thermodynamics applied to radiative heat exchange between the sun and the receiver [14]. In Figure 2.2, the concentrator aperture area is $A_a$ and the receiver area $A_r$ which is viewing the sun of radius $r$ at a distance of $R$. The half-angle subtended by the sun is $\_$. The receiver is shown behind the aperture for clarity.

For a perfect concentrator, the radiation from the sun on to the aperture and then on to the receiver is the fraction of the radiation emitted from the sun which is intercepted by the
aperture. The sun in not a blackbody, but for the purpose of approximate analysis, it has been assumed to be a blackbody at $T_s$ \[7\]

$$Q_{r-s} = A_s \frac{r^2}{R^2} \sigma T_s^4$$ \hspace{1cm} (2.4)

Figure 2.2: Sun at distance $R$ from the concentrator with aperture area $A_s$ and receiver area $A_r$ \[7\].

A perfect receiver radiates energy that is equal to $A_r T_r^4$, and a fraction of this, $E_{r-s}$, reaches the sun \[7\]

$$Q_{r-s} = A_s \sigma T_s^4 E_{r-s}$$ \hspace{1cm} (2.5)

When $T_r$ and $T_s$ are the same, from the second law of thermodynamics $Q_r$ is equal to $Q_s$ and from (2.4) and (2.5).

$$\frac{A_a}{A_r} = \frac{R^2}{r^2} E_{r-s}$$ \hspace{1cm} (2.6)

The maximum value of $E_{r-s}$ could be 1, and then the maximum concentration ratio for circular concentrators is given by \[7\]

$$CR_s = \left(\frac{A_a}{A_r}\right)_{circular,\ max} = \frac{R^2}{r^2} = \frac{1}{\sin \theta_s}$$ \hspace{1cm} (2.7)

A similar relation for linear concentration is given by \[7\]

$$CR_s = \left(\frac{A_a}{A_r}\right)_{linear,\ max} = \frac{1}{\sin \theta_s}$$ \hspace{1cm} (2.8)
From the above relations, and for the value of $s$, is 0.27, the maximum possible concentration ratio for circular concentration is 45 000 and for linear concentrators the maximum is 212 [7].

2.3 Summary

The solar irradiance falling just outside the earth’s atmosphere is 1367 W/m$^2$, but due to attenuation by the atmospheric particles, solar irradiance value of approximately 1000 W/m$^2$ reaches the earth surface at sea level at noon.

In this chapter the concept of solar radiation and theoretical limits of solar concentration has been outlined. This is the theoretical background for concentration optics which is concerned with the effects of the constituents of radiation (direct, diffuse and reflected radiation) falling on to the earth surface. The concept of geometrical concentration is essential for understanding different concentrator designs. Therefore concentrator ratio for both circular and linear concentrators has been derived using heat radiation transfer and the second law of thermodynamics.
3. Solar cell, PV module and system configuration

Solar cells are the building block of a photovoltaic (PV) system. Multiple cells are usually combined into a PV module. A complete system includes an inverter to transform the DC output from the cells into useable AC current, a charge controller, wirings to connect to components and a battery for electrical storage.

3.1 Solar cell structure

The photovoltaic effect is the process by which a solar cell converts sunlight into electricity. Solar cell is a semi-conductor diode that absorbs light particles (photons) of sunlight and creates electron-hole pairs. In order to generate electricity, the electron and hole need to be separated, and this is done in a solar cell by an artificial junction called the p-n junction. In a crystalline silicon cell, p-n junction (“n-type” with abundance of electrons having negative charge and “p-type” with abundance of holes having positive charge) is formed by diffusing phosphorus into silicon and introducing a small quantity of boron. A typical solar cell structure and the creation of electron-hole pair is illustrated in Figure 3.1.

![Solar cell structure](image)

**Figure 3.1:** A solar cell structure and the creation of electron-hole pair [11].

An electric field is generated at the p-n junction that provides the force or voltage which sweeps electrons to the n side and the holes to the p side. When the electric metal grid on the front and metal contact on the rear of the cells are connected through an external load, the freed electrons will flow through the circuit generating electricity.
3.1.1 Diode equation and cell current

The dark current-voltage, I-V curve of an ideal p-n junction is given by the actual diode equation known as Schockley’s equation

\[ I = I_o \left[ \exp \left( \frac{qV}{nkT} \right) - 1 \right] \]  \hspace{1cm} (3.1)

Where, \( I_o \) is the dark saturation current, \( V \) is the applied voltage, \( q \) is the absolute value of electronic charge, \( k \) is the Boltzmann’s constant, \( T \) is the cell temperature, and \( n \) is the ideality factor. The value of \( n \) lies between 1 and 2 and the value increases as the current decreases.

Under illumination from sunlight, the current produced is given by \[ I = I_o \left[ \exp \left( \frac{qV}{nkT} \right) - 1 \right] \] \hspace{1cm} (3.2)

where, \( I_L \) is the light generated current.

3.1.2 Solar cell materials and structures

Solar cells are made from different types of semiconductor materials that are deposited or arranged in various structures and designs using different manufacturing methods to reduce cost and to achieve maximum efficiency. Most solar cells are made of semiconductors. Certain semiconductors such as amorphous or polycrystalline silicon, gallium arsenide, cadmium telluride and copper-indium-diselenide are suitable for photovoltaic conversion of solar radiation.

Silicon is the most commonly used material and are available in various forms, viz, single-crystalline, multi-crystalline and amorphous. Poly-crystalline thin films are generally made from copper indium diselenide (CIS), cadmium telluride (CdTe), and thin film silicon. Thin films are often made from a number of layers of photo-sensitive materials. Single crystalline thin films include high-efficiency material such as gallium arsenide (GaAs). Solar cells are
arranged in various ways and the four basic structures are; homo-junction, hetero-junction, p-i-p and n-i-p, and multi-junction.

3.2 Photovoltaic modules

Solar cells are the basic elements of a PV module. Since cells are of low voltage, they are connected in series to form a module of a higher and more useful voltage. The modules are constructed with laminates and have a back sheet and a cover of low-iron glass which protects the front surface of the material while maintaining a high transmissivity. A structural outer casing is used to protect the glass and the solar cells.

3.2.1 PV module characteristics and performance

The performance of a PV module is characterized by a current-voltage curve (I-V) and is shown in Figure 3.2. The figure is a plot of voltage across the module for different values of current. I-V curves are obtained by measuring the current and voltage of the module by varying the resistance of the load. This is done at constant level of irradiance, while maintaining a constant cell or module temperature.

For low values of load resistance, the current is a maximum and the voltage across the module approaches zero. This is equivalent to short-circuit across the module, and the current output at zero voltage is called the short-circuit current, $I_{sc}$. This current is a function of the size of the module. The short circuit current is also directly proportional to the level of solar radiation.

As the load resistance is increased, the current decreases sharply until a point is reached when the module can no longer maintain the current, and it falls to zero. The voltage across the module at zero current is called the open-circuit voltage, $V_{oc}$ and is the output without load. The open-circuit voltage varies only a small amount as a function of solar irradiance. The voltage produced by a photovoltaic module is a function of how many cells are connected in series.
Figure 3.2: Photovoltaic panel output current as a function of the voltage across the panel. Data are for a cell temperature of 25°C and an air mass of 1.5 [28].

### 3.2.2 Maximum power point and fill factor

The product of the current and voltage is the power output for that operating condition. Maximum power point (MPP), is the value when the product \( V_{mp} \times I_{mp} \) is at its maximum value. The power output at MPP under a light intensity of 1000 W/m\(^2\) is known as the “peak power” of the cell or module and the solar cell or modules are rated in terms of “peak” watts, \( W_p \). The short-circuit current, open-circuit voltage and maximum power points are shown in figure 3.3.

The fill factor, \( FF \) is a measure of the junction quality and series resistance of a cell or module. It is an important characteristic in evaluating cell or module performance and is defined as a ratio of maximum power and a product of \( V_{oc} \) and \( I_{sc} \).

\[
\text{Fill Factor (FF)} = \frac{V_{mp} \cdot I_{mp}}{V_{oc} \cdot I_{sc}} \tag{3.3}
\]

\[
\text{Maximum power (P_m)} = V_{mp} \cdot I_{mp} = V_{mp} \cdot I_{mp} \cdot FF \tag{3.4}
\]
3.2.3 Efficiency of photovoltaic module

The conversion efficiency, $\eta_{pv}$ of a cell or module is the ratio of electrical energy generated to the irradiation falling on it. The efficiency is dependent on material properties, such as band gap energy, $E_g$, and on spectral distribution of the incident light. Sunlight is made up of photons that range in wavelength. When light falls on the surface of the module, some photons are reflected and do not enter the module and it is a loss. The actual efficiency is less than theoretical efficiency. The electrical efficiency of a solar cell or module is given by the following relation

$$\eta_{pv} = \frac{V_{mp}I_{mp}}{I_0A_o}$$

(3.5)

Where $I_0$ is the irradiance falling on to the cell or module and $A_o$ is the surface area.

The output of a PV module is limited by several factors and following are some important ones. A minimum energy of photon is required to create an electron-hole pair. Radiations at higher wavelengths do not produce electron-hole pairs, but heats the cell. There are optical and recombination losses that reduce the module output. Optical losses occur due to the reflection of the incident radiation. Where as recombination losses occur due to several mechanisms and are of three types. In auger recombination electrons recombines with the
holes giving up the excess of energy to another electron, which then comes back to its original energy state, releasing phonons. Recombination also occurs through traps. This occurs when impurities in the semiconductor or interface traps at the surface that gives rise to an allowed energy level in the otherwise forbidden energy gap. There are electrical effects such as sheet resistance which occurs due to the flow of electrons across the top layer to the grid, limiting the module or cell output.

### 3.2.4 Effects of temperature

The solar irradiation that is falling on to a solar cell is not fully converted into electrical energy. The electrical energy is removed from the cell through the external circuit; however the thermal energy is dissipated by heat transfer mechanisms. In a solar cell, at a fixed irradiation level, increasing cell temperature leads to decreased open-circuit voltage and a slightly increased short-circuit current. The $I_{sc}$ increases with temperature, because the band gap energy decreases and more photons have enough energy to create electron-hole pairs. But this effect is small. The main effect of increasing temperature for solar silicon cells is the reduction of $V_{oc}$ and the fill factor. Therefore the overall effect is the reduction of the cell output leading to the reduction of the efficiency of the module. To get rid of this, heat transfer from the module should be maximized so that the cells will operate at the lowest possible temperatures.

![Figure 3.4: The effect of temperature on the I-V characteristics of a solar cell [7].](image)

At high concentration of irradiation level, the cell reaches higher cell temperature, which reduces the output voltage. Therefore cooling is often required for concentrating solar systems. The effect of temperature on the I-V characterises of a solar cell is shown in figure 3.4.
3.2.5 Effects of irradiance

In a solar cell, the light-generated current is proportional to the flux of photons with energy above band gap. Irradiation level is proportional to photon flux, and increasing the radiation level increases the proportion of the photon flux which in turn generates proportionately higher current. Therefore, the short circuit current of a solar cell is directly proportional to radiation level. The open-circuit voltage increases logarithmically, and is usually neglected in practical applications. Solar cells respond to both diffuse radiation and beam radiation.

3.2.6 Effects of parasitic resistances

Solar cells have inherent parasitic series and shunt resistance associated with them, and both of which reduces the fill factor. Series resistance, $R_s$ is due to the metal contact particularly the front grid and the transverse flow of current in the solar emitter to the front grid. Series resistance, has no effect on the open-circuit voltage, but reduces the short-circuit current. The shunt resistance, $R_{sh}$ is due to the p-n junction idealities and impurities near the junction. It has no effect on the short-circuit current, but reduces the open-circuit voltage.

![Figure 3.5: The equivalent circuit of a solar cell](image)

Figure 3.5 shows the equivalent circuit of a solar cell with both series and shunt resistances and is given by the relation [12]

$$I = I_L - I_D - I_{sh} = I_L - I_o \left[ \exp \left( \frac{V + IR_s}{nkT/q} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}}$$

(3.6)
3.3 Photovoltaic module and solar cell interconnection

Electricity produced from a single solar cell is not sufficient for practical use. Cells with similar characteristics are connected and encapsulated to form modules. Modules are the basic building blocks of solar arrays. The maximum voltage from a typical single solar cell is about 600 mV, therefore cells are connected in series to obtain the desired voltage. Usually about 36 cells are connected for a nominal 12 volt system. Under 1000 W/m$^2$ the maximum current delivered by a cell is approximately 30 mA/cm$^2$ [20]. Cells are therefore connected in parallel to obtain the desired current.

3.4 Photovoltaic system configuration

A photovoltaic system consists of more than PV arrays (photovoltaic generator) composed of PV modules. In addition, it requires parts or subsystems, which is known as balance of systems (BOS). The BOS is generally composed of batteries (storage subsystem), the control unit and inverter, the mechanical support structure, the electrical wires, and protection devices such as fuses.

PV array is a number of photovoltaic modules connected together to give the required power with a suitable current and voltage. Most PV modules deliver direct current (DC) electricity at 12 or 24 V, but most of the household appliances operate on alternating current (AC) at 230 or 110 V. Therefore, an inverter is used to convert the low voltage DC supply to higher voltage AC.

There are two main types of PV systems, namely stand-alone and grid connected. A typical standalone system consists of a photovoltaic generator, batteries for energy storage and some form of control and the inverter in the case when AC current is required at the output form the system.

Grid connected systems are of two types, the first type is the one in which the grid merely acts as an auxiliary supply in which the grid functions as a back up and the other type is grid interactive in which the excess power from the PV generator supplies to the grid.
3.5 Summary

Solar cell is a semiconductor device that converts sunlight into electric current. When light impinges on to the cell, electron-holes are created and these are separated by electric fields at the junction. The electrical output from cell or PV module is described by $I-V$ characteristics and it depends on the material properties of the semiconductor. The effect of solar cell performance due to temperature, parasitic resistances, irradiance and the losses are important and it has an effect on the efficiency of the PV system. A photovoltaic system contains PV modules and balance of system. PV modules are connected together as per the required power with suitable current and voltage. PV systems can deliver both AC and DC current. The two main types of PV system are standalone and grid connected systems.
4. Photovoltaic Concentrator Technology

Concentrators are optical devices that concentrate sunlight on to solar cells using lenses or mirrors. Solar cells are the most expensive component of a PV-system and the use of concentrator results in the reduction of cell area required for producing a given amount of electrical energy. The primary aim of a concentrator is to significantly reduce the cost of electricity by replacing expensive PV cell area will less expensive optical materials such as plastic refractors or metal reflectors. In addition, concentrator device makes possible, the use of higher performance PV cells which would be prohibitively expensive without concentration. The performance of a photovoltaic concentrator system depends on the concentrator type, the solar cells used and the reflector materials of the concentrator. This chapter focuses only on concentrator with reflector surfaces.

Concentrator PV-systems have several advantages over flat-plate (non-concentrating) PV systems. Firstly, concentrator system increases the power output while reducing the area of cells needed. Secondly, the cell efficiency increases under concentrated light, but the increase in efficiency depends mainly on the design of the solar cell and the cell material. Finally, the cells used in concentrators are small, which is an advantage because it is harder to produce large-area, high-efficiency cell than to produce smaller-area cells.

Commercially viable concentrating PV-systems, for terrestrial use, have been a formidable challenge because the cost per peak watt of the system must always be less than that of conventional flat PV panels. In addition, there are technical barriers due to the difficult cell packing requirement resulting from the heat flux and electrical current density.

Extensive cell research has resulted in the development of higher concentration cells. However, the concentrators must be of low cost, yet permit highly accurate focusing with high optical efficiency and uniform illumination in all cells. The tracking mechanisms must be cheap and accurate. At high concentrator ratios, excess radiation is concentrated and the cell temperature increases. Cell efficiency decreases as temperature increases and finally the cooling and current extraction must be effective and cheap.
4.1 Solar concentrator

A variety of solar concentrators have been designed and some are as following: a) flat reflector concentrators, b) parabolic section reflector concentrators, c) paraboloid reflector in solid revolution, d) combined parabolic concentrator (CPC), e) Fresnel reflector concentrator, e) single-mirror two-stage concentrator (SMTS), f) dielectric single-mirror two-stage concentrator (DSMTS), g) concentrator with heliostat type reflectors with receptors on top of a central tower.

The optics of the concentrator can be Fresnel or classical lens or mirrors. Fresnel lens is a thin faceted structure having the same refraction properties as bulky classical lens but with a smaller thickness, so the price is less. Fresnel lenses are available with point focus, suitable for a circular or squared cell or with line focus suitable for linear array of cells. Trough shaped concentrator device contains a reflector or a mirror to focus the incoming sunlight into a receiver or a target. These concentrator devices can be designed to focus sunlight to a point or a line receiver.

The concentrating receivers have a small acceptance angle and do not absorb the diffuse light. Therefore, they have to track the sun. A tracking mechanism is used to keep the cell in focus. Point focus optics requires a two-axis tracking, where as for a linear optics both one-axis and two-axis tracking will work. The tracking mechanism can also be designed in different ways as per the requirement. Concentrators can be divided into different types based on the optical means to concentrate the light, number of sun tracking axis, and the mechanical mechanism that effect the tracking.

4.1.1 Ray tracing for solar concentrator design

Simple two-dimensional solar concentrator surfaces can be designed and their properties examined by ray tracing using graphical methods. A ray tracing procedure for a reflecting concentrator surface is governed by the law of reflection. In a vector notation, the law of reflection is expressed by [19]

\[ r'' = r - 2(n \cdot r)n \] (4.1)
Figure 4.1 shows the geometry with unit vectors $r$, $r''$ and $n$. Thus for drawing a reflecting surface with the rays converging to a target using ray-tracing, first the normal to the surface is determined from the tangent to the shape. This is done for the appropriate set of coordinates. The direction of the reflected ray then follows the law of reflection, where the angle of incidence equals the angle of reflection. The process is repeated for a series of coordinates. This geometrical method of ray-tracing is often time consuming for section other than conic sections.

These days most convenient method for examining complex surfaces, other can conic sections, such as SMTS is by using computer ray tracing, but the basics of ray tracing remains the same. For such surfaces, computer ray tracing is essential because of the surface interaction of the incident rays at two or more points which makes it a computationally intensive process.

Presently available ray tracing softwares such as Opticad can import data file in a convenient format from computer design softwares such as AutoCAD and can also export output data file in a format that can be used in computer aided manufacturing. Once the optical ray tracing has been done for a particular surface geometry, the same output files can be exported to computer aided manufacturing. These softwares, on one hand will make simple the graphically cumbersome and computationally intensive process of ray tracing of surface other than conic sections and on the other hand will further aid in manufacturing of high accuracy surfaces.
4.2 High performance concentrator solar cells

Solar cell efficiency will tend to increase with concentration, when the cell temperature is kept constant temperature close to ambient. Intensive solar research has resulted in higher solar efficiencies. The quoted efficiencies by the manufacturers are generally based only on beam component of sunlight. Hence, their efficiencies are not directly comparable with those of non-concentrating systems.

4.2.1 Effects of concentration on cell parameters

Increasing the solar concentration increases the cell theoretical efficiency and this is valid only when there are no series resistance losses and the temperature remains constant. The cell $I_{sc}$ increases linearly with concentration while $V_{oc}$ increase slightly under concentration, giving a net solar cell efficiency increase. This is an ideal condition that is true only when the dark saturation current of the solar cell is constant under concentration and there are no parasitic resistances [8]

$$I_o = \frac{I_{sc}}{e^{\frac{V_o}{nkT}}}$$  \hspace{1cm} (4.2)

where $I_{sc}$ and $V_{oc}$ are at normal one sun. For a concentration of $x$ time, $I$ increases to $xI$ so that the open circuit voltage under concentration $V_{oc}'$ will be [8]

$$V_{oc}' = \frac{kT}{q} \ln \left( \frac{xI_{sc}}{I_o} \right)$$  \hspace{1cm} (4.3)

substituting (4.2) into (4.3) and rearranging

$$\Delta V_{oc} = \frac{kT}{q} \ln x$$  \hspace{1cm} (4.4)

Where $x$ is the concentration ratio and $\Delta V_{oc}$ is the change in $V_{oc}$ due to concentration.

4.2.2 Effects of cell series resistance under concentration

The solar cell resistance has a larger effect under concentration than under one sun concentration. The power loss due to series resistance is proportional to $I^2R$. The choice for
solar cell and the arrangement of cell array is critical under high concentration. The high concentration effect will be considered in the cells manufactured for higher concentrations.

4.3 Reflective materials for solar concentrators

Selecting a reflector material which is both suitable as well as economical is a critical task while designing a solar concentrator. PV cells have more than 20 years of life, so the reflector surface too should retain its optical properties for that duration.

For photovoltaic application, photon with lower energy than the band gap of the solar cell does not contribute to photoelectric conversion but leads to overheating. High cell temperatures reduce the output voltage and a high reflectance in the infrared is therefore counterproductive in photovoltaic applications. In photovoltaic-thermal hybrid systems, the reflectance of the concentration surface material should be as high as possible at all solar wavelengths, since the wavelengths longer than the band gap wavelength will be used for heat production.

There are no metals with a combination of low reflectance in the near infrared wavelength along with high reflectance in the ultraviolet wavelength and visible light. However such a surface with a selective reflectance has been developed by the application of thin films on top of the reflecting metal. Metals like silver and aluminium are best for solar reflectors, having solar hemispherical reflectance of approximately 97% and 92% respectively [5].

4.3.1 Literature study

During this thesis work, a variety of resources such as web search engines, text books and research papers were used to investigate the reflector materials for solar concentrators and some of the reflector products are outlined in this section. 3M is an American company manufacturing solar reflector products. Their products are EPC305+ silver exterior grade, SA-85P aluminium film, exterior grade, SS-95P silver film interior grade. 3M reflector products have good optical properties but the prices are comparatively higher. Lately, 3M has stopped manufacturing solar reflector materials [9].
Alanod, a German company, manufactures a variety of aluminum grades. It sells products specifically for solar applications, and Miro extra bright is a solar reflector material. The company states that their product has proved weatherability due to the extra lacquer that has been used in the reflector surface [26].

Silver glass material is a proven reflector material that has been successfully applied in the LUZ-LS3 collectors in the United States of America. Where Flabeg 4 mm back-surface-silvered, low-iron glass is the reflector material in which a glass substrate is silvered from the backside and sealed with an oxidation protective layer [9].

Sol-gel coated silver/aluminum is another reflector material developed in CIEMAT laboratory in Madrid. $\text{SiO}_2$ sol-gel dense and thin coatings are applied to protect front surface silver and aluminum mirrors. Integrated solar reflectance is over 0.95 for coated silver and 0.85 for coated aluminum. These front surface mirrors have been reported to have long thermal stability up to 300 °C, good outdoor resistance, lower weight, and are specially applied for solar energy applications [27].

Australian National University has developed mirrors using glass-on-metal-laminate (GMOL) [6]. These mirror elements are made up of large sheets of 1mm thickness, back-silvered white glass, having 94% reflectivity and 96% shape accuracy. They are using two types of mirrors. The first one is a two-dimensional trough concentrators that reflect solar radiation to a line focus for use in linear photovoltaic concentrator receivers. The other one is a three-dimensionally curved, spherical panel for use with point focus, large-area dish solar concentrators. It is reported that both types of mirrors had undergone several thousand hours of accelerated environmental testing and the results have shown high resistance to environmental degradation.

The aluminum-polymer-laminated steel is a new reflector material developed and tested in Sweden. The weighted total and specular reflectance values are 82% and 77% respectively [4]. The durability of the reflector was tested in a climatic test chamber as well as outdoors in Älvkarleby, Sweden. Their results showed that, after one year outdoor exposure, the total specular solar reflectance decreased by less than 1%. It is also reported that when it was exposed in damp heat for 2000 hours under 1000 W/m² simulated solar radiation, the optical properties changed. The decrease of optical properties was found to be due to the degradation
of the protective polyethylene terephthalate (PET) layer caused by ultra-violet radiation and exposition to high temperature. Their conclusion was that the optical property degradation is climate dependent and the PET is not suitable as a protective coating under extreme conditions. Their outdoor testing indicated that the material can only withstand exposure in a normal Swedish climate.

A comprehensive evaluation of solar reflector materials was done in Sweden to find the stability of the optical properties [4]. The materials were silvered glass, anodised aluminium, thin film-coated anodised aluminium, laminated evaporated aluminium reflector, and lacquered rolled aluminium. Their result showed that reflectors of silvered glass, anodised aluminium, thin film-coated anodised aluminium, and lacquered rolled aluminium withstood accelerated testing well, while a laminated evaporated aluminium reflector which was specular initially became diffuse. Laminated and lacquered reflectors withstood outdoor ageing better than unprotected thin film-coated and anodised aluminium, which degraded significantly. Their conclusion is that the optical degradation depends on climatic conditions and on the protective layers, if applicable. Their recommendation is; due to the difference between the results from outdoor testing and accelerated ageing, a thorough understanding of corrosion processes is necessary before drawing conclusions about long-term performance from accelerated ageing tests. The solar reflector material manufacturer/ developer, its reflectance values and their costs in US$ are presented in Table 1. The prices for serial number 1-3, in the table has been taken from [9], these are reflective films, so the cost of substrate and laying down has to be added, which is about US$ 12/m². The price for serial number has been taken from [21].
<table>
<thead>
<tr>
<th>S. No</th>
<th>Manufacturers / developer</th>
<th>Reflector material, product</th>
<th>Solar reflectance %</th>
<th>Cost US$ / m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3M</td>
<td>3M's EPC305+ silver, exterior grade</td>
<td>94</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>3M</td>
<td>3M, SA-85P solar film, exterior grade</td>
<td>85</td>
<td>7</td>
</tr>
<tr>
<td>3</td>
<td>3M</td>
<td>3M, SS-95P silver flux, interior grade</td>
<td>94</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>Alanod</td>
<td>MIRO 27</td>
<td>92</td>
<td>22</td>
</tr>
<tr>
<td>5</td>
<td>Flabeg</td>
<td>4 mm glass/silver</td>
<td>93.8</td>
<td>x</td>
</tr>
<tr>
<td>6</td>
<td>ANU</td>
<td>Glass-on-metal-laminate</td>
<td>94</td>
<td>x</td>
</tr>
<tr>
<td>7</td>
<td>CIEMAT</td>
<td>Sol-gel coated silver / aluminium</td>
<td>95 silver / 85 aluminium</td>
<td>x</td>
</tr>
<tr>
<td>8</td>
<td>Vattenfall Utveckling</td>
<td>Aluminium-polymer-laminated steel reflector</td>
<td>82</td>
<td>x</td>
</tr>
</tbody>
</table>

**Table 1:** Solar reflector reflectivity and cost US$

### 4.3.2 Issues

Test results on reflective material done at laboratories in different locations show that oxidation attack on the reflective layer due to surface defects in the protective coating has been a limiting factor for all materials except silver/glass. The back-surface-silvered, low-iron glass used in the large LUZ solar thermal plant and GMOL has been proven to be a suitable material which can also withstand high temperatures and have shown high resistance to environmental degradation. The cost of silver/glass reflector material may not be economical in small scale application since their costs are higher. Anodized aluminium is a cheaper option, but it has a comparatively lower reflectance than silvered glass and its weatherability has not been ascertained. The aluminium-polymer-laminated steel reflector developed and tested in Sweden could be a cost-effective reflector in low concentrating PV/Thermal applications [4]. A thorough understanding of the mechanism that governs the corrosion of commercially available reflector material should be studied based on the ageing tests which will help to develop cost-effective and weatherability reflector material suitable for high concentration solar energy systems.
4.4 Summary

Concentrators are optical devices that concentrate sunlight using mirrors or lenses and are used to reduce the cell area for generating a given amount of electrical energy. The main advantages are the reduction in cell area, increase in cell efficiency and high efficiency solar cell. There are still challenges in this technology; a balance has to be struck between component costs and system performance. Concentrators are of two types and the difference is due to reflection or refraction of sunlight. Ray tracing is used to design both refractive and reflective concentrator surfaces. High performance solar cells are generally used in concentrator devices and their efficiencies are more. Reflector material plays a crucial role in the performance of the concentrator. Silver/glass reflector material has better performance and durability. A wide range of concentrator reflector materials are available for solar energy use, but long term performance and durability of low cost material for application in high concentration systems which operates at high temperature needs to be studied thoroughly.
5. Concentrator PV/T hybrid system

Concentrator photovoltaic/Thermal (PV/T) hybrid system consists of a concentrator device, solar cells and a heat sink (thermal receiver). The solar irradiation received on the concentrator aperture is focused on to the solar cell string which is partly converted into electricity and the remaining is thermal energy which is extracted for useful purposes by the heat sink. The heat transfer medium is generally air or water. The performance of a PV/T system is dependent on different parameters, such as the climatic condition of the site, the system orientation, the solar cell type, the mass flow rate of fluid medium. The challenges for hybrid concentrator PV/T hybrid systems are; to use cheap reflectors which can accurately concentrate the sun on to an area of solar cells; to accurately and reliably track the sun; to adequately cool the solar cells to maintain high power output; and to utilize thermal energy.

5.1 Prototype components

The concentrator PV/T hybrid system prototype used in this work has a single-mirror two-stage concentrator which has an approximately SMTS shape that focuses light linearly onto a strip of solar cell string. The prototype is shown in figure 5.1.

Figure 5.1: Photograph of concentrator PV/T hybrid system prototype
The SMTS concentrator is a design by Alarte, Benitez and Minano, at Universidad Politecnica de Madrid in Spain [21]. The prototype was built by Solar20 of Härnosand, Sweden and the geometrical concentration is approximately 20 x sun. The concentrator reflector material is from Alanod of Germany, and it is laminated on to a fibre glass base which acts as a structural support. The tracking mechanism is of single-axis type and has a microprocessor controlled sensors connected to electric motor which is coupled to a worm gear train. The structural components are made of aluminium and it has been used to reduce the total weight of the system. The major components of the prototype are described in the following sections.

5.1.1 SMTS concentrator

The SMTS concentrator is a design in which the solar cell string and the thermal receiver are at mirror edges and it also forms a part of mechanical support to the collector. This skilful design will reduce the total mass of other structural material. In the concentrator, there are two cell strings for a reflector mirror, where half of the mirror works as a first stage for one cell string and as a second stage for another cell string. Figure 5.2 shows the shape of the concentrator, where the rays that fall on a given reflector mirror is reflected towards either the opposite mirror and on to the solar string (ray a and b) or straight to the cell string (ray c).

![Figure 5.2: Cross-sectional view of single-mirror two-stage concentrator.](image_url)
The prototype concentrator is made up of two sections hinged at the centre. The concentrator aperture area is 1.2 m\(^2\) (0.71 m width and 1.7 m opening). The prototype has a single-axis type tracking system.

The prototype concentrator drawing was prepared by geometrical ray-tracing, in a way the geometry is built up by two parabolas. Based on the drawing a fibre glass mould was made and the aluminium was laminated on top of it to form the concentrator surface. Ray-tracing is a method of generating optical path in a system based on the laws of geometric optics. For a concentrating system, by the application of the laws of reflection, a light ray can be propagated from the source to the target, thereby generating an approximate shape of the system. To simplify computation, a number of assumptions on the optics are made. Therefore, the results derived from a ray-tracing are an approximation. The ray-tracing for two-stage reflection for surfaces, other than conic sections, like SMTS is more cumbersome.

### 5.1.2 Silicon solar cells

The prototype has a solar cell string which consists of 24 solar cells connected in series and is shown in figure 5.3. The cells are arranged in two rows of 12 cells each and a cell is 11.52 cm\(^2\) (4.8 cm x 2.4 cm). The cell string area is 28.32 cm\(^2\) (4.8 cm x 5.9 cm). The cells are laid on top of a rectangular aluminium plate (65 cm long x 6 cm wide x 0.8 cm thick). The cell manufacturer is Millennium Electric Ltd of Israel and it is a mono-crystalline silicon type and the cell string is shown in figure 5.3. The manufacturer’s specification of the solar cell is given in appendix 1.

![Figure 5.3: Photograph of solar cell string bonded to aluminium bar.](image)
5.1.3 Thermal receiver

The prototype thermal receiver is clamped to the back of the solar cell string and it has inlet and outlet pipes for fluid circulation. The solar cell base aluminium plate is clamped to a hollow rectangular aluminium device (71 cm long x 5 cm wide x 2 cm thick). The thermal receiver is shown in figure 5.4.

![Photograph of thermal receiver.](image)

For achieving higher electrical efficiency, it is important to minimise the temperature difference between the fluid and the solar cells. Therefore, a good heat transfer is required between the silicon cells and the circulating fluid, particularly due to the high heat flux generated at the centre of the cell. Most thermal resistance may occur between the silicon cell surface and the aluminium device. The existing receiver system and the fluid circulating arrangement is only a basic design, but it has to be improved with proper insulation on the outer surfaces to minimize heat losses. A glass cover on the concentrator aperture may be necessary to increase thermal performance of the system. If the concentrator surface is covered with glass it will protect from dust but the optical performance will be reduced to some extent due to inherent properties of glass.

5.1.4 Solar tracking

To achieve the required high solar radiation the concentrator must focus the incoming radiation onto the receiver all the time. Solar trackers are devices for orienting solar energy systems towards the sun. The purpose of a solar tracker is to get the highest possible output from costly solar cells. The tracking system in the prototype is a single-axis which is to be positioned along the earth’s east-west axis. It rotates around a horizontal axis so that the concentrator’s axis is at the same solar altitude angle as the sun. The tracker has a microprocessor, electronic circuits and sensors. If the concentrator is not properly aligned
towards the sun, a difference in signals is received by the sensors which is amplified and fed to the motor. The motor which is coupled to a worm gear arrangement then moves the concentrator to follow the sun. The electric motor is a wire drive motor from FHP Elmotor AB of Sweden.

5.1.5 Concentration ratio

The prototype manufacturer has stated the geometrical concentration ratio of the concentrator as 20. The geometrical concentration ratio is given by equation (2.2), which is a ratio of the aperture area and the receiver area. For this prototype, which is a linear concentrator, it is the ratio of the aperture opening (170 cm) and the solar cell string width (4.8 cm). The concentrator design requires two cell strings on both sides of the mirror ends. But for testing the prototypes manufacturer had provided only one cell string and it was put at the lower mirror end for convenience, because of this only the upper half of the concentrator has been evaluated. Therefore considering half the aperture and one cell string, the actual concentration ratio of the concentrator, \( CR_{g,a} \), is calculated as following

\[
CR_{g,a} = \frac{\text{aperture opening}}{2} \times \frac{1}{\text{cell width}} = \frac{170 \text{ cm}}{2 \times 4.8 \text{ cm}} = 17.7
\]

(5.1)

Out of the 24 solar cells in the string, five solar cells were broken during the tests. The thin wires were soldered to by-pass the damaged part. Two cells were completely by-passed and the remaining three were partially by-passed. By measuring the damaged portion of each cell, it was calculated that the limiting case would be the reduction of short-circuit current by 3.5\%. Therefore for calculating the electrical efficiency of the solar cell string the corrected concentration ratio \( CR_{g,c} \), value of 17.1 (17.7 x 0.965) has been used.

5.2 Current concentrator PV/T system activities

Many educational institutions, research groups and commercial companies are working on concentrator hybrid PV/T hybrid systems around the world. This section outlines some of the concentrator PV systems and hybrid concentrator PV/T systems. This literature study has been prepared using a variety of resources such as web search engines, text books and research papers.
5.2.1 Wall integrated PV system [3]

Vattenfall Utveckling AB of Sweden has developed a stationary concentrating photovoltaic system prototype for wall integration. It is a box type design with a thickness of 18 cm and the entry aperture of 55 cm. The system can be customized to be used as a south wall element with insulation on the back. The system has a Cu(InGa)Se$_2$ based Siemens ST5 thin film module. The parabolic reflector is designed so as to accept all incoming irradiation from south projection angles between 25° and 90°. The reflector material is anodized aluminium which has a solar reflectance of 83% at an incidence angle of 60°. The system is shown in figure 5.5.

![Figure 5.5: Photograph of wall integrated PV system from [3].](image)

The theoretic geometrical concentration ratio of the system is about 3.05, but the measurements have shown that the electrical power from the modules is only 1.9 times higher than the maximum electrical power from the system without concentrator. The fill factor drop has been due to ohmic losses in the front contact of the module and by high cell temperature resulting in a low open circuit voltage. Result shows that the effective solar height of 30° to 40° has been found to be optimal for this geometry, since the short circuit current was measured to be highest in that range.
5.2.2 Large bifacial photovoltaic-thermal MaReCo [5]

This is a large bifacial PV/T system, which is the development of the thermal MaReCo collector. MaReCo is short for maximum reflector collector using extremely low materials and is a patent product of Vattenfall Utveckling AB and Finsun Energy AB of Sweden. It consists of a vertical bifacial fin absorber in a long-east west trough. MaReCo is a heavily truncated asymmetrical combined parabolic concentrator (CPC) and has a concentrator ratio of 2.15. The acceptance angle is 22.5°. The system is a bifacial type where the photovoltaic cells are laminated on the front side of the absorber which is faced towards direct solar radiation. The back side is faced the upper reflector and it acting as a heat absorber. The reflector is made of aluminium sheet from Alanod, Germany and has a solar cell reflectance of 90% at 60° angle of incidence based on absorber area. The annual output from the system is estimated to be 800 kWh/m² of thermal energy and 200 kWh/ m² of electricity and the estimation was done using TRNSYS simulation. The designed have obtained this figure from a test for the Swedish climate on a standard version absorber that has a width of 143 mm and the glazing has a width of 630 mm.

5.2.3 The Älvkarleby PV/T CPC hybrid system [2]

The Älvkarleby PV/T hybrid prototype is a water cooled low concentrating compound parabolic concentrating (CPC) built at Vattenfall Utveckling AB, Älvkarleby, Sweden and is shown in figure 5.6. The concentrator trough is made of anodised aluminium and the solar cell is of conventional mono-crystalline silicon. The geometric concentration of the symmetric CPC is 4 and has an acceptance angle of 12°. The CPC is truncated to a height of 0.45 m and is extended 0.2 m on both sides of the PV module, in order to avoid end effects. The CPC is covered with a specially developed anti-reflection glazing to reduce heat losses and for the protection of module and reflector surface. The cogeneration of heat and electricity is increasing the total efficiency of the system. The yearly electrical and thermal output per square meter cell area is 250 kWh and 800 kWh respectively. The yearly electrical output of this prototype is double than that of conventional PV modules. The prototype developer has estimated that the electrical output could be increased by 20%, using optimised anti-reflective coatings and cells with low series resistance.
The chosen acceptance of the system requires the tilt angle adjustments for different time of a year for which a hydraulic system exists. To make the system simpler and to reduce cost, the developer has proposed to remove the hydraulic system for future commercial applications.

5.2.4 The combined heat and power system (CHAPS) [6]

Australian National University has developed CHAPS, which is a parabolic linear trough system that combines photovoltaic cells to generate electricity with thermal energy absorption to produce hot water. The cells are mono-crystalline silicon type with around 20% efficiency. They have developed two types of prototype. The first type is a domestic CHAPS with a 25x sun concentration system suitable for electricity generation and hot water for a home. This type has a laminated glass formed mirror rather than a glass-on-metal laminator (GOML) and water is carried by aluminium channel bonded to the cell tray. The other type is a 35x sun concentration single-axis tracking system, designed for installation on the roofs of commercial and light industrial buildings, to contribute to building heating, cooling and power requirements. The domestic CHAPS collector has a thermal efficiency of 50% and electrical efficiency upward of 10%.
5.2.5 (DSMTS) photovoltaic concentrator [21]

The Dielectric-Single Mirror Two Stage (DSMTS) photovoltaic concentrator is a design by Ruben Mohedano et al. at Polytechnical University of Madrid, Spain. The 30x sun concentration, DSMTS is a trough shaped photovoltaic concentrator which is designed to track the sun in single-axis. A dielectric and a mirror arrangement are placed near to the edge of reflector surface which has a photovoltaic array to allow the light to reach the target by total internal reflection. The main advantage of this shape is that the concentrators can be manufactured by simply bending aluminium. Test results have shown that the concentrator can achieve an acceptance angle of $\pm 1.63^\circ$ achieving an collection efficiency of 98% (at normal incidence) for a geometric concentration of 30 [13].

In addition, the aluminium concentrator surface has lowered the weight of the system to 24 Kg/m², which will lower the cost of materials including the cost of the supporting structure.

5.2.6 Single-Mirror Two-Stage (SMTS) collector [21]

The Single-Mirror Two-Stage (SMTS) photovoltaic concentrator is a design by Alarte, Benitez and Minano, at the Polytechnical University of Madrid, Spain. The concentrator has an acceptance angle of $\pm 1.5^\circ$, around 90% of the theoretical maximum corresponding to its concentration [21]. The high concentration-acceptance angle product has made the collector less sensitive to tracking or manufacturing errors, which will reducing the manufacturing cost. For cooling a heat sink is bonded on the back of the solar cell string which also acts as a part of the mechanical structure of the collector.

5.2.7 EUCLIDES project [16]

Under the European Joule program, Euclides project with a 480 kWp concentrator system has been built in Tenerife, Canary Islands. This system uses reflective troughs with a concentration of 32x and BP Solar laser-groove buried grid, 19% efficient silicon cells. It consists of 14 one-axis tracking reflective parabolic troughs each measuring 84 m in length. The reflector is of very light weight material using innovative space-frame design developed at the Polytechnical University of Madrid. The cooling of the PV cells is done by passive
cooling method employing heat sinks built of compression bonded, thin aluminium fins. The overall efficiency of the system is 13% and it is projected to produce power at half the cost of power from a crystalline flat-plate plant.

5.2.8 Issues

The heat produced by a PV system is important; data shows that a PV/T hybrid system can generate thermal energy which is 4 times the electrical energy. This is further strengthened by ANU’s CHAPS system which has achieved a thermal efficiency of 50% and electrical energy of 10% around. Concentrator optics play a crucial role in system performance, designs like DSTMS has achieved collection efficiency of 98% for a geometrical concentration of 30 [13]. The term “optical efficiency” is not fully defined in [13], but most probably they mean the percentage of rays incident on the aperture that actually hits the target or absorber. Weight of the system can play a crucial role in reducing the cost/Wp generated by the system. At present, DSMTS design has one of the lowest weight per aperture area which is 24 kg/m². Oxidation attack on the reflective material has been a limiting factor, this need a thorough understanding of the surface properties of the reflector material based on ageing tests. Accurate tracking system has been in use in concentrator systems but its reliability to last up to 20 years in outdoors climate needs to be considered. Its cost-effectiveness in small scale must be thoroughly studied.

5.3 Summary

PV/T hybrid system is a combination of a PV and a thermal system. Concentrator PV/T systems concentrate sun on to small cell areas by using relatively cheap materials reducing the cell cost. The technology has its challenges, such as cheap reflectors with optical accuracy, reliability and accuracy of the tracking devices, cooling of the solar cells. The major components of the prototype are the SMTS concentrator, solar cells, thermal receiver and the solar tracking mechanism. A novel design and cost cutting measures such as low weight aluminium components and microprocessors controlled solar trackers have been used to build the prototype. A wide range of PV/T systems have been designed and are operation in different parts of the world. The thermal energy achieved has been four times the electrical energy. Novel concentrator shapes such as DSMTS has achieved optical collection efficiency of up to 98%.
6. Measurement method and setup

The concentrator PV/Thermal hybrid prototype was tested in a series of outdoors field trials at Solar Energy Research Centre (SERC), Borlänge, Sweden to evaluate the optical, thermal and electrical efficiencies. The measurement methods and the instruments used during the experiments are described in the following sections.

6.1 Optical efficiency and concentration ratio

The efficiency of a concentrator solar energy system is highly dependent on the optical properties of the surface material and the concentrator profile. Therefore the optical performance of the concentrator surface was evaluated using different methods. The solar cells in the prototype are of exposed type since there is no anti reflector layer on top of the cell.

6.1.1 Optical efficiency

The optical efficiency of a solar cell in a concentrator system is evaluated by measuring the short-circuit currents, $I_{sc}$. Since the short circuit current is directly proportional to the irradiance on the solar cell string. The optical efficiency of the concentrating system is obtained by measuring short-circuit with and without concentration. The standard testing method for calculation is by measuring the short circuit current with corrections for the geometrical concentration ratio, $CR_g$, and the irradiation, $I$, and the relation is given by [5]

$$\eta_{opt} = \frac{I_{sc,measured}}{I_{sc,standard\_module}} \cdot \frac{I_{STC}}{CR_g \cdot I}$$ (6.1)

However, in the work, it was not possible to find the optical efficiency, $\eta_{opt}$ using equation (6.1). Since the manufacturer’s specification has short-circuit current value for a PV module with 4x36 cells under Standard Test Condition (STC). Out of the 144 cells in the original module, only 24 cells have been used by the prototype manufacturer to match the concentrator design with the required geometrical concentration ratio.
The optical efficiency of the concentrating system was obtained by measuring $I_{sc}$ of the solar cell string under solar concentration and it was compared to the measured value of $I_{sc}$ under one sun using following relation, which is simplified version of equation of (6.1) [5]

$$\eta_{opt} = \frac{I_{sc,with \_ \ concentrator}}{CR_{g,a} I_{sc,without \_ \ concentrator}}$$

(6.2)

To measure $I_{sc}$ under one sun, the cell string was connected to ampere-meter and an adjustable load. When the adjustable load resistance was set at the lowest value, the current was at the maximum and the voltage across the module approached zero. A digital pyranometer was used to measure the solar irradiance. The solar cell string and the pyranometer were put together on a board and were adjusted to a suitable tilts to read irradiance values of 500 W/m$^2$ and 1000$^2$ W/m. The measured $I_{sc}$ values at irradiance value of 500 and 1000 W/m$^2$ were 0.16 and 0.33 Amperes respectively, which shows that $I_{sc}$ is directly proportional to that of the total irradiance on falling on to the cell string.

### 6.1.2 Concentration ratio

A 21x micrologger, from Campbell Scientific Ltd, UK, was used for the evaluation of the concentration ratio of the prototype and the measurement was done manually. Custom made photodiode connections and a suitable resistance was added to the micrologger circuit. One photo diode was used to measure the irradiance under one sun as reference value and another was used to measure the under solar concentration and the multiplication factor gave the concentration ratio of the prototype. During measurements, both the photo diodes were positioned perpendicular to the incoming radiation. Its working principle is that short-circuit current in the micrologger circuit remains constant at a fixed point under constant irradiance (in a sunny and clear sky day) and the change is only in voltage. Measurements were taken at different points marked (39 points in three rows of the cell string) on the solar cell string to evaluate solar concentration. Likewise, measurements were taken outside the cell string area to estimate the amount of concentrated sunlight strayed outside of the cell string area due to the concentrator surface geometry.
A simple calorimetric experiment was also done to measure the concentration ratio. A transparent water vessel was kept in front of the solar cell target which obstructed the irradiation reaching the solar cell string. This increased the water temperature and the values were recorded at fixed interval of time. The heat gained by the water vessel during the test period was calculated and the value was compared to available beam irradiation data (from SERC monitoring station) during the time of the experiment. The multiplication factor of the two is the concentration ratio of the concentrator.

### 6.2 Current voltage measurement

Current and voltage were measured to find the electrical outputs and to calculate the electrical efficiency of the solar cell string of the prototype. A volt-meter, ampere-meter and an adjustable load was connected to the cell string. For measurement under one sun, the cell string was positioned perpendicular towards the sun and the variable load adjusted for current and voltage measurement. The maximum power point and the beam irradiance data was used to calculate the efficiency. The experimental set up is shown in figure 6.1.

![Figure 6.1: Current-voltage measurement circuit.](image)

Electrical efficiency under solar concentration was calculated using the following relation [5]

\[
\eta_{pv} = \frac{V_{mp} I_{mp}}{I_a A_s CR_{g,c}}
\]  

(6.3)

Where \( CR_{g,c} \) is the corrected concentration ratio (see chapter 5.1.5).
6.3 Thermal measurements

The thermal energy generated in the solar cell string is dissipated by a combination of heat transfer mechanisms. The heat loss mechanism is the same as in flat plate collectors, but the back losses are more important than in thermal collectors, since a PV/T system operating at higher temperature to collect more thermal energy will decrease the electrical output due to higher cell temperature.

The solar cell string in the prototype has a thermal energy receiver or an active cooling device on the back side and it was thermally insulated during the experiment to reduce heat losses. During the experiment, tap water was circulated to extract the heat generated in the solar cell string. The inlet water temperature and the outlet water temperatures were measured using a thermocouple module (80 TK Fluke). The test was done at two different inlet water temperature and the respective outlet water temperatures were measured. The steady state thermal efficiency, $\eta_{th}$ of the prototype is calculated by the relation

$$\eta_{th} = \frac{nC_p(T_o - T_i)}{A_a I} \quad (6.4)$$

where, $C_p$ is the heat capacity of water, $n$ is the flow rate, $T_i$ is the inlet water temperature and $T_o$ is the outlet water temperature, $I$ is the beam solar irradiance and $A_a$ is the half aperture area.

6.4 Summary

The prototype was tested outdoors at SERC, Borlänge. The optical efficiency was evaluated using the short-circuit current method. A simple calorimetric method was used to measure the concentration ratio. A micrologger and a customized circuit measured its circuit reference voltage under one sun and the voltage under solar concentration, the multiplication factor was the concentrator ratio of the concentrator. The electrical efficiency was evaluated by measuring the current and voltage by adjusting the variable resistor and the experimental set up consisted of an ampere-meter, volt-meter and a variable resistor. Water as a heat transfer fluid was circulated on the thermal receiver of the system and the inlet an outlet water temperatures were measured to calculate the thermal efficiency of the prototype.
7. Experiments, observations and measurements

The tests were done between May 18 and 28, 2004 at SERC, Borlänge situated at latitude 60.29°N and longitude 15.25°E. The approximate SMTS concentrator is horizontally symmetrical and is two cell strings for one reflector concentrator, where half of the mirror works as a first stage for one cell string and as a second stage for another cell string. Therefore this system can even work with only one cell string with half the output and the prototype manufacturer has also supplied one cell string. All calculations are based on the performance of the upper half of the concentrator aperture. The prototype is a single-axis horizontal tracking system and for gaining optimal irradiation for long duration tests, the concentrator was manually positioned towards the sun at some interval of time. The concentrating receivers have a small acceptance angle and do not deal with diffuse light. Therefore beam irradiation data from SERC weather station was used for calculations, but the beam irradiation data seems to be high because these are the values obtained during intermittent sunshine period.

7.1 Optical efficiency and concentration ratio

7.1.1 Optical efficiency

The optical efficiency of the SMTS concentrator was obtained by measuring the short-circuit currents both under one sun and under solar concentration and the values are 0.33 A and 1.92 A respectively. The geometrical concentration ratio is said to be 20 by the prototype manufacturer, but the actual geometrical concentration ratio $CR_{g,a}$ is 17.7 (see chapter 5.1.5). The optical efficiency of the concentrator prototype was calculated using equation (6.2)

$$\eta_{opt} = \frac{I_{sc,with \_ concentrator}}{CR_{g,a} I_{sc,without \_ concentrator}} = \frac{1.92}{17.7 \times 0.33} = 0.33$$

7.1.2 Optical concentration ratio

The optical concentration ratio was measured using the micrologger and a customized circuit described in chapter (6.1.2). The cell string under concentration is shown in figure 7.1.
Measurements were taken at top, bottom and middle points of the solar cell string. Measurements were also taken 5 cm and 10 cm above the cell string to estimate rays strayed outside of the cell string area. The data are given in Table 1 and the concentration ratios at different points are plotted in figure 7.2. The obtained values were compared with the reference value to find the concentration ratio. The table shows a large variation in concentration ratio of the solar cell string at different points and its value ranged between 11 and 5.6.

![Figure 7.1: Photograph of cell string under solar concentration.](image)

**Table 1:** Concentration ratio at different points of the solar string under concentration.

<table>
<thead>
<tr>
<th>Date: 21-05-2004</th>
<th>Time: 11:35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insolation</td>
<td>1045 W/m²</td>
</tr>
<tr>
<td>Reference</td>
<td>15 mV</td>
</tr>
<tr>
<td>Air temperature</td>
<td>13.2 °C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Measurement mV</th>
<th>Distance (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Reading (top)</td>
<td>135</td>
</tr>
<tr>
<td>Reading (centre)</td>
<td>123</td>
</tr>
<tr>
<td>Reading (bottom)</td>
<td>130</td>
</tr>
<tr>
<td>Reading (5 cm above)</td>
<td>43</td>
</tr>
<tr>
<td>Reading (10 cm above)</td>
<td>11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Concentration ratio</th>
<th>Distance (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Reading (top)</td>
<td>9</td>
</tr>
<tr>
<td>Reading (centre)</td>
<td>8.2</td>
</tr>
<tr>
<td>Reading</td>
<td>8.7</td>
</tr>
</tbody>
</table>
Similarly, four random points were selected and measurements were taken from bottom end of the cell string up to 150 mm, at an interval of 5 mm. The obtained values were compared with the reference value to find the concentration ratio. The concentration ratio value was then averaged for equal distances to evaluate the performance of the concentrator and is plotted in figure 7.3.

**Figure 7.2:** Concentration ratio measured at different points on the solar cell string.
The shaded area $A_1$ shows the area within the cell string, and the other areas $A_2$, $A_3$, $A_4$, shows the area outside the cell string. The percentage of light that is falling on the cell is calculated using the following

$$\% = \frac{A_1}{A_1 + A_2 + A_3 + A_4} = \frac{48 \times 6.8}{(6.8 \times 48) + (4.2 \times 22) + (2.3 \times 25) + (1.3 \times 55)} = \frac{326.4}{547.8} = 0.6$$

The result shows that 60% of the light is falling within the cell area having a cell with of 48 mm, while the remaining 40% light is strayed between 48 and 150 mm.

The optical concentration ratio was also estimated by a basic calorimetric experiment. A transparent water vessel filled with water was put in front of the concentrator’s solar cell string. The heat gained by water was measured by recording the rise in water temperature. The amount of irradiance intercepted by the water vessel area was estimated by calculating the heat gained by the water. The measured values are presented in Table 2 and the rise in temperature is shown in figure 7.4.

**Table 2:** Concentration ratio by calorimetric method.

<table>
<thead>
<tr>
<th>Date: 21-05-2004</th>
<th>Units</th>
<th>Time (second)</th>
<th>Temp. of water ($T_w$) $^\circ$C</th>
<th>Beam radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time:11:30</td>
<td></td>
<td>0</td>
<td>18</td>
<td>1001</td>
</tr>
<tr>
<td>Irradiance</td>
<td>1033  $\text{W/m}^2$</td>
<td>60</td>
<td>19.2</td>
<td>1006</td>
</tr>
</tbody>
</table>
The irradiance under solar concentration is 6.49 times the beam irradiance data under one sun. The reason for the lower value from this test is due to the lower concentration ratio at that particular area (where the water vessel was put) and heat loss from the vessel. This is a basic experiment to estimate the concentration ratio and this value has not been used for any further data analysis.

### 7.2 Electrical efficiency

The current-voltage characteristics of the solar cell string under both under one sun and under solar concentration were measured using a set up described in chapter (6.2). For calculations,
beam irradiation data was used and the value is taken as an average for the time duration during which the tests was done. During the test period, out of the 24 solar cells, 5 cells were damaged and the broken cell parts were bypassed by soldering with wires. The total solar cell string area after subtracting the bypassed area is 0.025 m$^2$ and this solar cell area has been taken calculations. These tests were done with water circulation in the thermal receiver.

The current $I_{mp}$, and voltage, $V_{mp}$, at maximum power point of the solar cell string was found from $I$-$V$ curve shown in figure 7.5.

Under one sun condition $I_{mp}$ is 0.29 A and $V_{mp}$ values is 10.92 V, and the maximum power point is 3.17 W. Equation (3.3) has been used to calculate the fill factor

$$\text{Fill Factor (FF)} = \frac{V_{mp} \cdot I_{mp}}{V_{oc} \cdot I_{sc}} = \frac{10.92 \times 0.29}{12.91 \times 0.33} = 0.743$$

The electrical efficiency of the cell was calculated using equation (3.5)

$$\eta_{pv} = \frac{V_{mp} \cdot I_{mp}}{I.A_{d}} = \frac{10.92 \times 0.29}{949 \times 0.025} = 0.133$$

The electrical efficiency of the cell string under one sun condition is 13.3%. The beam irradiation data has been averaged for the duration in which the measurements were taken.

**Figure 7.5:** Current-voltage characteristics of cell string under normal and concentrated irradiance.
Similarly under solar concentration $I_{mp}$ and $V_{mp}$ values are 1.7 A and 10.95 V respectively and the maximum power point is 18.6 W. Equation (3.3) has been used to calculate the fill factor

$$\text{Fill Factor (FF)} = \frac{V_{mp} \cdot I_{mp}}{V_{oc} \cdot I_{sc}} = \frac{10.95 \times 1.7}{13.11 \times 1.92} = 0.739$$

Equation (6.3) is used for calculating the efficiency of the solar cell string under solar concentration.

$$\eta_{pv} = \frac{V_{mp} \cdot I_{mp}}{I_{A_g} \cdot CR_g} = \frac{10.95 \times 1.7}{949 \times 0.025 \times 5.6} = 0.14$$

Here, $CR_g$ is the concentration ratio obtained from actual measurement from the above test.

The electrical efficiency of the cell string under solar concentration is 14%. This calculation is done with the concentration ratio of 5.6 from chapter (7.1.2). The value has been taken, since the point with the lowest concentration ratio will allow current that is proportional to the irradiance at the point. This has been done to compare the electrical efficiency of the cell under both one sun and under solar concentration.

The corrected geometrical concentration ratio of the prototype is 17.1 from chapter (5.1.5), considering this value the electrical efficiency has also been calculated as following

$$\eta_{pv} = \frac{V_{mp} \cdot I_{mp}}{I_{A_g} \cdot CR_g \cdot c} = \frac{10.95 \times 1.7}{949 \times 0.025 \times 17.1} = 0.046$$

The electrical efficiency of the prototype is 4.6%.

### 7.3 Thermal efficiency

This test has been done for a basic understanding of the thermal performance of the prototype. After nearly one week of waiting for clear sunshine, the sun appeared for a less than an hour and the tests were carried out during that time. Tap water was circulated in the thermal
receiver on the back side of the solar cell string. The thermal efficiency, \( \eta \), of the prototype is calculated by using equation (6.4), where the concentrator aperture area, which is one half of the total aperture area, is 0.6 m and the beam irradiance values were assumed to be 90% of the total irradiance. The thermal receiver on the back side of the cell string was insulated with as 15 mm thick glass wool. The thermal performance of the prototype is shown in figure 7.6. The water inlet and outlet water temperatures were measured using a thermocouple module. At a flow rate of 0.1 litres per minute at irradiance of 790 W/m\(^2\) with the water inlet temperature of 11.1 °C, the average thermal efficiency is 14%. The ambient temperature was 12.3 °C during the test and the hot water reached to a maximum temperature of 23.2 °C.

![Figure 7.6: Thermal performance of prototype](image)

Likewise, a similar test was done with a flow rate of 0.18 litres per minute at irradiance of 805 W/m\(^2\) with the inlet water temperature of 11.1 °C and the average thermal efficiency is 16%. The hot water reached a maximum temperature of 19.1 °C.
8. Experimental results

8.1 Optical efficiency

The measured optical efficiency of the SMTS concentrator prototype is 33% and the remaining 67% is the optical losses in the prototype’s SMTS concentrator. The obtained value is low compared to a theoretical maximum optical efficiency of 90% for SMTS designs [21]. The large difference in the values is largely due to the imperfect concentrator surface geometry. The result of the concentration ratio measurement also shows that there is a large variation in values within the solar cell string ranging from 11 to 5.6. Measurements taken at points outside the cell string showed that a considerable amount of the concentrated light is straying outside the target.

8.2 Electrical efficiency

The efficiency of the solar cell string under one sun is 13.3%. Under solar concentration the same cell string has an efficiency of 14% and this value is obtained using the lowest concentration ratio, 5.6, from the concentration ratio test. The test was done with cold water circulation on the thermal receiver, due to which the solar cell temperature should not have increased to more than 25 °C.

The actual electrical efficiency of the prototype is 4.6% and this value is obtained using the corrected geometrical concentration ratio of 17.1.

The solar cell manufacturer’s specification has stated an electrical efficiency of 17 % under standard test condition (STC). The short circuit current for the (for a 36x4) module was stated to be 19.2 A and this seems to be quite large compared to the prototype’s cell string (with 24 cell) which measured a value of 0.33 A under one sun and 1.92 A under concentration sun. One of the reasons for lower short-circuit current is due to 24 solar cells in the string connected in series.
8.3 Thermal efficiency

This test was done for the basic understanding of the thermal performance of the prototype. The average thermal efficiency was 14\% at a water flow rate of 0.1 litres per minute and the hot water reached a maximum temperature of 23.2 °C. For a similar test the average thermal efficiency was 16\% at a water flow rate of 0.18 litres per minute. The hot water reached a maximum temperature of 19.1 °C. If the average of the two values is taken the thermal efficiency of the system is 15\%. The thermal receiver was fully insulated with a 15 mm glass wool; still the outlet water temperature was difficult to measure because the temperature reading was fluctuating due to the small rise in temperature. The test should have been done with the more accuracy using a calorimetric experimental set-up which measures the total system energy uptake based on storage tank temperature readings.
9. Discussion and conclusions

Solar cells under concentrated sunlight have several advantages. The main reason of using high concentrator surfaces is to significantly reduce the cost of electricity, provided low cost concentrator can be built. The increase in cell temperature demands cooling and if the thermal energy is utilized, the photovoltaic-thermal cogeneration system can be a cost-effective solution. The disadvantages of concentration system are that all practical systems have optical losses and series resistance in cell string causes a decrease in electrical output. Due to the negative temperature coefficient of solar cells, high cell temperature will decrease the electrical output of the system. The temperature effect can be reduced by cooling of solar cells, which can be done by several methods, but previous studies [15] indicates that active water cooling is the most effective method for low-concentrating line-focusing systems. A detail test has to be done to investigate for high concentration line focusing concentrators such as SMTS.

The optical efficiency of the system is 33% which is not satisfactory compared to a SMTS which has achieved around 90% theoretical maximum corresponding to its concentration [21]. Due to this, the solar cell efficiency under concentration has dropped from 14% to 4.6% and the thermal efficiency is about 15%. The low optical efficiency has caused the reduction of both electrical and thermal efficiency by the same proportion. Figure 7.3 shows the average concentration ratio across 4 different points of the solar cell string. From this we can estimate the amount of light falling inside and outside the cell area and the result shows that 60% of the light is falling inside the solar cell string area. The total reflectance of the reflector surface is 0.92 according to the manufacturer, but in practice this value will be less due to dust and dirt and the value is assumed to be 0.85 considering the losses. Figure 7.2 shows the uneven illumination on the solar cells and the related table 1, gives the lowest concentration ratio of 5.6 and a mean concentration ratio of 7.9 for the solar cell string area. Considering the mean concentration value of 7.9 and the cell with the lowest illumination (one of the darkest cell on figure 7.1) has a mean illumination of 5.6, the reduction in efficiency due to uneven illumination is the ratio of the two which is equal to 0.71. Therefore the overall reduction in efficiency is 0.36 which is the product of light falling on to the receiver (0.6), the limited reflectance due to dust and dirt (assumed 0.85) and the reduction of efficiency due to uneven illumination (0.71). The value obtained is close to the optical efficiency of the concentrator...
surface which is equal to 0.33. From this we can come to a conclusion the low optical efficiency is due to mismatches in the surface geometry, imperfect overall reflector profile and uneven illumination.

The electrical efficiency of the prototype is 4.6 % and the main reason has been mainly due to the effects of large variation in illumination on to the solar cell string due to imperfect concentrator surface geometry. The characteristics for series connected cells are that the cell with the lowest output dictates the output of the cell string. Therefore, the solar cell string performance is limited by the performance of lowly illuminated cell. This implies that, for a line focus system such as SMTS, all cells in a solar cell string should not be connected in series, as was done in the prototype.

The electrical efficiency of the cell string under one sun and under concentration are 13.3% and 14% respectively. At higher concentration the cell short-circuit current increases linearly with concentration while $V_{oc}$ increase slightly under concentration, giving a net solar cell efficiency increase. On the other hand, at higher concentration, the cell reaches higher temperature, which reduced the output voltage. The result shows that the difference in efficiency is marginal because the tests were done without water circulation on the thermal receiver. Had the cell been cooled the efficiency at higher concentration would have increased to a larger extent.

The prototype manufacturer has used graphical ray tracing methods to design the concentrator surface. However, for surfaces, other than conic sections, like SMTS, the surface interaction of the incident rays at two or more points makes ray tracing a computationally intensive process and often the surfaces are far away from ideal surface. Commercially available optical softwares have been used in designing high accuracy surfaces such as head light reflectors of cars. These can also be used in designing solar concentrator reflectors. In addition, the output data files from these softwares are compatible with computer aided manufacturing softwares which will help in manufacturing surfaces with higher accuracy. At present, computer aided manufacturing would not be economical for making solar concentrators. A low cost manufacturing method with higher accuracy has been developed [13]. Using this method, a dielectric single-mirror two-stage (DSMTS) concentrator has been manufactured by simply bending reflector sheets. This can also be applied for manufacturing SMTS concentrators.
The concentrator surface plays a major role in the overall performance of a concentrator PV/T hybrid system. In a concentrator PV/T system with a concentration of 25, an electrical efficiency of more than 10% and a thermal efficiency of around 50% have been achieved [6]. High accuracy concentrator surfaces, low cost high reflective concentrator material, simple tracking devices and a thermal receiver in combination with a simple manufacturing method will help reduce the cost of solar electricity.
10. Suggestions for future work

This work has been done to evaluate the performance of the prototype. The results may not be exact, since the system has a much more dynamic performance than the steady state analysis that has been done. Each components dynamic behaviour need to be modelled. An analytical model for the PV/T prototype has to be developed. This would be best achieved using computer modelling and simulation softwares would facilitate this type of analysis. The simulation results then need to be compared to the experimental data.

Ray-tracing using optical softwares will facilitate to design synthetic concentrator surfaces like SMTS. Ray-tracing followed by mechanical calculations using small and large displacement theories for sheet metal bending needs to be done to make trough shaped concentration manufacturing cost-effective and to achieve higher surface accuracy.
### List of Symbols and Abbreviations

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ac</td>
<td>Alternating current</td>
</tr>
<tr>
<td>$A_a$</td>
<td>Aperture area</td>
</tr>
<tr>
<td>$A_r$</td>
<td>Area of the concentrator receiver</td>
</tr>
<tr>
<td>$AM$</td>
<td>Air mass</td>
</tr>
<tr>
<td>$AR$</td>
<td>Anti-reflective coating</td>
</tr>
<tr>
<td>BOS</td>
<td>Balance of system components</td>
</tr>
<tr>
<td>c-Si</td>
<td>Crystalline silicon</td>
</tr>
<tr>
<td>$C$</td>
<td>Concentration ratio</td>
</tr>
<tr>
<td>$CR_g$</td>
<td>Geometric concentration ratio</td>
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<tr>
<td>$CR_o$</td>
<td>Optical concentration ratio</td>
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<td>CIvG</td>
<td>Copper-indium-gallium-diselenide</td>
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<td>Direct current</td>
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<td>$E_g$</td>
<td>Band gap (eV)</td>
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<td>$FF$</td>
<td>Fill factor (%)</td>
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<tr>
<td>$G_{sc}$</td>
<td>Solar constant (1376 W/m$^2$)</td>
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<tr>
<td>DSMTS</td>
<td>Dielectric single-mirror two-stage</td>
</tr>
<tr>
<td>h</td>
<td>Plank’s constant</td>
</tr>
<tr>
<td>$I$</td>
<td>Irradiance (W/m$^2$)</td>
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<tr>
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<td>$I_{sc}$</td>
<td>Short-circuit current (A)</td>
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<td>$I_{MP}$</td>
<td>Current at maximum power point (A)</td>
</tr>
<tr>
<td>k</td>
<td>Boltzmann’s constant</td>
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<tr>
<td>$\nu h$</td>
<td>Flow rate</td>
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<td>Maximum power point</td>
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<tr>
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<td>Ideality factor</td>
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<tr>
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<td>poly-crystalline silicon</td>
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<td>$P_{max}$</td>
<td>Power maximum (W)</td>
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<td>PV/T</td>
<td>Photovoltaic-thermal</td>
</tr>
<tr>
<td>q</td>
<td>Absolute value of electric charge</td>
</tr>
</tbody>
</table>
$R_s$  Series resistance  \\
$R_{sh}$  Shunt resistance  \\
STC  Standard Test Condition  \\
SMTS  Single-mirror two-stage  \\
$T_i$  Temperature inlet  \\
$T_o$  Temperature outlet  \\
V  Voltage (V)  \\
$V_{mp}$  Voltage at maximum power point (V)  \\
$V_{oc}$  Voltage open circuit (V)  \\
$W_p$  Peak watt, the nominal power of a cell or PV system, measured at STC

**Greek letters**

- $\text{Si}$  Amorphous silicon  \\
- $\lambda$  Wavelength (nm or $\mu$m)  \\
- $\eta$  Efficiency  \\
- $\eta_{op}$  Cell efficiency under concentrated light  \\
- $\eta_{pv}$  Solar cell conversion efficiency  \\
- $\eta_{oh}$  Optical efficiency  \\
$\sigma$  Stefan-Boltzmann’s constant  \\
$\theta_v$  Half acceptance angle  \\
$\zeta$  Solar zenith angle  \\
- $\alpha$  Angle of incidence
**Appendix 1:** Manufacturer’s specification of PV module.

<table>
<thead>
<tr>
<th>Characteristics of a PV module</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PV module:</strong> MILLENNIUM ELECTRIC, MULTISOLAR, Manufacturer</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>STC power (manufacturer)</th>
<th>PNom</th>
<th>300 Wc</th>
<th>Technology</th>
<th>Si-mono</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module size (W x L)</td>
<td>0.117 x 0.229 m²</td>
<td>4 x 36</td>
<td>Rough module area</td>
<td>Amodule 0.03 m²</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specifications for the model (manufacturer or measurement data)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature reference cond. Tref 25 °C</td>
</tr>
<tr>
<td>Open circuit voltage Voc 21.8 V</td>
</tr>
<tr>
<td>Maximum power point voltage Vmpp 17.4 V</td>
</tr>
<tr>
<td>=&gt; maximum power Pmpp 306.2 W</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>One-diode model parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shunt resistance Rsh 100 ohm</td>
</tr>
<tr>
<td>Series resistance Rs 0.09 ohm</td>
</tr>
<tr>
<td>Diode quality factor Gamma 1.20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Special parameters for use in behaviour of PV arrays under partial shadings or mismatch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverse characteristics (darkness) Arev 3.20 mA/V² (quadratic factor, per cell)</td>
</tr>
<tr>
<td>Number of by-pass diodes per module 1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model results for standard conditions (STC: T=25°C, G=1000 W/m², AM=1.5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum power point voltage Vmpp 17.2 V</td>
</tr>
<tr>
<td>Maximum power Pmpp 306.5 Wc</td>
</tr>
<tr>
<td>Efficiency (/ module area) Eff_mod 114.3 %</td>
</tr>
<tr>
<td>Efficiency (/ cells area) Eff_cells 17.0 %</td>
</tr>
</tbody>
</table>
References


