OPERATION OF TWO-AXIS SOLAR TRACKING BY THE DISCHARGE OF WATER FROM A TANK HANGING BY A NON-CIRCULAR SPROCKET WHEEL

Master of Engineering in Manufacturing Systems Engineering

by

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A dissertation submitted to the Department of Mechanical Engineering, University of Moratuwa in partial fulfillment of the requirements for the Degree of Master of Engineering in Manufacturing Systems Engineering

by

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August 2009

DECLARATION

This Dissertation paper contains no material which has been accepted for the award of any other degree or diploma in any University or equivalent institution in Sri Lanka or abroad, and that to the best of my knowledge and belief, contains no material previously published or written by any other person, except where due reference is made in the text of this Dissertation.

I carried out the work described in this Dissertation under the supervision of Dr. G. K. Watugala & Dr. W. K. Wimalasiri.

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Abstract

Two-axis solar tracking system operated by the discharge of water from a bottom hole of a tank filled with water was designed, constructed and tested. The water tank is hanged by a chain passing over a non-circular sprocket wheel which is fixed to the rotating shaft along the first solar tracking axis. A counterweight is also hanged by another chain passing over a regular circular sprocket. In the morning, the tank is full and the water tank and the counterweight on either side of the shaft balance in such a way that the solar panel is facing the East as required. This study shows that the contour of the non-circular sprocket wheel can be designed taking into consideration the reduction of weight of water tank with time and the required rotation for solar tracking. In addition to the hourly tracking by the above mechanism, provision has been made to tilt the second tracking axis of the solar panel manually on a weekly basis to compensate for the seasonal variation of the Sun's declination.

Results show that the additional cost involved in making this mechanism is justifiable when considering the increase of about 30% of more solar power obtainable by two-axis tracking.

The paper published regarding this tracking system at Sri Lanka Association for the Advancement of Science (SLAAS) in 64th Annual Sessions held on 01-06 December 2008 shown in Appendix A.

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CHAPTER 01 – INTRODUCTION

It is well known that single-axis tracking can increase the output of solar panels especially on cloudy days with couple of hours of sunshine in the morning or afternoon and not at midday. In some rural villages of Sri Lanka, the national grid is not available and solar panels are being increasingly used. Consequently, and any low-technology manageable by the villagers to do tracking and increase the total output of solar panels will improve the return from the big investment for the solar panel. The high capital cost of solar panels is a big drawback in popularizing this proven technology in these areas. To improve the return on investment, the output from the solar panel should be increased. Describe below is an open-loop control system for solar tracking which is more dependable and cheap[6]. Because (a) the movements of the Sun can be predictable and (b) even less precise tracking can increase the solar panel output, the use of open-loop method is acceptable. The increase of 30%-40% of output due to tracking reported Stine & Geyer [1].

1.1. Why solar technology

Solar technology is not novel for us. The history of solar technology spans from the 7th Century B.C. to today [5]. We started out concentrating the sun's heat with glass and mirrors to light fires. Today, we have everything from solar-powered buildings to solar- powered vehicles. Since Sri Lanka situated near the equator we have good solar radiant all over the year.

Use of Solar energy has good economic payoffs. Many of solar projects have simple payback periods for less than 3 years. Building a solar project saves us the natural fuel resource for the future. Households consume a large part of the energy production. Solar projects to reduce energy consumption have a significant beneficial effect on fossil fuel emissions. This is something that our great-grandparents understood, but we have lost over the last century of extreme dependence on fossil fuels. Being at the mercy of (or in the center of) Middle East turmoil, and paying out money for foreign oil is not wealth.

1.2. Why Need Tracking?

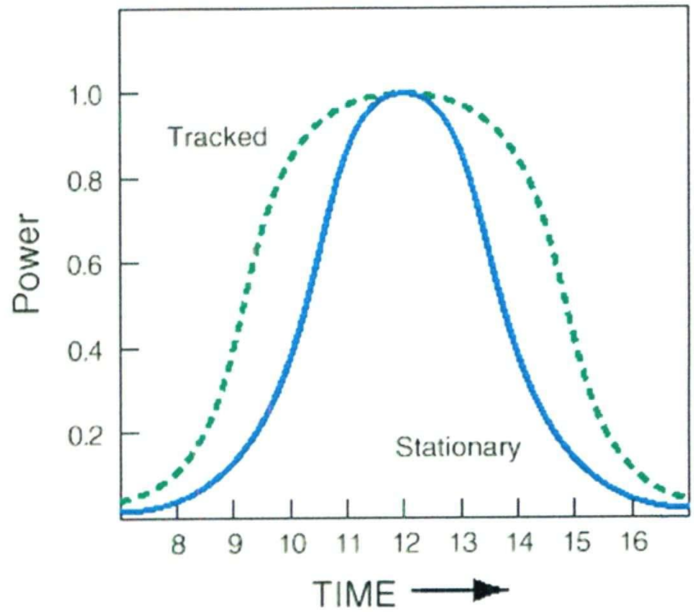


Fig.1.1 Graph showing power output for tracked and non tracked array.

source: Murdoch University research centre

Solar energy devices work most efficiently, when they are oriented favorably, based on their geometry, to the incoming solar rays [6]. For a flat plate, this orientation is optimum when the rays are perpendicular to the plate (see fig 1.1). Since the position of the sun is continually changing, the receiving surface must also be continually reoriented to maintain the optimal orientation condition.

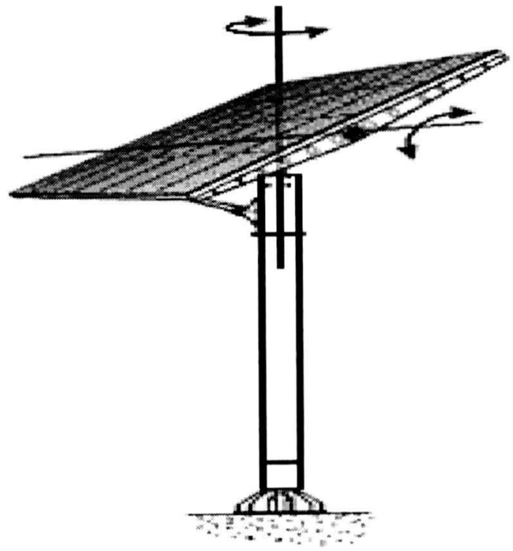


Fig. 1.2 Two axis tracking system
source: University of Strathclyde

Solar tracking has been a very popular area of research and there are large numbers of publications. Previous research can be classified as (a) Active tracking and (b) Passive tracking [3]. Depending on whether an external devices is actively involved in calculating the moving parameters and activating the tracking mechanism or not. Similarly, previous research work can be classified according to (a) One-axis tracking and (b) Two-axis tracking (see fig 1.2). [6]

1.3 . Objectives

The main objectives of my research project to Design, Construct and Test a low cost passive solar tracking mechanism, which can be simply constructed and operated. The purpose of this project is to overcome the bottleneck of prevailing tracking systems as requires frequent inspection, maintenance and adjustments to achieve maximum efficiency. Therefore, it is evidential to construct a low cost hybrid solar tracking system to overcome the drawbacks of existing both active and passive trackers.

CHAPTER 02 - LITERATURE REVIEW

2.1. Solar power

The energy supply from the sun is truly enormous: on average, the earth's surface receives about $1.2*10^{17}$W of solar power [7]. This means that less than one hour enough energy is supplied to the earth to satisfy the entire energy demand of the human population over the whole year. Indeed, it the energy of sunlight assimilated by biological organisms over millions of years that have made possible the industrial growth as we know. Most of the other renewable means of power generation also depend on the sun as the primary source: hydroelectric, wind and wave power all have the same origin. Solar cells did not have to wait long to find application. The year 1958 witnessed the launch of Vanguard, the first satellite to use electricity from the sun. The technology has been developing ever since. Much interest in solar electricity appeared particularly in the wake of the oil crisis in the early seventies. Today, the direct conversion of light into electricity, or photovoltaic, is becoming accepted as an important form of power generation.

Photovoltaic power generation is reliable, involve no moving parts, and the operation and maintenance costs are very law. The operation of a photovoltaic system is silent, and creates no atmospheric pollution. Photovoltaic systems are modular, and can be quickly installed. Power can be generated where it is required without the need for transmission lines.

Solar electricity suffers one major drawback at present, and that is the high capital cost of photovoltaic installation. Nevertheless, as the production volume continues to grow and research brings in new developments, the impact of photovoltaic in power generation is set to increase at a rapid rate.

At present not only in Sri Lanka but also in entire world there is a power crisis. Due to that, now world is becoming to use renewable energy sources instead of non-renewable energy sources. This is a good trend in the energy sector in the world. Therefore experiments and projects associated with renewable energy sources are very essential.

2.1.1. What are Solar Cells?

Solar cells are devices which convert solar energy directly into electricity, either directly via the photovoltaic effect, or indirectly by first converting the solar energy to heat or chemical energy.

The most common form of solar cells are based on the photovoltaic (PV) effect in which light falling on a two-layer semi-conductor device produces a photo-voltage or potential difference between the layers. This voltage is capable of driving a current through an external circuit and thereby producing useful work.

2.1.2. The Origins of Solar Cells

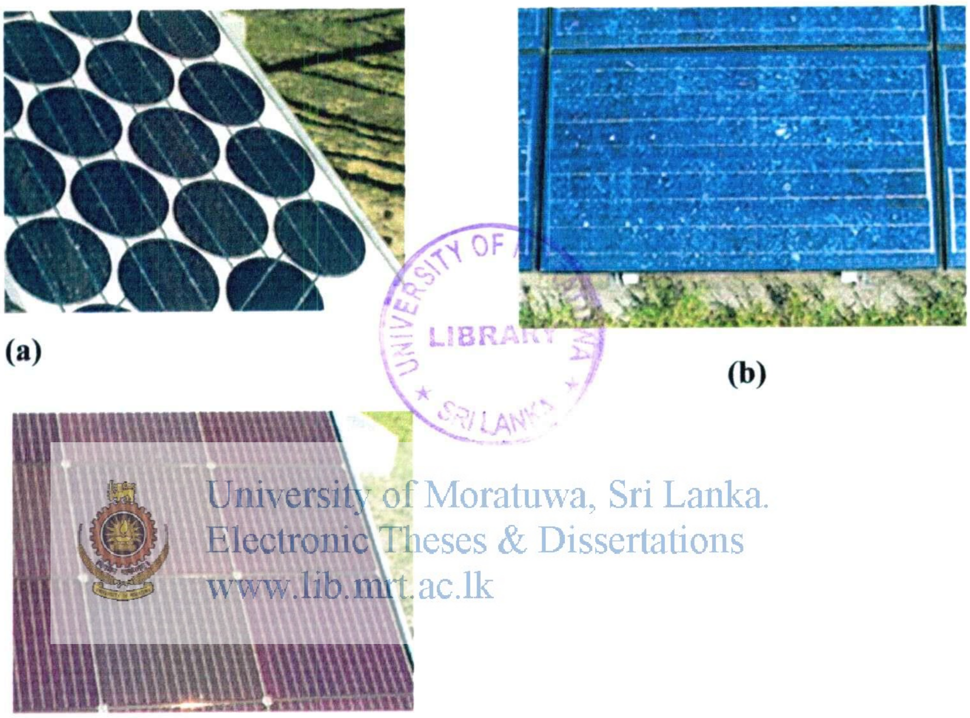
Although practical solar cells have only been available since the mid 1950s, scientific investigation of the photovoltaic effect started in 1839, when the French scientist, Henri Becquerel discovered that an electric current could be produced by shining a light onto certain chemical solutions.

The effect was first observed in a solid material (in this case the metal selenium) in 1877 [2]. This material was used for many years for light meters, which only required very small amounts of power. A deeper understanding of the scientific principles, provided by Einstein in 1905 and Schottky in 1930, was required before efficient solar cells could be made. A silicon solar cell which converted 6% of sunlight falling onto it into electricity was developed by Chapin, Pearson and Fuller in 1954, and this kind of cell was used in specialized applications such as orbiting space satellites from 1958.

Today's commercially available silicon solar cells have efficiencies of about 18% of the sunlight falling on to them into electricity, at a fraction of the price of thirty years ago. There is now a variety of methods for the practical production of silicon solar cells (amorphous, single crystal, polycrystalline), as well as solar cells made from other materials (copper indium dieseline, cadmium telluride, etc).

2.1.3. How are Solar Cells made?

Silicon solar cells are made using single crystal wafers, polycrystalline wafers or thin films[2]. Single crystal wafers are sliced, (approx. 1/3 to 1/2 of a millimeter thick), from a large single crystal ingot which has been grown at around 1400 °C, which is a very expensive process. The silicon must be of a very high purity and have a near perfect crystal structure (see figure 2.1 (a)).



(a) (b)

(c)

Fig. 2.1 Different types of Silicon solar cells

Source: The Australian Institute of Energy

Polycrystalline wafers are made by a casting process in which molten silicon is poured into a mould and allowed to set. Then it is sliced into wafers (see figure 2.1 (b)). As polycrystalline wafers are made by casting they are significantly cheaper to produce, but not as efficient as monocrystalline cells. The lower efficiency is due to imperfections in the crystal structure resulting from the casting process. Almost half the silicon is lost as saw dust in the two processes mentioned above.

Amorphous silicon, one of the thin film technologies, is made by depositing silicon onto a glass substrate from a reactive gas such as silane (SiH_4) (see figure 2.1 (c)). Amorphous silicon is one of a number of thin film technologies. This type of solar cell can be applied as a film to low cost substrates such as glass or plastic. Other thin film technologies include thin multicrystalline silicon, copper indium dieseline/cadmium sulphide cells, cadmium telluride/cadmium sulphide cells and gallium arsenide cells.

There are many advantages of thin film cells including easier deposition and assembly, the ability to be deposited on inexpensive substrates or building materials, the ease of mass production, and the high suitability to large applications [3].

In solar cell production the silicon has dopant atoms introduced to create a p-type and an n-type region and thereby producing a p-n junction. This doping can be done by high temperature diffusion, where the wafers are placed in a furnace with the dopant introduced as a vapour. There are many other methods of doping silicon. In the manufacture of some thin film devices the introduction of dopants can occur during the deposition of the films or layers.

A silicon atom has 4 relatively weakly bound (valence) electrons, which bond to adjacent atoms. Replacing a silicon atom with an atom that has either 3 or 5 valence electrons will therefore produce either a space with no electron (a hole) or one spare electron that can move more freely than the others, this is the basis of doping. P-type doping, the creation of excess holes, is achieved by the incorporation into the silicon of atoms with 3 valence electrons, most often boron and n-type doping, the creation of extra electrons is achieved by incorporating an atom with 5 valence electrons, most often phosphorus (see figure 2.2).

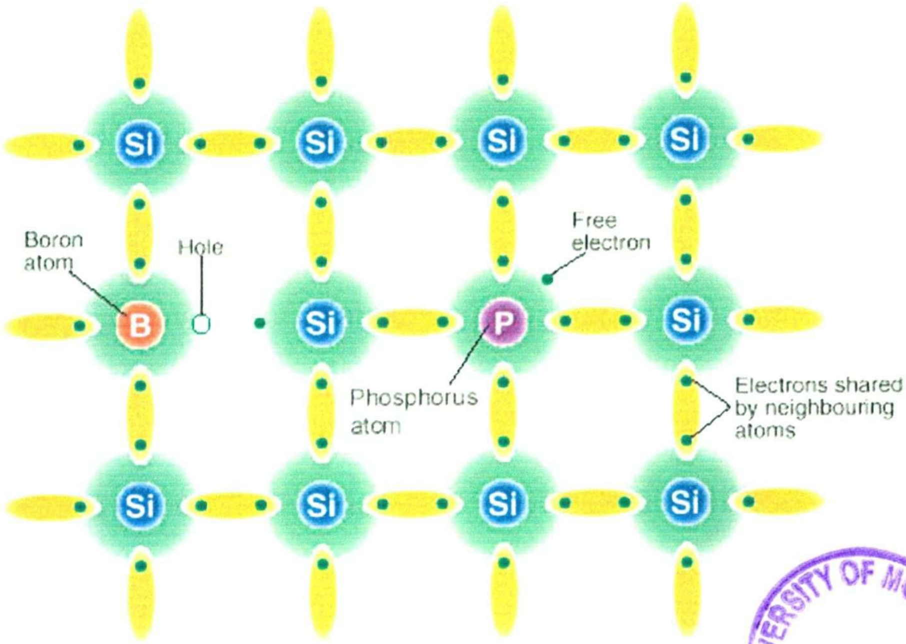


Fig. 2.2 Silicon Crystal Lattice with Dopant Atoms.

Source : University of Strathclyde

Once a p-n junction is created, electrical contacts are made to the front and the back of the cell by evaporating or screen-printing metal on to the wafer. The rear of the wafer can be completely covered by metal, but the front only has a grid pattern or thin lines of metal otherwise the metal would block out the sun from the silicon and there would not be any output from the incident photons of light.

2.1.4. How do Solar Cells Work?

To understand the operation of a PV cell, we need to consider both the nature of the material and the nature of sunlight. Solar cells consist of two types of material, often p-type silicon and n-type silicon. Light of certain wavelengths is able to ionize the atoms in the silicon and the internal field produced by the junction separates some of the positive charges ("holes") from the negative charges (electrons) within the photovoltaic device [4]. The holes are swept into the positive or p-layer and the electrons are swept into the negative or n-layer. Although these opposite charges are attracted to each other, most of them can only recombine by passing through an external circuit outside the material because of the internal potential energy barrier. Therefore if a circuit is made (see figure 2.3) power can be produced from the cells under illumination, since the free electrons have to pass through the load to recombine with the positive holes.

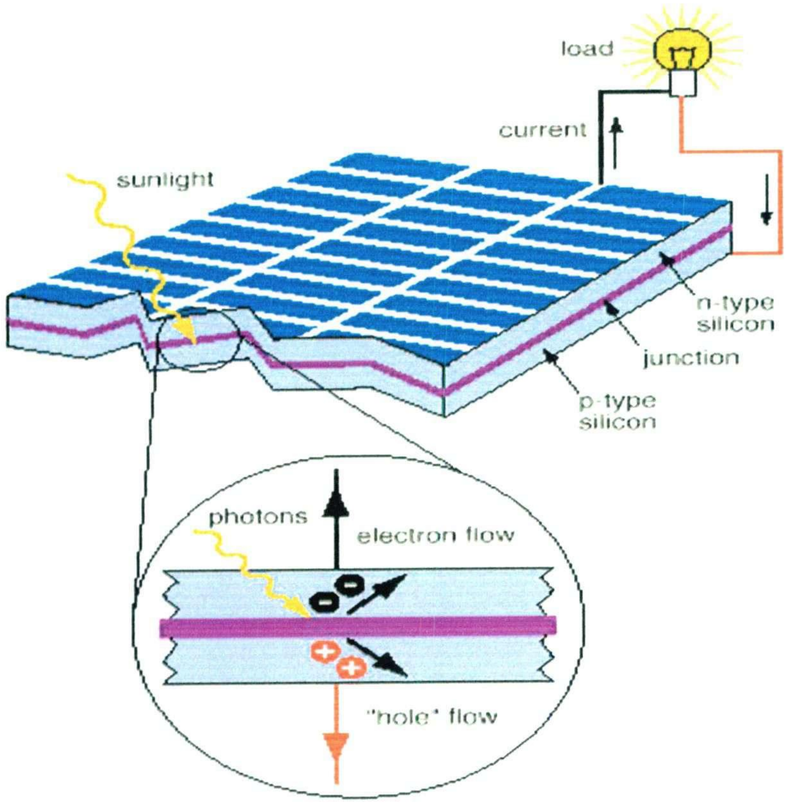


Fig.2.3 The Photovoltaic Effect in a Solar Cell
Source: Solar Lighting Guide

The amount of power available from a PV device is determined by;

- The type and area of the material;
- The intensity of the sunlight; and
- The wavelength of the sunlight.

Single crystal silicon solar cells, for example cannot currently convert more than 25% of the solar energy into electricity, because the radiation in the infrared region of the electromagnetic spectrum does not have enough energy to separate the positive and negative charges in the material.

Polycrystalline silicon solar cells have an efficiency of less than 20% at this time and amorphous silicon cells, are presently about 10% efficient, due to higher internal energy losses than single crystal silicon.

A typical single crystal silicon PV cell of 100 cm^2 will produce about 1.5 watts of power at 0.5 volts DC and 3 amps under full summer sunlight ($1000Wm^{-2}$). The power output of the cell is almost directly proportional to the intensity of the sunlight. (For example, if the intensity of the sunlight is halved the power will also be halved).

An important feature of PV cells is that the voltage of the cell does not depend on its size, and remains fairly constant with changing light intensity. However, the current in a device is almost directly proportional to light intensity and size. When people want to compare different sized cells, they record the current density, or amps per square centimeter of cell area.

The power output of a solar cell can be increased quite effectively by using a tracking mechanism to keep the PV device directly facing the sun, or by concentrating the sunlight using lenses or mirrors. However, there are limits to this process, due to the complexity of the mechanisms, and the need to cool the cells. The current output is relatively stable at higher temperatures, but the voltage is reduced, leading to a drop in power as the cell temperature is increased.

Other types of PV materials, which show commercial potential, include copper indium dieseline ($CuInSe_2$) and cadmium telluride (CdTe) and amorphous silicon as the basic material.

2.1.5. PV System Performance

PV System out depends on

1. Module efficiency during operation.
2. Losses in the DC PV system and subsequently in power conditioning and or storage.
3. The locally available sunlight and the tracking design.

The most important performance parameters of PV system are the temperature and irradiance.

All PV modules lose a small efficiency with increased temperature. This loss varies somewhat among different PV technologies, but as a rule of thumb about 0.2% loss per each degree Fahrenheit is expected. Hence voltage decreases with increasing temperature. The voltage decrease of a silicon cell is typically 2.3mV per ^{0}C.

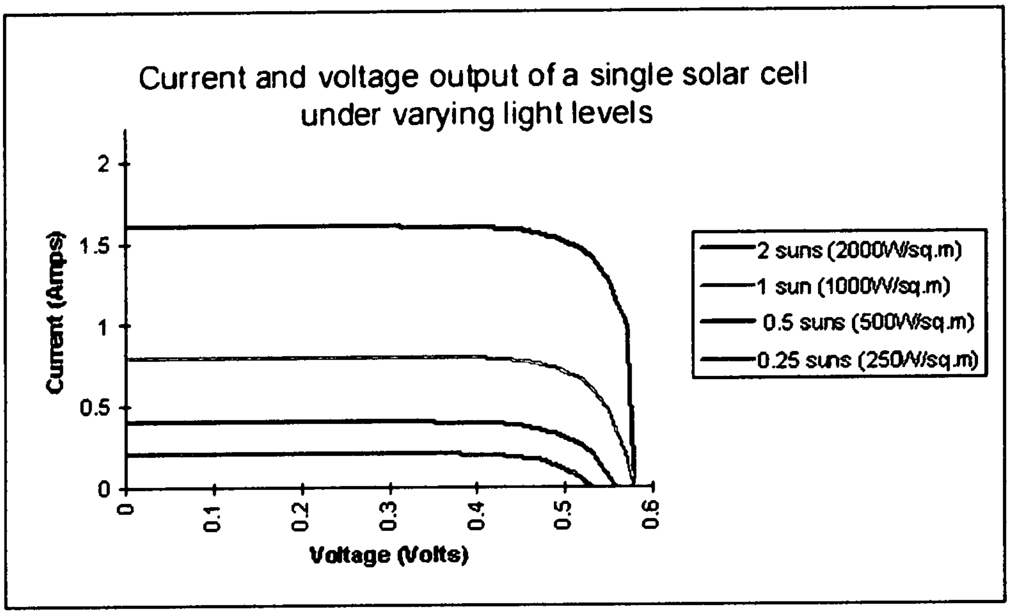


Fig. 2.4 showing current and voltage output of a solar cell at different light intensities.
Source: Bright Solar Energy Co.,Ltd.

The solar-cell characteristics under different levels of illumination are shown above figure 2.4 [17]. In this case light generated current is proportional to the flux of photons. Then short-circuit current of a solar panel is directly proportional to the irradiance.

Semiconductors are almost totally transparent to photons that have less energy than their band gaps because this kind of light does not have enough energy to absorb. Such photons pass right through the semiconductor as if it were glass. But almost all light with more energy than needed to free an electron in a given semiconductor is absorbed by that semiconductor and generates free electrons and holes.

Semiconductors are transparent to light that does not have enough energy to generate an electron hole pair. If it wants to absorb all of the solar photons, the semiconductor band gap would have to be very small. Then almost all of the sunlight would have sufficient energy to generate electrons and holes and would be absorbed. Then current s would be as large as possible. Unfortunately, it doesn't work. It would get a lot of current; but the voltage –the oomph with which the current is driven- would be negligible this is because the electric field that drives the current is proportional to the material's band gap. A small band gap means a tiny voltage.

But it cannot be archived a giant band gap producing a giant voltage, because band gap is increased, more and more of spectrum of solar photons lack the energy to produce electrons and holes .The semiconductor becomes transparent to a large proportion of sunlight.

2.2. PV Panels

As single PV cells have a working voltage of about 0.5 V, they are usually connected together in series (positive to negative) to provide larger voltages. Panels are made in a wide range of sizes for different purposes. They generally fall into one of three basic categories:

- Low voltage/low power panels are made by connecting between 3 and 12 small segments of amorphous silicon PV with a total area of a few square centimetres for voltages between 1.5 and 6 V and outputs of a few milliwatts. Although each of these panels is very small, the total production is large. They are used mainly in watches, clocks and calculators, cameras and devices for sensing light and dark, such as night-lights.

- Small panels of 1 - 10 watts and 3 - 12 V, with areas from $100cm^2$ to $1000cm^2$ are made by either cutting $100cm^2$ single or polycrystalline cells into pieces and joining them in series , or by using amorphous silicon panels. The main uses are for radios, toys, small pumps, electric fences and trickle charging of batteries.

- Large panels, ranging from 10 to 60 watts, and generally either 6 or 12 volts, with areas of 1000 cm^2 to 5000 cm^2 are usually made by connecting from 10 to 36 full-sized cells in series. They are used either separately for small pumps and caravan power (lights and refrigeration) or in arrays to provide power for houses, communications pumping and remote area power supplies (RAPS). The manufacturer under the following standard conditions specifies the module parameters

Irradiance	1 kW/m^2
Spectral distribution	AM1.5
Cell Temperature	25°C

The three most important electrical characteristics of a panel are the short- circuit current, open-circuit current, and the maximum power point as functions of the temperature and irradiance.

2.2.1. Arrays and Systems

If an application requires more power than can be provided by a single panel, linking a number of panels together can make larger systems. However, an added complexity arises in that the power is often required to be in greater quantities and voltage, and at a time and level of uniformity than can be provided directly from the panels. In these cases, PV systems are used, comprised of the following parts described in [6] (see figure 2.5):

(a) a PV panel array, ranging from two to many hundreds of panels;

(b) a control panel, to regulate the power from the panels;

(c) a power storage system, generally comprising of a number of specially designed batteries;

(d) an inverter, for converting the DC to AC power (eg 240 V AC)

(e) backup power supplies such as diesel startup generators (optional)

- framework and housing for the system

- trackers and sensors (optional);

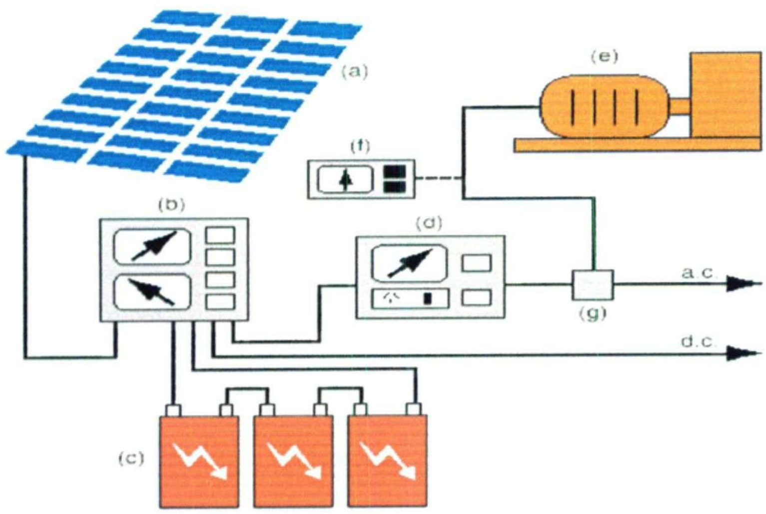


Fig. 2.5 Elements of a PV System

Source: Murdoch University research centre

Fig. 2.6 Tracked PV Array containing 16 panels.
Source: Murdoch University research centre

Arrays generally run the panels in series/parallel with each other, so that the output voltage is limited to between 12 and 50 volts, but with higher amperage (current). This is both for safety and to minimize power losses. Panels currently cost about $3 - 6 per Watt. That is, a 50 Watt panel presently costs about $200. Eight years ago, this same 'standard' panel would have cost about $500 at a cost of about $8 - 10 per Watt.

Arrays of panels(see fig 2.6) are being increasingly used in building construction where they serve the dual purpose of providing a wall or roof as well as providing electric power for the building. Eventually as the prices of solar cells fall, building integrated solar cells may become a major new source of electric power.

The daily energy output from PV panels will vary depending on the orientation, location, daily weather and season. On average, in summer, a panel will produce about five times its rated power output in watt hours per day and in winter about two times that amount.

2.3. Current Applications and Development

2.3.1. Rooftop PV

For most of the eighties and early nineties the major markets for solar panels were remote area power supplies and consumer products (watches, toys and calculators). However in the mid nineties a major effort was launched to develop building integrated solar panels for grid connected applications [2]. Rooftop PV is now driving the development of the market in Japan, Europe and the USA.

2.3.2. Cathodic Protection Systems

Cathodic protection is a method of protecting metal structures from corrosion. It is applicable to bridges, pipelines, buildings, tanks, wells and railway lines [2]. To achieve cathodic protection a small negative voltage is applied to the metal structure and this prevents it from oxidising or rusting. The positive terminal of the source is connected to a sacrificial anode that is generally a piece of scrap metal, which corrodes instead of the structure. Photovoltaic solar cells are often used in remote locations to provide this voltage.

2.3.3. Electric Fences

Electric fences are widely used in agriculture to prevent stock or predators from entering or leaving an enclosed field (see fig 2.7). These fences usually have one or two 'live' wires that are maintained at about 500 volts DC. These give a painful, but harmless shock to any animal that touches them. This is generally sufficient to prevent stock from pushing them over. These fences are also used in wildlife enclosures and secure areas. They require a high voltage but very little current and they are often located in remote areas where the cost of electric power is high. These requirements can be met by a photovoltaic system involving solar cells, a power conditioner and a battery [2].

Fig. 2.7 Electric Fences

Source: The Australian Institute of Energy

2.3.4. Remote Lighting Systems

Lighting is often required at remote locations (see Fig. 2.8) where the cost of power is too high to consider using the grid. Such applications include security lighting, navigation aids (eg buoys and beacons), illuminated road signs, railway crossing signs and village lighting. Solar cells are suited to such applications, although a storage battery is always required in such systems. They usually consist of a PV panel plus a storage battery, power conditioner and a low voltage, high efficiency DC fluorescent lamp. These systems are very popular in remote areas, especially in developing countries and this is one of the major applications of solar cells [2].

Fig. 2.8 Remote Lighting Systems

Source: The Australian Institute of Energy

2.3.5. Telecommunications and Remote Monitoring Systems

Good communications are essential for improving the quality of life in remote areas [2]. However the cost of electric power to drive these systems and the high cost of maintaining conventional systems has limited their use. Photovoltaic has provided a cost-effective solution to this problem through the development of remote area telecommunications repeater stations. These typically consist of a receiver; a transmitter and a PV based power supply system. Thousands of these systems have been installed around the world and they have an excellent reputation for reliability and relatively low costs for operation and maintenance.

Similar principles apply to solar powered radios and television sets, emergency telephones and monitoring systems. Remote monitoring systems may be used for collecting weather data or other environmental information and for transmitting it automatically via radio to the home base.

2.3.6. Solar Powered Water Pumping

There are more than 10,000 solar powered water pumps in use in the world today. In developing countries they are used extensively to pump water from wells and rivers to villages for domestic consumption and irrigation of crops (see fig 2.9). A typical PV-powered pumping system consists of a PV array that powers an electric motor, which drives a pump. The water is often pumped from the ground or stream into a storage tank that provides gravity feed. No energy storage is needed for these systems. PV powered pumping systems are widely available from agricultural equipment suppliers and they are a cost-effective alternative to agricultural wind turbines for remote area water supply [2].

Fig 2.9 Solar Powered Water Pumping

Source: The Australian Institute of Energy

2.3.7. Rural Electrification

Storage batteries are widely used in remote areas to provide low voltage electrical power for lighting and communications as well as for vehicles [2]. A PV powered battery charging system usually consists of a small PV array plus a charge controller. These systems are widely used in rural electrification projects in developing countries.

2.3.8. Water Treatment Systems

In remote areas electric power is often used to disinfect or purify drinking water [2]. Photovoltaic cells are used to power a strong ultraviolet light that can be used to kill bacteria in drinking water. This can be combined with a solar powered water pumping system.

2.3.9. Miscellaneous Applications of Solar Cells

Photovoltaic can be used in a variety of applications including:

i. Consumer products such as watches, toys and calculators
ii. Emergency power systems
iii. Vaccine and blood storage refrigerators for remote areas
iv. Aeration systems for ponds
v. Power supplies for satellites and space vehicles
vi. Portable power supplies for camping and fishing

Photovoltaic can be used in a variety of environments, on Earth, Space and Mars

2.4. Solar tracking mechanisms

There are numerous ways to convert the solar energy into either electricity or heat, be it on an industrial or commercial scale. One common method is through the use of photovoltaic (PV) cells. Clifford and Eastwood [18] has described the power output of PV cells depends on a number of factors. These include the operating temperature, irradiance and incident angle of the solar radiation. The daily average output of the PV cells can be enhanced by a solar tracker, which forces sunlight to be incident normally (perpendicularly) to the PV cell at all times, mimicking the behaviour of certain flowers which follow the sun during the day. The presence of a solar tracker is not essential for the operation of a solar panel, but without it, performance is reduced. Tests have shown that extra power can be produced per annum using a variable elevation solar tracker. Some current devices change the orientation of the PV cell, but this need not necessarily be the only method. An ideal tracker would allow the PV cell to accurately point towards the sun, compensating for both changes in the altitude angle of the sun (throughout the day) latitudinal offset of the sun (during seasonal changes) and changes in azimuth angle. The slow movement of the sun requires a damped system that will also respond slowly and avoid an oscillatory movement. Other desirable aspects would include the nocturnal repositioning of the solar tracker to anticipate the alignment of sunrise, opposite to that of the previous day's sunset, reducing energy losses in the morning. Various sensing equipment and actuating devices, both electrical (active) and mechanical (passive), are in use today.

Al-Mohamad [8] has described a solar collector or photo-voltaic module receives the maximum solar-radiation when the Sun's rays strike it at right angles. Tilting it from being perpendicular to the Sun will result in less solar energy collection by the collector or the module. Therefore, the optimal tilt angle for a solar energy system depends on both the site latitude and the application for which it is to be used. Many solar applications are mounted either on a fixed rack or on a tracking rack. Fixed collectors or modules producing heat or electricity throughout the year are usually installed and tilted at an angle equal to the latitude of the site in which the collector or module faces directly the Sun. Of course, the optimal position is suitable for the time when the Sun is at midpoint in the sky (i.e. spring and fall seasons). The energy collected by the solar system in both winter and summer is far less due to several reasons such as clouds in winter and temperature scattering in summer in addition to the Sun's changing altitude. But nevertheless in such cases, it is desirable that the average yearly collection of energy is maximized (i.e. the angle position of the collector or module is adjusted to receive maximum energy). A Sun-tracking mechanism increases the amount of solar energy that can be received by the solar collectors or photo-voltaic modules. Consequently this would result in a higher daily and annual output power harnessed. The use of a tracking system is more expensive and more complex than fixed mounts. However they can become cost-effective in many cases because they provide more power output through out the year and in many cases this increase exceeds 25%. Commercially, tracking systems are available either as a single-axis or a dual-axis design. The single-axis tracker follows the Sun's apparent east-to-west movement across the sky, while the dual-axis tracker, in addition to east–west tracking, tilts the solar collector or module to follow the Sun's changing altitude angle. To investigate the improvement in the daily output power of a photo-voltaic module, a single-axis Sun-tracking system was designed based on a programmable logic controlling unit. A suitable controlling program was also developed to accomplish the control operation with the possibility of implementing this arrangement as a data-acquisition system for solar radiation values during daytime.

Rizk and Chaiko [9] has pointed out extracting useable electricity from the sun was made possible by the discovery of the photoelectric mechanism and subsequent development of the solar cell – a semi conductive material that converts visible light into a direct current. By using solar arrays, a series of solar cells electrically connected, a DC voltage is generated which can be physically used on a load. Solar arrays or panels are being used increasingly as efficiencies reach higher levels, and are especially popular in remote areas where placement of electricity lines is not economically viable. This alternative power source is continuously achieving greater popularity especially since the realization of fossil fuel's shortcomings. Renewable energy in the form of electricity has been in use to some degree as long as 75 or 100 years ago. Sources such as Solar, Wind, Hydro and Geothermal have all been utilized with varying levels of success. The most widely used are hydro and wind power, with solar power being moderately used worldwide. This can be attributed to the relatively high cost of solar cells and their low conversion efficiency. Solar power is being heavily researched, and solar energy costs have now reached within a few cents per kW/h of other forms of electricity generation, and will drop further with new technologies such as titanium oxide cells. With a peak laboratory efficiency of 32% and average efficiency of 15-20%, it is necessary to recover as much energy as possible from a solar power system. This includes reducing inverter losses, storage losses, and light gathering losses. Light gathering is dependent on the angle of incidence of the light source providing power (i.e. the sun) to the solar cell's surface, and the closer to perpendicular, the greater the power. If a flat solar panel is mounted on level ground, it is obvious that over the course of the day the sunlight will have an angle of incidence close to 90°in the morning and the evening. At such an angle, the light gathering ability of the cell is essentially zero, resulting in no output. As the day progresses to midday, the angle of incidence approaches 0°, causing an steady increase in power until at the point where the light incident on the panel is completely perpendicular, and maximum power is achieved. As the day continues toward dusk, the reverse happens, and the increasing angle causes the power to decrease again toward minimum again. From this background, we see the need to maintain the maximum power output from the panel by maintaining an angle of incidence as close to 0° as possible. By tilting the solar panel to continuously face the sun, this can be achieved. This process of sensing and following the position of the sun is known as

Solar Tracking. It was resolved that real-time tracking would be necessary to follow the sun effectively, so that no external data would be required in operation.

2.4.1. Electronic (active) trackers

Clifford and Eastwood [18] has pointed out a common solution is that of a centrally pivoted PV cell being moved, about this pivot, by one or more motors linked to an electronic sensor. This is probably the simplest electronic method available, with the motor being powered by the cell itself. The panel is positioned out of reach, to avoid human interference, although leaving it more susceptible to wind drag. However, as PV power is reduced, this is not a very elegant solution. Another type of electric solar tracker is shown in Fig. 2.10 and includes a sensor that aims to minimize the angle between the line of the sun and a face perpendicular to the panel. When this angle is reduced to zero the sunlight strikes the panel at 90^0. Also, in this design, the central pivot was not horizontal (one bearing was nearer the ground than the other) giving the correct elevation for non-equatorial locations. Again the panel itself produced the power for the motor. Electronic solutions command the majority of the market for solar trackers, but they deplete the power produced by the PV panel for its own operation, and also have the added expense of fitting and maintaining an electric motor and control system.

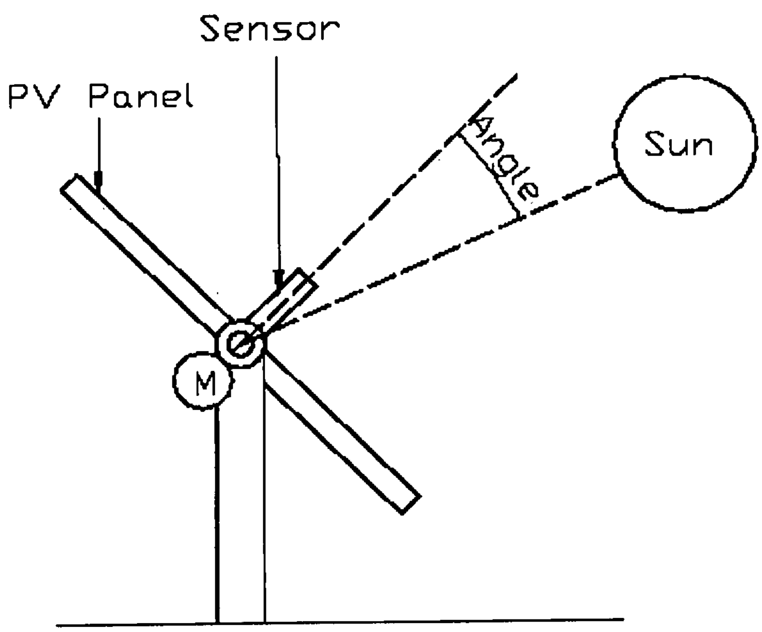


Fig. 2.10 An electronic (active) solar tracker.
Source: Clifford and Eastwood 2004, pp 270

2.4.2. Mechanical (passive) trackers

Clifford and Eastwood [18] has discussed a passive solar tracker supplied by Zomeworks Ltd. is illustrated in Fig. 2.11. Two identical cylindrical tubes (each at either side of the panel and equal distances from the central pivot) are filled with a fluid under partial pressure. Using suitably placed shades, the sun heats the fluid causing evaporation and transfer from one cylinder to the other. This mass imbalance is used to move the solar panel. Damping is used to limit the speed of movement. This simple system can be made relatively cheaply and uses none of the PV cell's power. However, it begins each day pointing in the wrong direction, losing sight of the sun as it attempts to reposition itself. The use of refrigerants to fill the cylinders needs careful consideration. Despite these draw backs, it is a commonly used method.

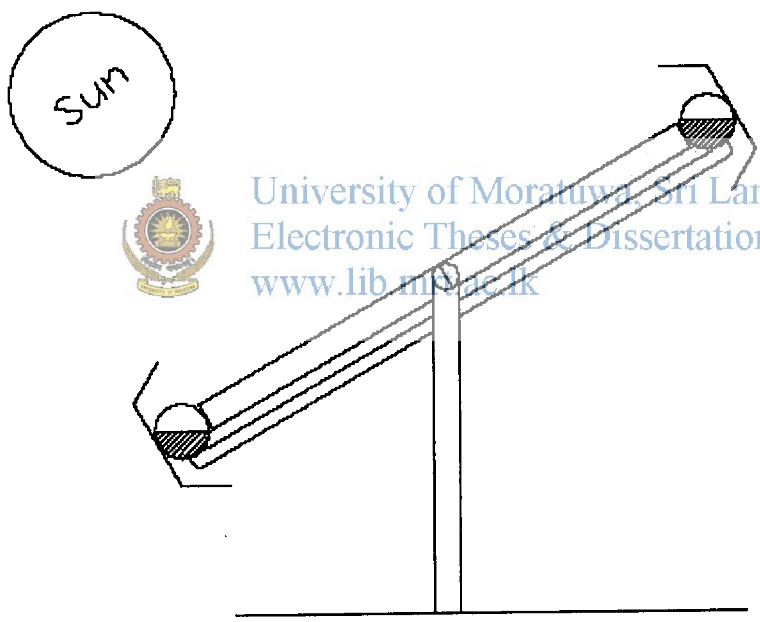


Fig. 2.11. A passive solar tracker using two identical cylindrical tubes filled with a fluid under partial pressure.
Source: Clifford and Eastwood 2004, pp 270

2.4.3. Photoelectric sensors (feedback mechanism)

Photoelectric sensors generate a differential signal whenever the orientation of the device is not optimal [16]. This signal is used in a feedback mechanism to reorient the receiver until the best orientation is achieved. Such devices have not proved to be very reliable because they fail to discriminate between the obscured sun and a bright spot, in a broken cloud. The feedback mechanism misconduct orientates the receiver towards the bright spot rather than the sun. In this way, the tracking fails. Furthermore, these devices are not dependable under foggy or misty or dusty conditions.

2.4.4. Clock mechanisms

The second type of mechanisms which track the sun, use clock mechanisms to control the orientation of the receiver at different times of a day [16]. Unfortunately, to accurately follow the sun in its daily motion as well as its yearly (seasonal) motion, the devices have to be complex in their construction besides being expensive to build.

Another disadvantage with both types of systems mentioned above, is the energy requirement during the tracking because these are not mass balanced. Due to the imbalance, far more torque is required to correct the position of the receiver as compared to the balanced systems. Many times, it is not possible to attain the correct position, especially when the sun appears in the sky after a long interval of cloudy condition. Under such conditions, significant amount of torque is required for the receiver to attain the optimal orientation.

2.4.5. Utilizing a driving motor or electronic control devices

Some of tracking systems each utilizing a driving motor and electronic control devices therefore were developed or proposed [16]. However, these tracking systems require a continuous electric power supply and are somewhat complicated for technology transfer to developing countries where sunshine is so abundant that the utilization of solar energy is favourable while, however, electric power supply networks have not yet been adequately developed.

2.4.6. Heat responsive elements

The devices include heat responsive elements which exert forces when they are heated by the radiant energy from the sun and become limp when shaded [16]. When the heat responsive element is heated by the solar energy within a certain range of the azimuth or altitude angle, the solar collector can be rotated to a position to face the position of the sun. The latter one which is provided for turning a parabolic trough solar collector about an east-west horizontal axis and the alignment of the solar collector is accomplished by the heating of a long wire held in tension by a spring.

The latter one cannot track the sun after the sun has been covered with clouds for a certain time period, and from the same reason, tracking of the sun about the north-south axis cannot be realized. Furthermore, the application of this mechanism is limited to solar collectors with a parabolic trough reflector. These defects or disadvantages of the tracking mechanisms disclosed in the prior patents will be understood by those skilled in the art from the disclosures of these patents.

2.4.7. Tracker system with helical groove guide

In this system, the solar collectors are carried by a rotary pole, supported by a chamber of variable volume [16]. The fluid contained in the chamber is displaced from the chamber by the dead load force of the sun collectors and of the rotary pole, penetrating through a nozzle in this process. The rotary pole thus sinks and is rotated about its vertical axis through the interaction of a bolt with a helical groove guide, tracking the sun movement from east to west. The return to the initial position "to the east" is performed every morning at sunrise by lifting the rotary pole with muscle power; tracking along the horizontal axis, according to the elevation angle is not performed in case of such tracker system.

In spite of the robust construction, this tracker has proved to be not without problems as far as the technical application is concerned.

For one, this tracker does not work without the daily intervention of an operator, lifting the rotary pole and thus positioning the sun collectors in their initial position. Secondly, the sun collectors' weight is limited because of the required human muscle power. Thirdly, the varying ambient temperature causes, based on the temperature dependent viscosity of the fluid in the chamber, deficiencies as regards the tracking speed which can lead to considerable failures in case of larger temperature differences, for example in summer/winter cycles and can thus under certain circumstances make the system useless.

For the above reasons, this construction proves hardly suitable and/or unsuitable for application in such solar assemblies as solar-thermal collectors, storage collectors, sunlight concentrators, flat mirrors for solar towers but also in photovoltaic modules with amplification mirrors.

2.4.8. Expansion of liquids (Track Rack Passive Solar Tracker)

The functional part of this solar tracker (see fig 2.12) consists of two canisters filled with a liquid and mounted at opposite ends of the solar panel frame [10]. The canisters are connected together by a narrow pipe. A shadow panel is mounted on top of each canister. The shadow panel casts a shadow onto its canister in relation to the angle of the sun. As the sun warms up the canisters the liquid inside expands. The liquid in the canister with the least shadow from its shadow panel develops a higher pressure forcing it into the other, cooler canister. This unbalances the frame causing it to turn on its axle until the shadows on both panels are equal, at which point the sun will be perpendicular to the solar panel and the tracker stops.

In order to reduce movement caused by wind, a hydraulic damper is used. The tracker can withstand wind loads of up to 120kg/m2. Friction in the wind damper can cause positioning errors of up to 10 degrees to the tracker's optimum location towards the sun. The loss of power due to the positioning error is easily offset by using modern solar panels which have a special micro-pyramid shaped surface coating to reflect sunlight back onto the solar cells, which enables considerably more irradiation absorption from slight misalignments than earlier solar panel designs.

It can easily be seen from the above facts that precision positioning to a fraction of a degree as obtained with active systems has negligible benefits. The single axis system has an adjustment for optimizing the solar panel tilt towards the sun according to the yearly seasons. Making this adjustment twice yearly is all that is needed to maintain optimum performance [10].

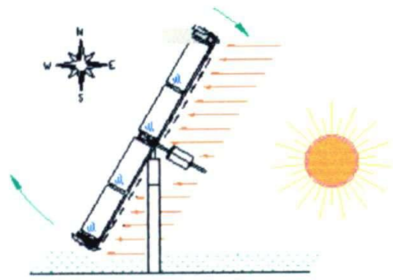
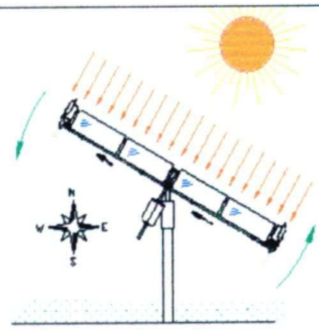
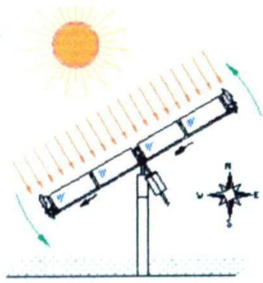
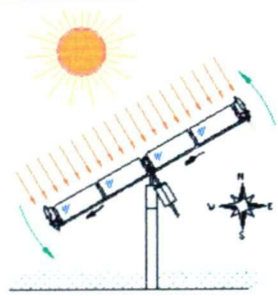
In the early morning the solar panel is still facing westwards roam the previous evening. As the rising sun warms the lower canister, which has the least shadow on it, pressure builds up forcing its liquid to transfer into the upper canister. The frame then becomes out of balance and rotates towards the east.	
The temperature differential and the corresponding pressure is due to the shadow-panels. When the sun is no longer perpendicular to the solar panel one of the canisters will be in more shadow than the other causing the Tracker to rotate until shadow equilibrium is once again achieved, then tracker rotation ceases.	
The tracker follows the sun from east to west as the day progresses.	
At sundown the tracker is facing west and "sleeps" there until the following sunrise when the Tracker "wakes up" and aligns itself once again to the east	

Fig. 2.12 Track Rack Passive Solar Tracker

Source: http://zomeworks.com

2.4.9. WattSun Solar Tracker

The WattSun Solar Tracker, built by Array Technologies, utilizes a patented, closed loop, optical sun sensing system to sense the sun's position and track it [13]. The optical sun sensor consists of a square post machined to a cone tip with four individual optical sensors. Figure 2.13 shows a photo of the optical sun sensor with the individual optical sensors mounted at approximately 45 degrees to the face of the square post. The optical sun sensor is mounted such that its axis is parallel to the center axis of the solar collector. When the cone tip is pointed toward a light source (the sun) the controller circuitry sums the signals from the four individual sensors. The closed loop system feeds information to the controller electronics about the direct component of sunlight available, the diffuse amount of sunlight, the total amount of sunlight as well as the differential amount of sunlight on the opposing sensors. The control electronics then provides a signal to the azimuth-elevation motors to move the optical sun sensor until the individual optical sensors balance.

Fig. 2.13. Optical Sun Sensor device used to provide feedback to the electronics **control system**

Source: Beshears et al, 2003, pp 04

The test set-up consisted of the Wattsun Tracker Mechanism with a frame attached to provide a sun pointer mechanism to allow us to monitor the tracking accuracy of the overall system using the Wattsun optical sun sensor. The overall Wattsun Tracker system mechanism is shown in Fig. 2.14.

Fig. 2.14 Overview of the Wattsun Tracker with a frame added to provide a sun pointer for monitoring overall system tracking accuracy

Source: Beshears et al, 2003, pp 04

2.4.10. Automatic sun-following system with a pyrheliometer

Another sun-tracking mechanism use automatic measurement of direct solar radiation with a pyrheliometer (Fig.2.15). The actuator has two axes of motion [11]. A computing program was created to calculate the position of the sun under cloudy conditions to ensure correct orientation of the pyrheliometer during those periods. The determination of the error signal and the strategy of control are described. The velocities of the axes are relatively low, but the design of the system ensures long time working without expensive maintenance. For solar irradiation below 140 W/m2 the registration falls suddenly to zero, but above this value the system works stably. It is possible to use this type of tracker with larger and heavier systems, like solar panels and concentrators. Other cheaper tracking sensors could be used. Digital control should be used to get higher resolution and better response.

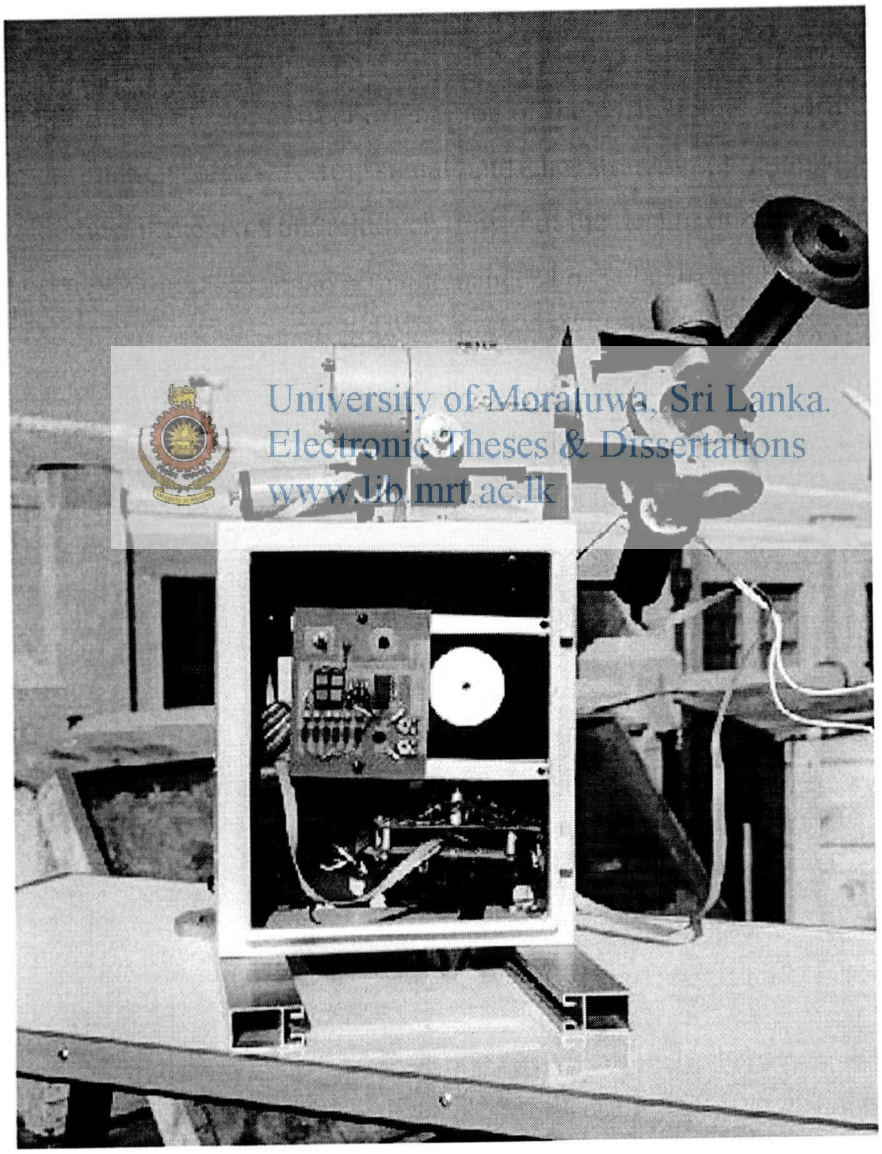


Fig. 2.15 Automatic sun-following system with a pyrheliometer.

Source: Roth et al,2004, pp.394

2.4.11. Maximum power point tracking (MPPT) system

Maximum power point tracking (MPPT) is used in photovoltaic (PV) systems to maximize the photovoltaic array output power, irrespective of the temperature and irradiation conditions and of the load electrical characteristics [12]. A new MPPT system has been developed, consisting of a Buck-type dc/dc converter, which is controlled by a microcontroller-based unit. The main difference between the method used in the proposed MPPT system and other techniques used in the past is that the PV array output power is used to directly control the dc/dc converter, thus reducing the complexity of the system. The resulting system has high-efficiency, lower-cost and can be easily modified to handle more energy sources (e.g., wind-generators). The experimental results show that the use of the proposed MPPT control increases the PV output power by as much as 15% compared to the case where the dc/dc converter duty cycle is set such that the PV array produces the maximum power at 1 kW/m2 and 25^0C.

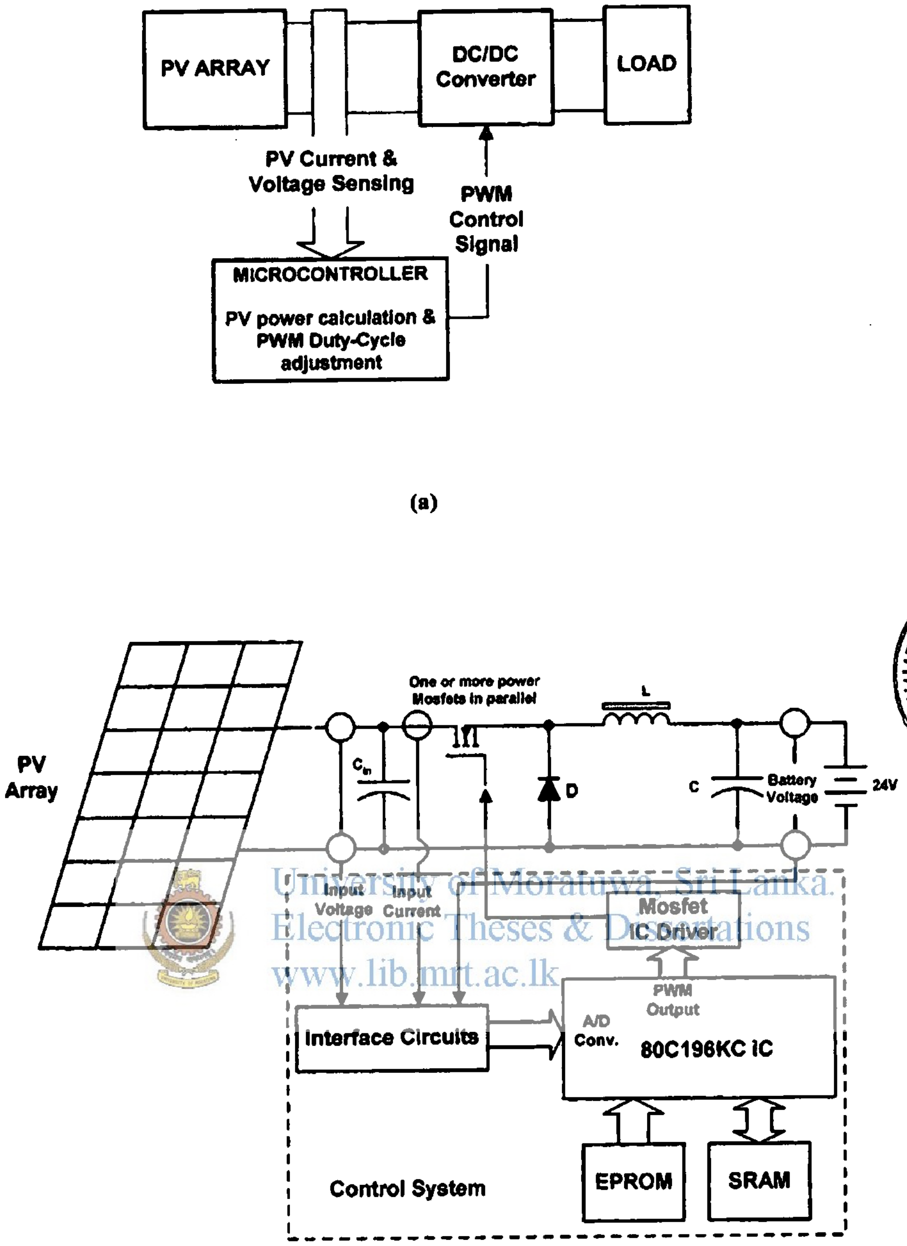
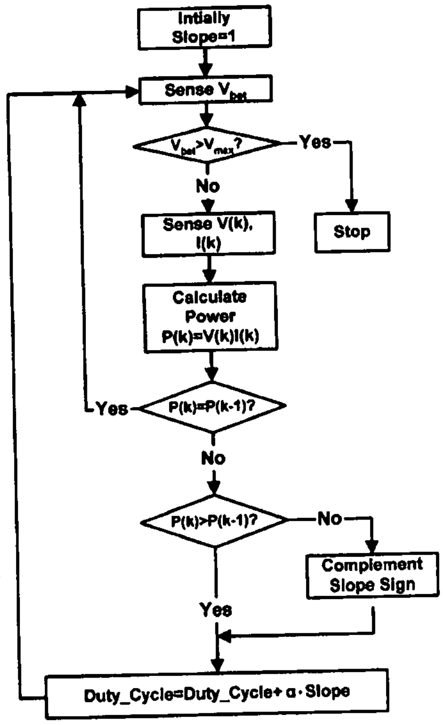


Fig. 2.16. Tracking system: (a) block diagram and (b) more detailed diagram.

Source: Koutroulis et al, 2001, pp.52

A block diagram of the this system is shown in Fig. 2.16(a). A Buck-type dc/dc converter is used to interface the PV output to the battery and to track the maximum power point of the PV array. A more detailed diagram is illustrated in Fig. 2.16(b). The converter power switch consists of one or more parallel-connected power MOSFET's. The fly back diode is of a fast switching type. The output inductor is wound on a ferrite-core with air-gap to prevent core saturation that might be caused by a large dc current component value. In the configuration of Fig. 2.16(b) a battery stack is used as the PV array load. For given atmospheric conditions, the battery charging current depends on the PV output power and the battery voltage. The battery voltage increases according to the charging level and it is monitored to prevent overcharging. The system control unit consists of: a) Intel's 80C196KC low-power consumption, CMOS microcontroller with external EPROM and SRAM; b) interface circuits which comprise of sensors and signal conditioners connected to the microcontroller A/D converter; c) IC driver for the power MOSFET(s). The power consumed by the control unit is about 1 W and supplied by the battery which is being charged by the dc/dc converter. The microcontroller unit 80C196KC features a 10-bit, eight channels, successive approximation A/D converter, used by the control program to measure the signals required for the power flow control. The 10-bit resolution is adequate for the present application. Also, it features three PWM outputs with program controlled duty cycle and 39.2-kHz maximum frequency when driven by the 20-MHz clock of the unit. Each of the PWM outputs can be used to control a separate MPPT system. This type of microcontroller was chosen because it has the necessary features for the proposed system, such as an on-chip A/D converter, PWM outputs, 16-bit architecture, high clock rate, low-power consumption and low cost. The converter input current, , has the pulse-type waveform for both continuous and discontinuous conduction modes. A current transformer with a rectifier-RC filter combination can be connected to the secondary winding for the measurement of the current mean value which is proportional to the PV array output current. For a higher accuracy, a Hall-effect sensor or a current shunt could be used. However, the Hall-effect sensor is more expensive and the current shunt has more power losses.



(a)

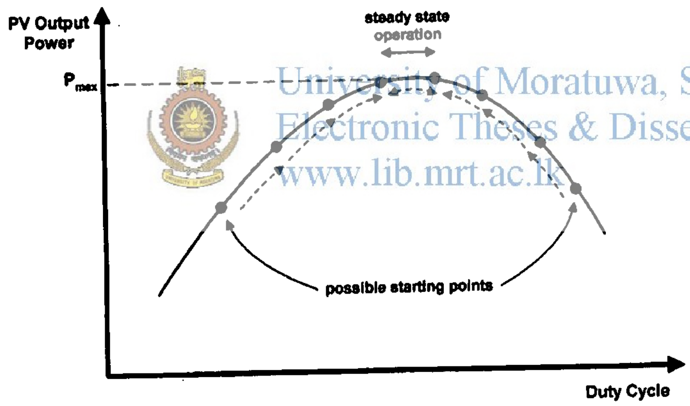


Fig. 2.17. MPPT control: (a) program flowchart and (b) MPP tracking process.

Source: Koutroulis et al, 2001, pp.52

The flowchart of the control program is shown in Fig. 2.17(a). "Slope" is a program variable with values either 1 or 1, indicating the direction that must be followed on the hill-shaped PV array output power curve in order to increase its output power, while "α " is a constant between 0 and 1. Since an 8-bit CPU register is used to store the PWM duty cycle in the present application, the value of "α " is made equal to 1/256. Initially, the value of "Slope" is set to 1. In each iteration, the dc/dc converter input voltage and current are measured and the input power is calculated. The input power is compared to its value calculated in the previous iteration and according to the result of the comparison; the sign of "Slope" is either complemented or remains unchanged. Then, the PWM output duty cycle is changed accordingly. The MPP tracking process is shown in Fig. 2.17(b). The starting points vary, depending on the atmospheric conditions, while the duty cycle is changed continuously, according to the above-mentioned algorithm, resulting in the system steady state operation around the maximum power point. The battery voltage is monitored continuously and, when it reaches a predetermined level, the battery charging operation is stopped in order to prevent overcharging.

2.4.12. Phototransistors system

Many different methods have been proposed and used to track the position of the sun. Rizk and Chaiko has proposed the simplest of all uses an LDR – a Light Dependent Resistor to detect light intensity changes on the surface of the resistor [9]. Other methods use two phototransistors covered with a small plate to act as a shield to sunlight, as shown in Fig. 2.18

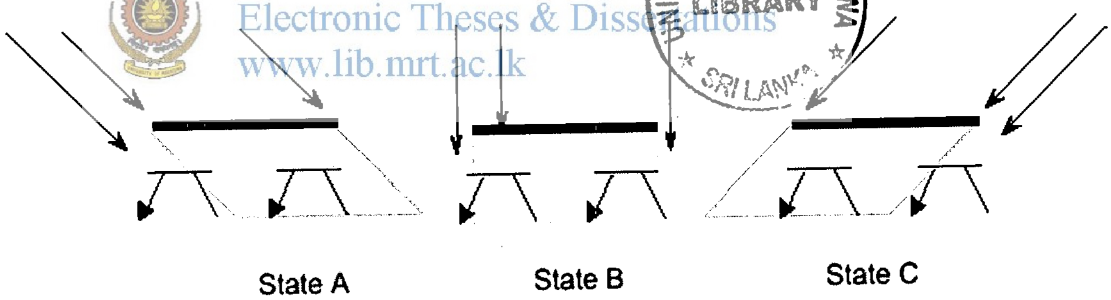


Fig. 2.18 Alternative solar tracking method
Source: Rizk and Chaiko 2008,pp.313

When morning arrives, the tracker is in state A from the previous day. The left phototransistor is turned on, causing a signal to turn the motor continuously until the shadow from the plate returns the tracker to state B. As the day slowly progresses, state C is reached shortly, turning on the right phototransistor. The motor turns until state B is reached again, and the cycle continues until the end of the day, or until the minimum detectable light level is reached.

The problem with a design like this is that phototransistors have a narrow range of sensitivity, once they have been set up in a circuit under set bias conditions. It was because of this fact that solar cells themselves were chosen to be the sensing devices. They provide an excellent mechanism in light intensity detection – because they are sensitive to varying light and provide a near-linear voltage range that can be used to an advantage in determining the present declination or angle to the sun.

As a result, a simple triangular set-up was proposed, with the two solar cells facing opposite directions, as shown in Fig. 2.19. In its rest position, the solar cells both receive an equal amount of sunlight, as the angle of incidence, although not 90°, is equal in both cases as seen in Fig.2.20.

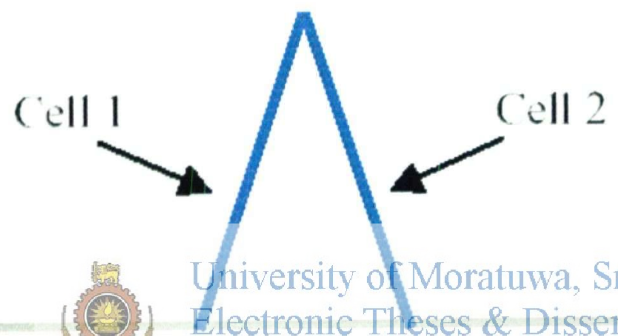


Fig. 2.19 Set-up of solar reference cells

Source: Rizk and Chaiko 2008,pp.314

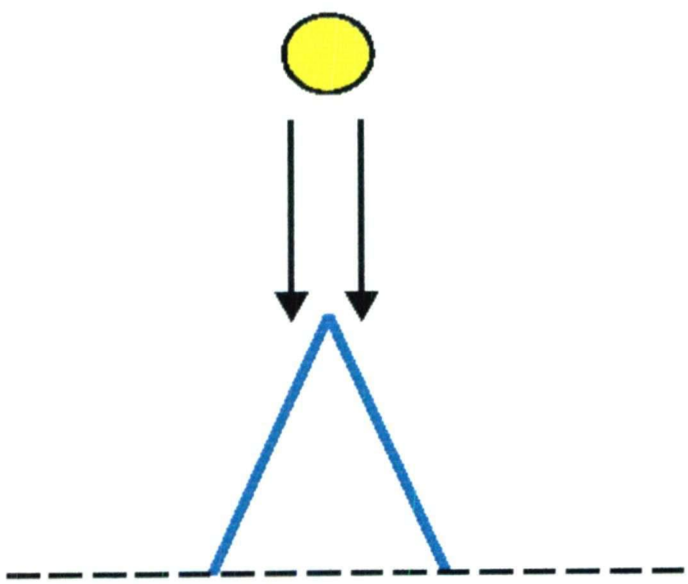


Fig. 2.20 Solar reference cells at rest position

Source: Rizk and Chaiko 2008,pp.314

It can be seen in Fig. 2.21 that as the sun moves in the sky, assuming that the solar tracker has not yet moved, the angle of incidence of light to the reference panels will cause more light to fall on one cell than the other. This will obviously cause a voltage difference, where the cell that is facing the sun will have higher potential than the other. This phenomenon will result in a detectable signal at each cell, which can be processed by a suitable circuit.

Fig. 2.21 Solar reference cells at a significant angle to the sun

Source: Rizk and Chaiko 2008,pp.316

The final stage involved coupling the circuitry to the motor and mounting it onto the bracket. The final product is seen complete in Fig. 2.22. It has a Solarex 9W solar array made of polycrystalline silicon mounted on the flanges, which was borrowed from the tech officers. Quite simply having two test subjects carried out testing. The first scenario involved removing the panel from the tracker and laying it in a flat orientation. The output was connected to a load that would dissipate 9W that would match the panel's rating. 9W at 12V corresponds to a current of 0.75A, so by Ohm's law; a load resistance was calculated as being 16Ω. A 15 Ω 50W resistor was the closest value found and was connected to the panel. The tracking device still requires power, but a 12V battery that is connected in a charging arrangement with the solar panel supplies it. The voltage across and current through the load was monitored using two separate multimeters, and was recorded every half hour on a clear day into an Excel spreadsheet. The readings were taken on a span of days that possessed similar conditions including no cloud cover. The readings are shown below in a graph generated by Excel in Fig. 2.23.

Fig. 2.22 A prototype solar tracker

Source: Rizk and Chaiko 2008,pp.314

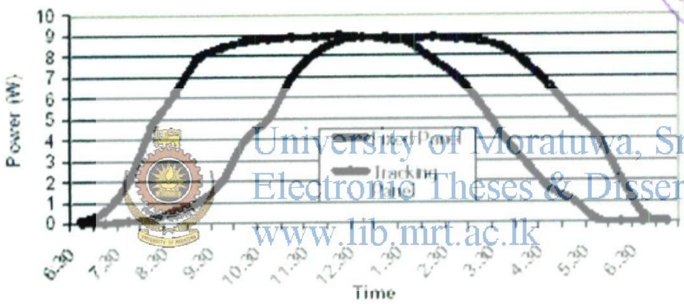


Fig. 2.23 Experimental results of power increase for tracked panel

Source: Rizk and Chaiko 2008,pp.314

It is possible to calculate a percentage increase and an average increase by writing the appropriate calculations in excel. It was found that in this case, the fixed panel provided an average of 39% of its 9W, or 3.51W, calculated over a 12- hour period. By contrast, the tracked solar panel achieved an overall 71% output, or 6.3W over the same time frame. At the earlier and later hours, the power increase over the fixed panel reached up to 400%. This amounts to an average 30% increase in power simply by maintaining the solar panel as perpendicular as possible to the sun. To ensure that power was not being wasted, the device itself was also monitored for current drawn to power itself. When the device was at rest, an ammeter was placed in series with the battery. The total current at 12V was measured as only 4mA, which corresponded to a power dissipation of 48mW under no load.

CHAPTER 03- METHODOLOGY

3.1. Solar Energy

The sun supplies almost all the energy used on the earth. This energy drives the climate, the growth in plants (through photosynthesis) and provides heat and light. The sun is essential for life on earth. The sun has a diameter of 1,390,000 km and (on average) is a distance of 1.5 ′ $10^{\wedge 8}$ km from earth. As summarized in Table 1, the sun is composed of several layers in an onion like structure. This structure affects the nature of the solar energy reaching the earth [2].

Layer	Radius	Characteristics
Sun's interior		
Inner core	0-159,000 km	Very dense 10^5kg/m^3, very hot 40′ 10^6K, contains 40% of the mass of the sun and generates 90% of the sun's energy, energy transferred away by X-ray and gamma-ray radiation.
Outer core	159,000-480,000 km	Density and temperature reduces as distance from the centre increases.
Convecting zone	480,000-695,000	Density has fallen to 70kg/m^3, and temperature to 130,000K, convective heat transfer (heat transfer by fluid/gas motion) occurs in this region.
Photoshpere	Surface of the convecting zone	Upper layer of the convecting zone and the source of most solar radiation, this layer is opaque (absorbs and emits a continuous spectrum of radiation), temperatures are around 5,000K. Density is very low: 10^{-5} kg/m_3
Sun's atmosphere		
Reversing layer	Depth: a few hundred km	Transparent solar atmosphere composed of gases at a temperature of $<$ 5,000K.
Chromoshpere	Depth: approx 10,000 km	Transparent gases at a temperature of $>$ 5,000K
Corona		A region of gas of almost negligible and high temperature of 10^6K

Table 1: The structure of the sun.
Source: The Australian Institute of Energy

Although the solar surface and atmosphere comprise regions of very different temperatures, the sun is often equated to a black body (i.e. a perfect radiator) at a temperature of 5,762K. The energy released from the sun comes about due to a fusion reaction in which hydrogen nuclei combine to from helium, releasing energy in the process. The evidence is strong that the overall reaction is:

$$4\,{}^{1}H + 2\,e \rightarrow {}^{4}He + 2\ neutrinos + 6\ photons$$

In this reaction, the final nuclei (Helium) have less internal energy than the starting particles (Hydrogen). This difference is released as energy of motion of the nuclei and electrons in the solar gas, low energy photons and high energy neutrinos. The amount of energy involved is 26 MeV (or 26 x 10^{6} eV) each time the abovereaction take place. 90% of the energy generated by the sun comes from this fusion reaction.

The sun's energy reaches the earth as solar radiation, which is composed of discrete 'packets' of energy known as photons. The energy of a photon is dictated by its frequency:

$$E = hv$$

where E is the photon energy (J), h Planck's constant (6.62 x 10^{-34} Js) and v the frequency of the photon (Hz). The sun radiates photons over a range of frequencies; these frequencies are related to the radiation wavelength (λ) by the equation

$$\lambda = c/v$$

where c is the speed of light in a vacuum (3 x 10^{8} m/s).

The range of wavelengths that the sun emits is known as the solar spectrum (figure 3.1). The majority of solar radiation lies within the wavelength range of 0.2 – 2.5 mm. The types of radiation emitted by the sun are classed by their wavelength. At shorter wavelengths there is X-rays, Gamma rays and ultraviolet radiation, while at the longer wavelengths there is infrared radiation and radio waves.

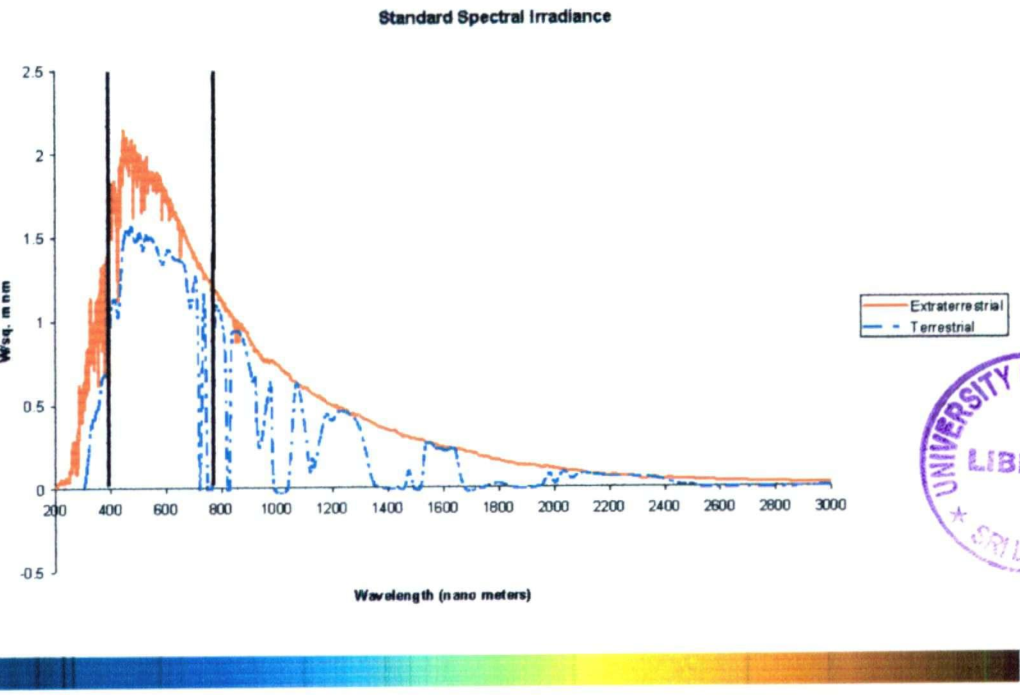


Figure 3.1: Standard spectral irradiance (lower spectrum corresponds to wavelength portion 400-800 mm).

Source: The Australian Institute of Energy

Photons in the shorter wavelength portion of the spectrum have higher energy than those in the longer wavelength portion. The intensity of solar radiation (J/s or W/m^^{2}) is known as the Radiant Flux Density (RFD), often referred to as irradiance or insolation. Outside the earth's atmosphere insolation levels are approximately 1.35 kW/m^2. At the surface of the earth insolation levels are lower, e.g. at the equator at sea level insolation is approximately 1kW/m^^{2}. The shape of the solar spectrum changes as it reaches the earth's surface (the dotted line in figure 26). The missing portions of the spectrum are caused by the absorption of various wavelengths of solar radiation by the elements in the earth's atmosphere. The power contained in the various portions of the solar spectrum are shown in table 2.

Wavelength range (nm)	0-380	380-780	780+
Fraction of RFD in range	0.07	0.4729	0.4571
Energy in range (W/m^2)	95	640	618

Table 2: breakdown of irradiance into wavelength ranges.
Source: The Australian Institute of Energy

Solar radiation reaching the surface of the earth has two components – direct or beam radiation and diffuse radiation. As the name suggests beam radiation arrives directly from the sun diffuse radiation is the portion of solar radiation, which is scattered in the Earth's atmosphere. On a clear day beam radiation makes up about 90% of the total reaching the earth's surface. The ratio of direct and diffuse radiation changes with the quantity of cloud and haze in the atmosphere (atmospheric turbidity): e.g. on heavily overcast days the beam component of solar radiation will be 0%. The total solar irradiance G ($W/m^{\wedge 2}$) at a point on the earth's surface is therefore the sum of the diffuse and beam radiation:

$$G = G_{beam} + G_{diffuse}$$

The direct component, $G_{beam,}$ of solar radiation falling on any surface can be calculated with knowledge of basic solar angles as follows table 03 & figure 3.2.

Angle	Symbol	Description
Zenith	Y	angle between beam radiation and the vertical
altitude	B	angle between beam radiation and the horizontal
solar azimuth angle	G_s	angle between N-S and the solar beam
incidence angle	Q	angle between the beam radiation on a surface and the normal to that surface
The surface-azimuth	G	angle between the surface normal and N-S
The surface-solar azimuth angle	A	angle between the incident beam and the surface normal
The tilt angle	f	angle of the surface above the horizontal

Table 3: some basic solar angles.
Source: The Australian Institute of Energy

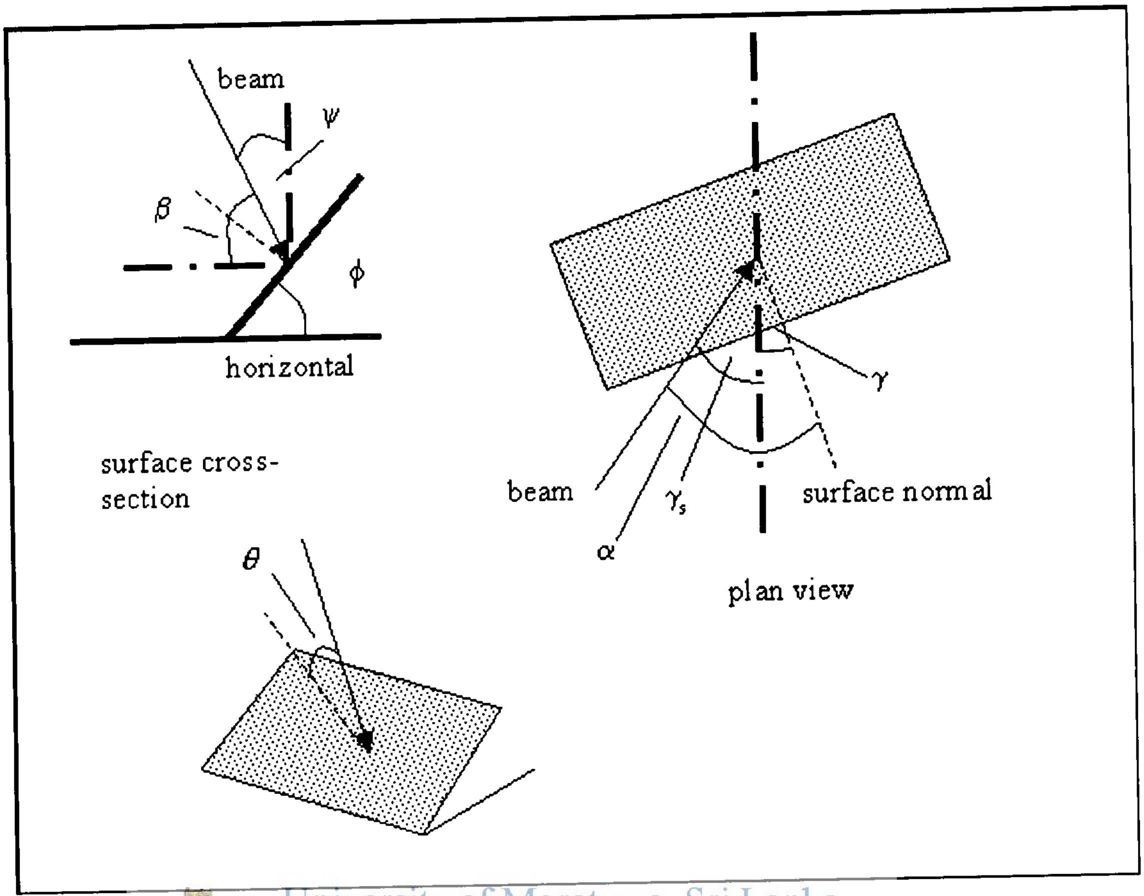


Figure 3.2: basic solar angles.
Source: The Australian Institute of Energy

The beam radiation falling on the surface can be split into its horizontal and vertical components:

$$G_v = G_n \, cosb \; cosa \; cosf$$

$$G_h = G_n \, sinb \; sinf$$

The total radiation intensity falling on the surface (W/m^2) is therefore

$$G_s = G_n \, (sinb \; sinf + cosb \; cosa \; cosf)$$

Diffuse radiation is assumed to be of equal intensity from all portions of the sky, so if the intensity of diffuse solar radiation falling on the ground is G_d, the radiation falling on a vertical surface will be $0.5G_{d.}$ Depending on the material from which the surface is constructed, the incident radiation will either be reflected (r), absorbed (a) or transmitted (t). So for an incident intensity of G_n, the reflected radiation intensity would be r $G_{n.}$ The sum of the fractions for each process is unity:

$$r + a + t = 1.0$$

Opaque materials such as concrete will absorb and reflect solar radiation, transparent materials such as glass will reflect, absorb and transmit solar radiation. The preceding information can be used to estimate the solar radiation falling on a surfaces of different orientations and of different properties. This information can be used when designing a solar collector system.

By far the most common type of solar collector is the flat plate solar collector, these are often found on the roofs of buildings (figure 3.3) throughout the US and in southern Europe. In these collectors solar energy is used to heat water, which can then be used inside the building. A typical collector has the following features.

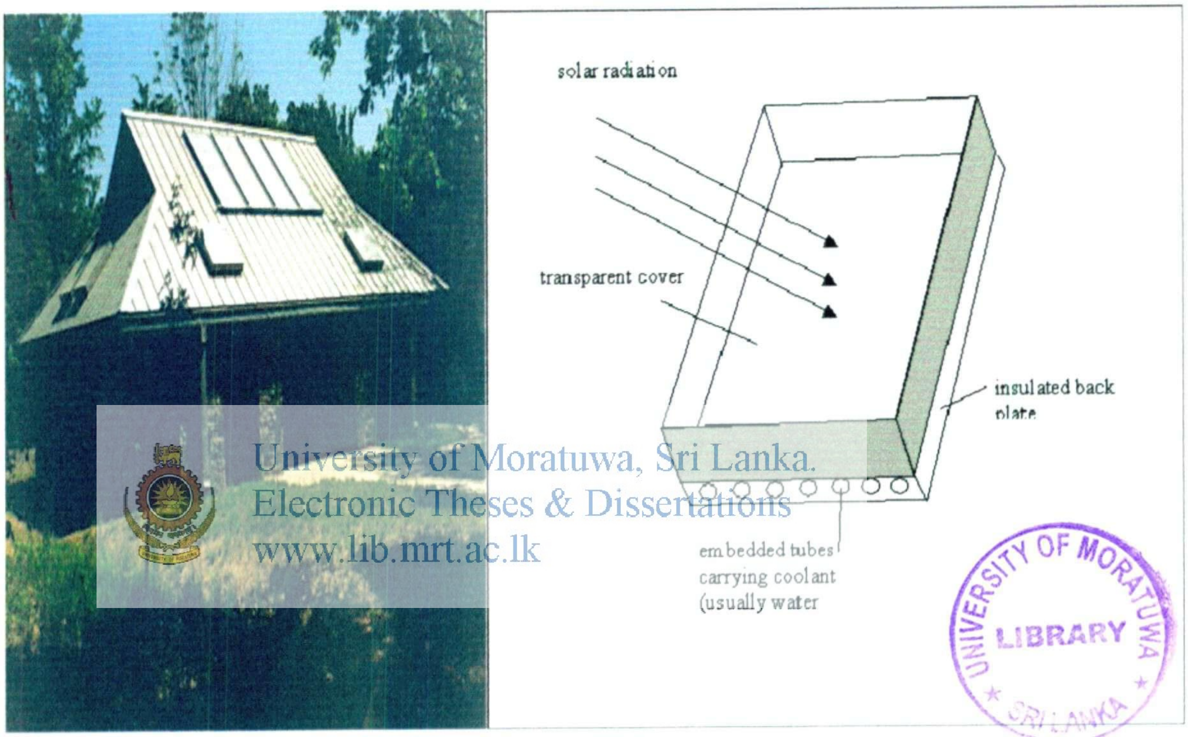


Figure 3.3: solar collectors on a building
Source: The Australian Institute of Energy

The rate at which heat is absorbed by the collector (W) is given by:

$$Q_p = G_s At\, a$$

where G_s is the incident radiation (W), A the area of the collector (m^2), t the transmission factor of the cover and a the absorptance of the back plate. The losses from the collector are calculated from

$$Q_L = UA(T_c - T_a)$$

where U is the collector U-value (W/m^2 °C) , T_c is the average collector plate temperature and T_a is the air temperature. The useful rate of energy recovery from the collector is therefore

$$Q_R = G_s At\, a - UA(T_c - T_a)$$

The temperature rise in the water flowing through the collector is given by:

D $T = Q_s/mC$

where m is the water flow rate to the collector (kg) and C is the water specific heat (J/kg °C). The simplest solar collector is a window, which admits heat and light into a building, reducing both fossil fuel consumption for heating and electrical energy consumption for lighting.

3. 2. Sun Path

Sun path refers to the apparent significant seasonal-and-hourly positional changes of the sun (and length of daylight) as the Earth rotates, and orbits around the sun(table 04) . The relative position of the sun is a major factor in the heat gain of buildings and in the performance of solar energy systems[14]. Accurate location-specific knowledge of sun path and climatic conditions is essential for economic decisions about solar collector area, orientation, landscaping, summer shading, and the cost-effective use of solar trackers(fig 3.4 & 3.5)

Date	Sunrise	Sunset	Length	Change	Dawn	Dusk	Length	Change
Today	05:54	18:25	12:31		05:31	18:48	13:17	
+1 day	05:54	18:25	12:31	00:00 equal length	05:32	18:48	13:16	00:01 shorter
+1 week	05:55	18:27	12:32	00:01 longer	05:33	18:50	13:17	00:00 shorter
+2 weeks	05:57	18:28	12:31	00:00 shorter	05:34	18:51	13:17	00:00 equal length
+1 month	06:00	18:31	12:31	00:00 equal length	05:38	18:53	13:15	00:02 shorter
+2 months	06:05	18:28	12:23	00:08 shorter	05:43	18:50	13:07	00:10 shorter
+3 months	06:03	18:15	12:12	00:19 shorter	05:42	18:36	12:54	00:23 shorter
+6 months	06:10	17:54	11:44	00:47 shorter	05:47	18:17	12:30	00:47 shorter

Table 04 Colombo - Sunrise, sunset, dawn and dusk times
Source: http://www.gaisma.com

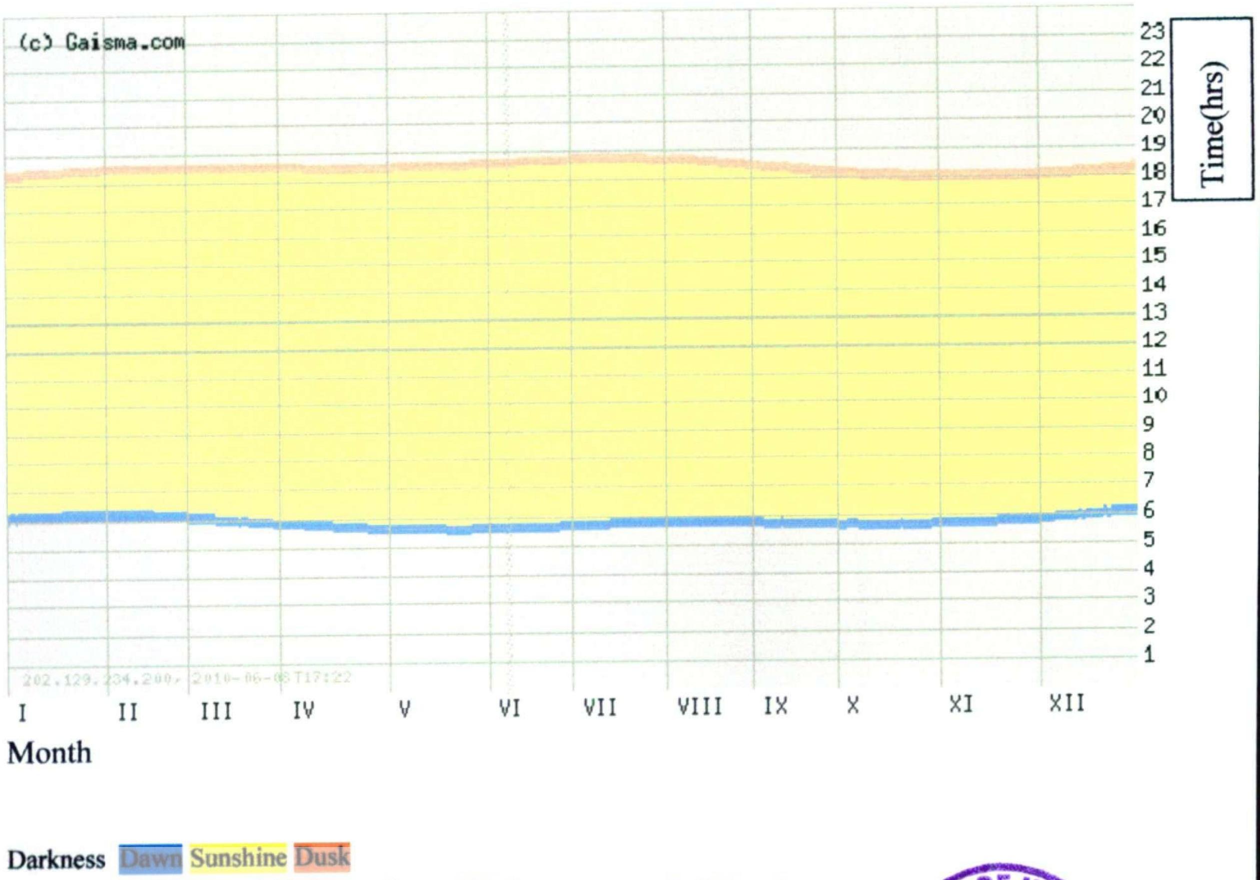


Fig. 3.4 Graph of Sunrise, sunset, dawn and dusk times- Colombo
Source: http://www.gaisma.com

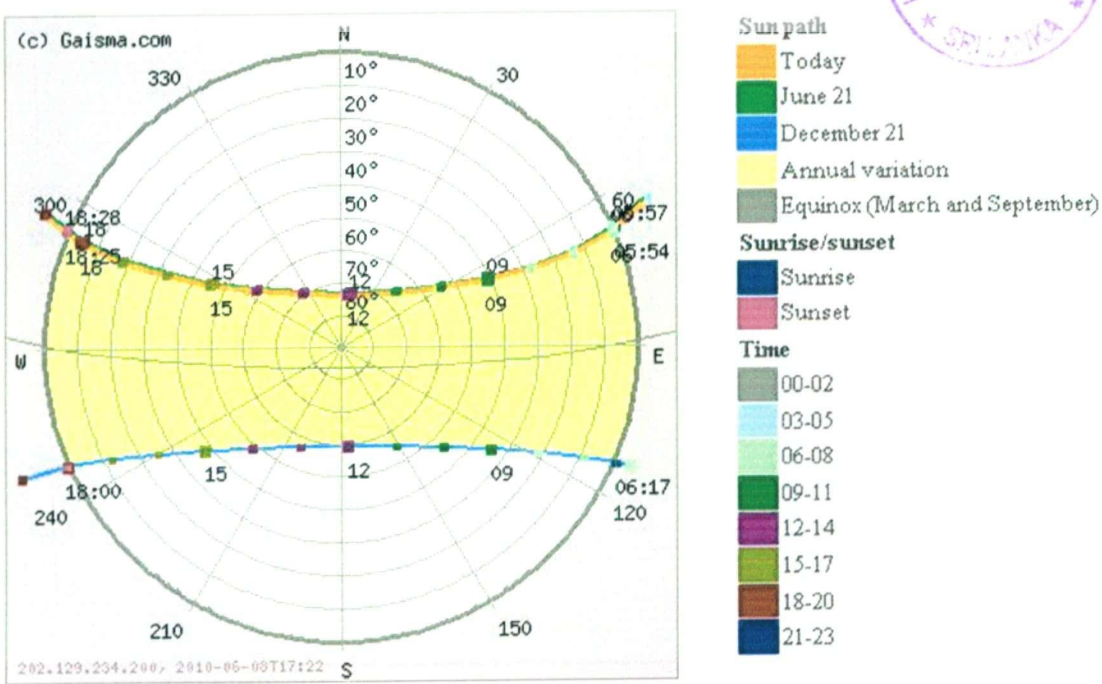


Fig. 3.5 Sun path diagram – Colombo
Source: http://www.gaisma.com

3.3. Tracking method

There are two commonly discussed methods of tracking control. These are active, or closed loop, control system and the passive, or open loop, control systems. Systems of the active or closed loop, type "actively" make some measurement of where the collector is and then, if alignment is not proper, activate devices that can change the orientation of the collector. The sensing devices that make the system an active one are usually light sensitive detectors such as photovoltaic (solar) cells or phototransistors. The former devices, if operated within certain constraints, produce electrical currents and voltages that are related to the intensity of the sunlight falling on them.

Systems of the passive, or open loop, control type respond to pre-programmed control steps in order to track the sun. For example, a minicomputer working in conjunction with and accurate clock and programmed to calculate the necessary collector position as a function of time of day and year feeds information to the drive train. When we analysis the mechanism of shaft rotating used for the previous experiments, maintaining a constant the angular velocity is the most important for such experiment. Designing a new solar tracking mechanism by means of water discharging method would be more convenient to get accurate results for tracking the sun. Selecting a water discharging method should be controlled very smoothly may be advanced for fine tuning the discharge and calibrating the angular velocity when the sun travels its orbit. We fixed a Ventury meter which calibrated by Institute of Technology (ITI), Sri Lanka for the purpose of measuring water discharge flow and control of water discharge. Therefore we rest assured our raw data readability and credibility over this experiment.

3.3.1. Study of the pattern of water discharge from a bottom hole of a water tank

As the first step, the discharge pattern of water from a tank was studied. The type of the tank is shown in Fig 3.6. The discharge tube was the plastic tube used in hospitals for intravenous injections, which is also readily available. Assuming that the tracking starts at 0800 hrs, the drop weight of the tank with time is given in Table 05. The weight of the water tank vs. time graph is given in Fig. 3.7.

Time, hrs	0800	1000	1200	1398	1600
Tank kg	120.21	98.20	76.17	54.24	34.19
Tank weight as a %	100	81.7	63.4	45.1	28.4

Table 05: Variation of weight of water tank with time

Fig. 3.6 Water tanks used for the study

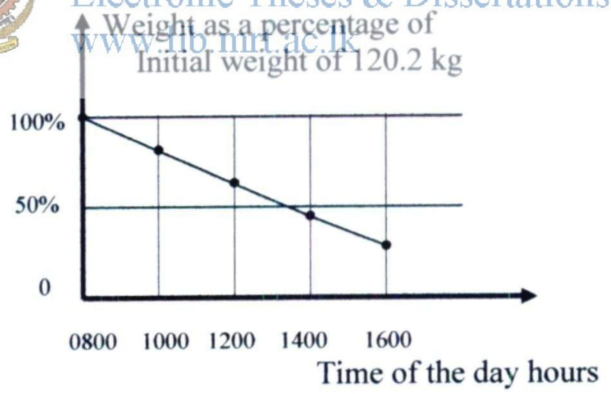


Fig. 3.7 Graph of the weight of tank vs. time of day

3.4. Design of the noncircular sprocket wheel

As a first step, a bicycle sprocket wheel was taken and mounted on the shaft with an eccentricity as sketched in Fig. 3.8.

At the start of the tracking in the morning, the chain supporting the water tank is tangential to the wheel at the lowest distance from tracking axis. Using the following notation

M = mass of the counterweight

R = radius of the circular sprocket wheel

$\breve{m}$ = mass of the water tank (whose variation with time has been experimentally found)

$\breve{r}$ = radius of the noncircular wheel (which is designed to have optimum solar tracking)

The equation for torque balance gives us

$$M\,g\,R \;=\; \breve{m}\,g\,\breve{r}(\theta) \qquad \text{(Eq. 1)}$$

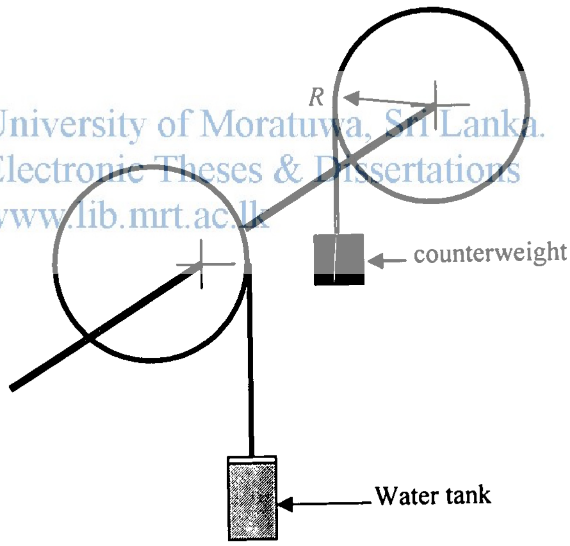


Fig. 3.8 Mounting arrangement of water tank and counterweight

In Eq. 1, the variation of $\breve{m}$ has been found. To get the required variation of θ with time, $\breve{r}$ (θ), can be chosen.

3.5. Eccentrically mounted sprocket wheel for testing the concept

Because of the limitation of resources, a truly noncircular sprocket wheel was not designed according to Eq. 1. Instead, a sprocket wheel was mounted with an eccentricity as shown in Fig. 3.9. With this arrangement it was possible to prove the validity of this concept as shown in Fig. 3.10.

Fig. 3.9 Sprocket wheel mounts with an eccentricity

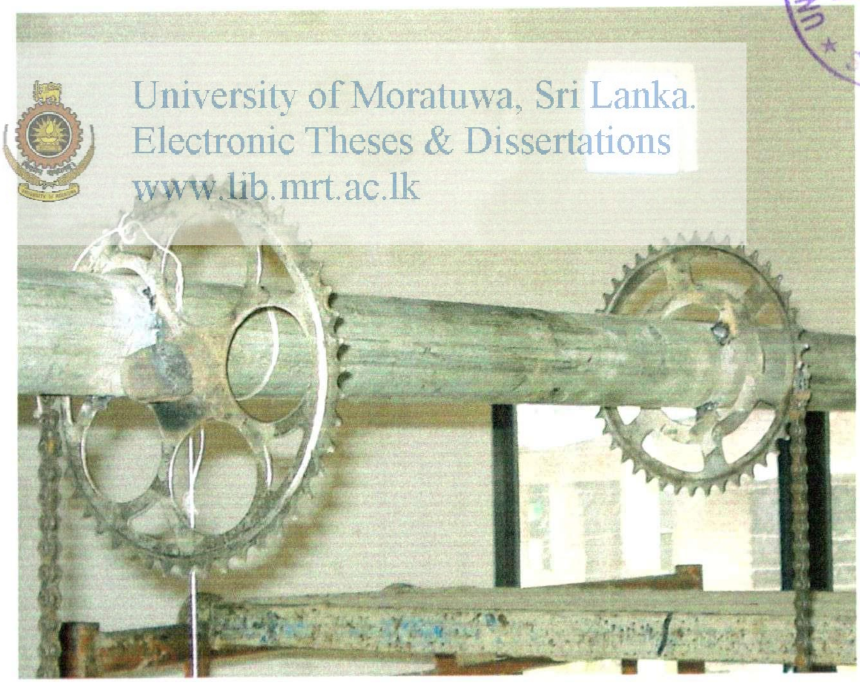


Fig. 3.10 Eccentric Wheel & Regular Wheel

3.6. Cost Analysis

In the market there are lots of solar tracking devices available and they can be readily bought and installed. The only trouble is that all these gadgets are either expensive, or complex, or must be recalibrated frequently, or require an outside source of power with constant frequency and voltage and a separate feed back path to correct their errors, or some combinations of the above. What the world has long needed is a simple, inexpensive, self-contained solar tracker that works on the energy it receives directly from the sun. Further the solar industry will continue to see impressive gains in efficiencies and cost reductions as economies of scale come into play with larger production facilities.

On the other hand price of locally develop two axis solar tracking system is given in appendix-E inclusive all cost of materials, components, subassemblies and labour. Introduction of this kind of tracking system is very much advantages to developing country like Sri Lanka as this can be manufactured easily with locally available materials and labour. Also it will provide some employment opportunities to local technical personnel. Further life time and durability, functionality of the system is high compared to imported systems as this has been design by considering all ingenious factors like daily and yearly local solar insolation variations, wind speed, rain falls, humidity and other environmental factors. Having considering all these factors it is productive to use this locally develop gravity operated tracking system.

Dramatic decreases in the cost of solar systems plus higher efficiency and longer system life spans all mean that installing a solar electric system makes good financial sense. Generating own clean, renewable solar power can significantly lower monthly utility bill and provide a hedge against future rate increases. Therefore anyone use solar energy get the benefits of, save money every month by lowering your electric bills, utilize free energy from the sun to reduce the effect of utility rate increases, enjoy energy independence by becoming your own power producer and protect the environment by using clean, renewable energy in your home.

Solar energy can be substantially making use in rural areas of Sri Lanka, where there is no grid electricity available. Apart from that, solar energy has number of advantages compared to other sources of energy. Among them, non- pollute is the most important factor in present world. As a tropical country Sri Lanka get substantial amount of solar energy through out the year, so that solar systems can be economically used. Solar systems are simple; do not have moving parts and last long time.

But on the other hand this source of energy is highly unreliable as the amounts of power that can be produce depend on amount of sunlight falling into the system.

With the introduction of this single axis tracking the above issue can be resolve partially. But variation of solar irradiation through out day will cause to change in gain. That cannot be forecast exact output at a particular time frame, as depends on factors of whether condition, height of sun over the sky etc. With shiny sky solar irradiation can be maximize whereas in the condition of diffuse light passing thin clouds will reduce the energy and further in very bad weather conditions with thick, dark clouds light intensity could falls to very low value resulting only very small portions from maximum energy. The height of sun over the horizon varies with seasons. When the sun is very high in the sky, rays travel through the atmosphere more quickly over the shorter distance than when sun is low in sky and light is scattered more and becomes more diffuse when passing through fog or pollution.

Presently there are some technical issues that have overcome to get the maximum output from solar system. The main issue is the changes in the direction of sunrays, as result difficulties in tracking. There are no any tracking mechanisms available with most of common solar energy systems, due to high cost. With the proposed gravity operated systems the above issues will be overcome into certain extent by having simple no power consuming and efficient tracking mechanism. Research has reveals that one axis tracking can improve the efficiency by about 25% and two axes tracking by about 40%, but with increased cost and complexities. With increase efficiency solar energy can be popularize in rural areas as that following advantages further no running cost, pollution free, almost maintenance free, driven by never ending source of energy and suitable for remote locations. But solar energy has following disadvantages of high capital cost, restriction of power generation on day time and high dependence on unreliable whether and climatic condition. But the annual energy production is maximum when the array is tilted at the latitude angle. Using inaccurate solar data will cause design errors, so should try to find accurate, long-term solar data for your system location. Cost of importing a similar capacity single axis solar tracking system to Sri Lanka

Cost of 100W panel	=	Rs. 60,000.00
Cost of increase 25W (using new panel)	=	Rs. 15,000.00
Cost of New tracking system (See Appendix)	=	Rs. 12,670.00
Cost saving of developing this system for 100W	=	Rs. 2,330.00

Table 06 Economic Analysis

CHAPTER-04 - RESULTS & DISCUSSION

An object of this research is to find how to eliminate defects or disadvantages in the prior art by providing a solar tracking mechanism with no electric power supply and no electric control devices for tracking the sun.

Another object of this research is to provide a solar tracking mechanism capable of substantially continuously tracking the sun movement with time, even if the sun disappears for a relatively long time, by utilizing a plurality of compound parabolic concentrators arranged in the east-west direction.

According to this for achieving these and other objects, there is provided a solar tracking mechanism for continuously tracking the movement of the sun with time secured to a base set on the ground through a frame and the solar tracking mechanism comprises a solar radiant energy receiver secured to be rotatable about a rotating shaft which is supported by the frame and extends horizontally in the east-west direction, a device for catching a solar beam of the sun travelling with time, and a mechanism operatively connected to the device for rotating the rotating shaft together with the solar radiant energy receiver.

4.1 Observed rotations of the tracking shaft with time

The observed rotations of the tracking shaft with time is plotted in Fig. 4.3. It is seen that the rotation is not linear and not in full range (0^0- 120^0) with the tracking duration as we expected because the noncircular sprocket wheel was not custom-made. By employing a custom-made non-circular wheel and a suitable gear ratio, the solar panel can be rotated as desired to track the sun as closely as possible.

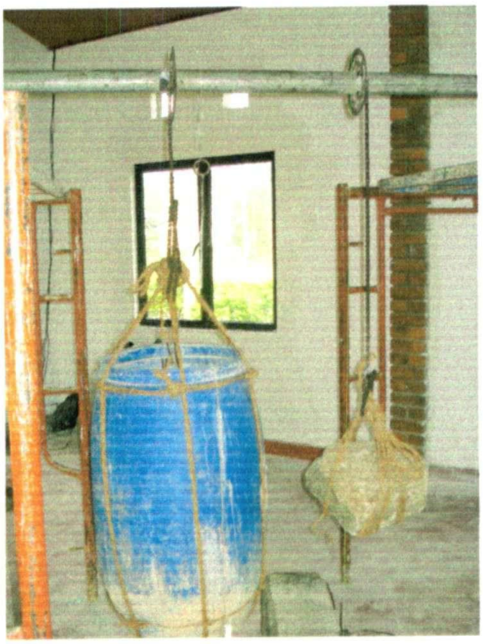


Fig. 4.1 Tested system in test 3

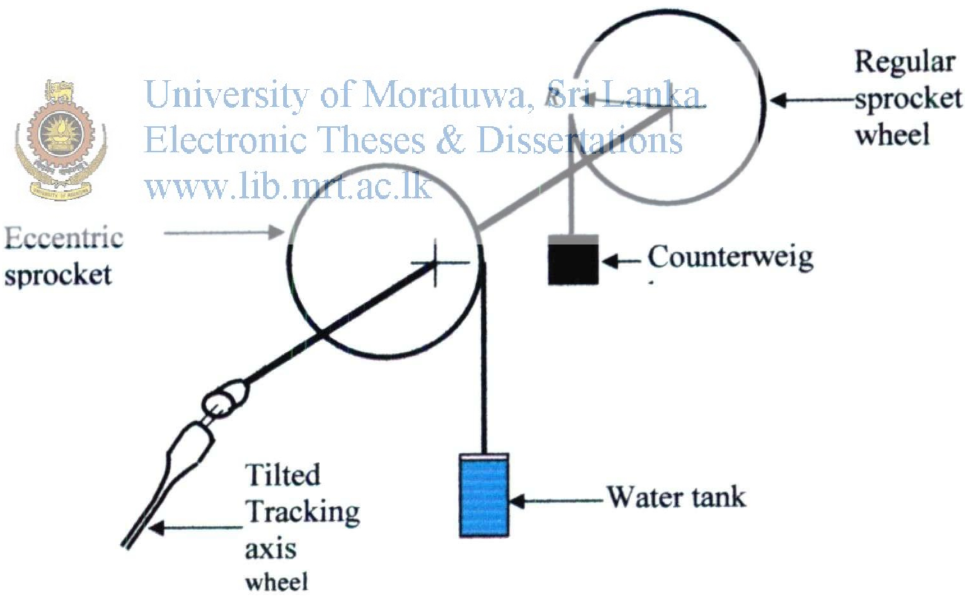


Fig. 4.2 Arrangement of water tank and counterweight and tilted tracking axis

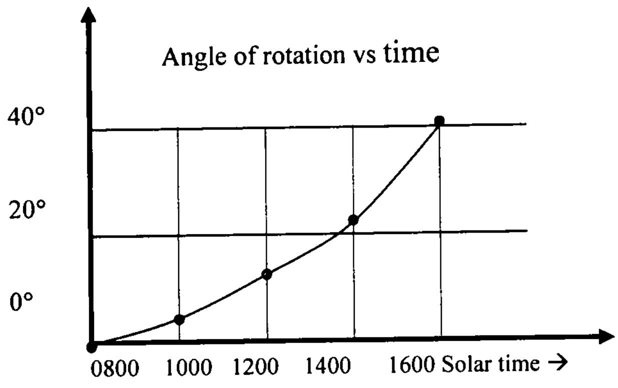


Fig. 4.3 Observed rotation of the shaft with time

4.2 Discussion and further research underway

A low-cost solar tracker which is working on open-loop mode was designed, constructed and tested. The tracker is working entirely on mechanical principles and labour force available in rural Sri Lanka can attend to the operation and maintenance of the proposed mechanism. Efforts are underway to fine tune the system and obtain more accurate tracking.

CHAPTER-05 – CONCLUSIONS

The success of our work will make solar energy accessible to the average consumer because of reduced costs. Solar thermal projects leads to energy reliability and security of Sri Lanka. Solar projects save money for the industry and businesses by avoiding power outages. The development of such a solar technology helps to protect air quality, so that it will directly benefit for the children and the elderly, by using a clean, non-polluting fuel source. The saving of fossil fuel is an advantage for being a green environment. Even though solar tracking devices are available in the market presently, there are restrictions to get desired outcomes. When implementing solar thermal projects, we have to face for a problem to meet feasible for ROI due to either expense or its complexity. And also we have identified some other difficulties in operating the project, because it has to be recalibrated frequently, or require an outside source of power with constant frequency and voltage and a separate feedback path to correct their errors, or some combination of the above. What the world has long needed is a simple, inexpensive and self-contained solar tracker that works on the energy it receives directly from the sun.

Considering the findings and facts that has been justified it is advantage to use passive tracking system compared to active tracking systems with respect to system complexities, energy wastages and cost. But it was revealed that available passive tracking systems are not considerably matched with the requirements demanded by Sri Lankan solar energy sector. One of the main problems with such systems is narrowness of tracking range. This angle is sufficient for non-tropical countries as their day lighting time is short.

It is an advantage to have a simple, low cost and no power consuming tracking system, so that ordinarily villagers can profitably make use of this system with some economical solar panel to fulfil their daily electricity requirements. It can be assured that, proposed alternative energy system will effectively fill the gap and fulfil the energy demand of remote areas of Sri Lanka where the electricity from national grid is unavailable. Further consumers of this system can enjoy additional benefits such as energy independence as "Fuel" is already plentifully delivered free everywhere in Sri

Lanka, minimal maintenance, maximum reliability, reduce vulnerability to power loss and system is easily expanded, environmentally friendliness. Of all the renewable energy sources available, solar cells have the smallest environmental impacts. Electricity produced from photovoltaic cells does not result in air or water pollution, deplete natural resources, or endanger animal or human health. The main disadvantage of having solar panel is the variation of current level due to varying light conditions. Because of this reason it is difficult to forecast exact output and build a control system using direct solar energy. Therefore components like converters are used to maximize the power drawn from panel or else store energy in a battery and use that current.

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Appendix –A

The paper publish @ SLAAS

The paper published regarding this tracking system at Sri Lanka Association for the Advancement of Science (SLAAS) in 64th Annual Sessions held on 01-06 December 2008.

Link @ SLAAS :

1. http://www.slaas.org ⇨ Publication ⇨ Annual Session 2008

   Abstract Ref No :314/C

   Page No: 67

2. http://www.slaas.org/publications_files/2008_p1_abstracts.pdf

Sri Lanka Association for the Advancement of Science

Proceedings of the 64th Annual Sessions

1 - 6 December, 2008

Part I - Abstracts

Sri Lanka Association for the Advancement of Science - 2008

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Sri Lanka Association for the Advancement of Science
Vidya Madiraya, Vidya Mawatha, Colombo 7, Sri Lanka

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Operation of two-axis solar tracking by the discharge of water from a tank hanging from a non-circular sprocket wheel

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Department of Mechanical Engineering, University of Moratuwa, Moratuwa

Two-axis solar tracking system operated by the discharge of water from a bottom hole of a tank filled with water was designed, constructed and tested. The water tank is hanged by a chain passing over a circular sprocket wheel mounted eccentrically on a shaft free to rotate about a North-South axis. A counterweight is also hanged by another chain passing over a circular sprocket wheel mounted on the same shaft.

In the morning, the water tank is filled to top. The water tank and the counterweight on either side of the shaft balance in such a way that the solar panel is facing the East as required. As the water drips out from bottom hole of the tank, the reduction in weight causes the shaft to rotate until the moments by the water tank and the counterweight equalize.

This study shows that a custom-designed noncircular sprocket wheel can be used instead of the eccentric circular wheel, and the contour of the non-circular sprocket wheel can be designed taking into consideration the reduction of weight of the tank with time and the required rotation for solar tracking. In addition to the hourly tracking by this mechanism, provision can be made to tilt the solar panel about the second tracking axis manually on a weekly basis to compensate for the seasonal variation of the Sun's declination. The additional cost involved in making this robust mechanism is justifiable because two-axis tracking can give about 30% more solar power on average and much more on days which are cloudy at noon but not in the morning or afternoon.

To prevent vibrations due to wind, the water tank and the counterweight can be placed at ground level and be surrounded by a shield.

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Appendix –B

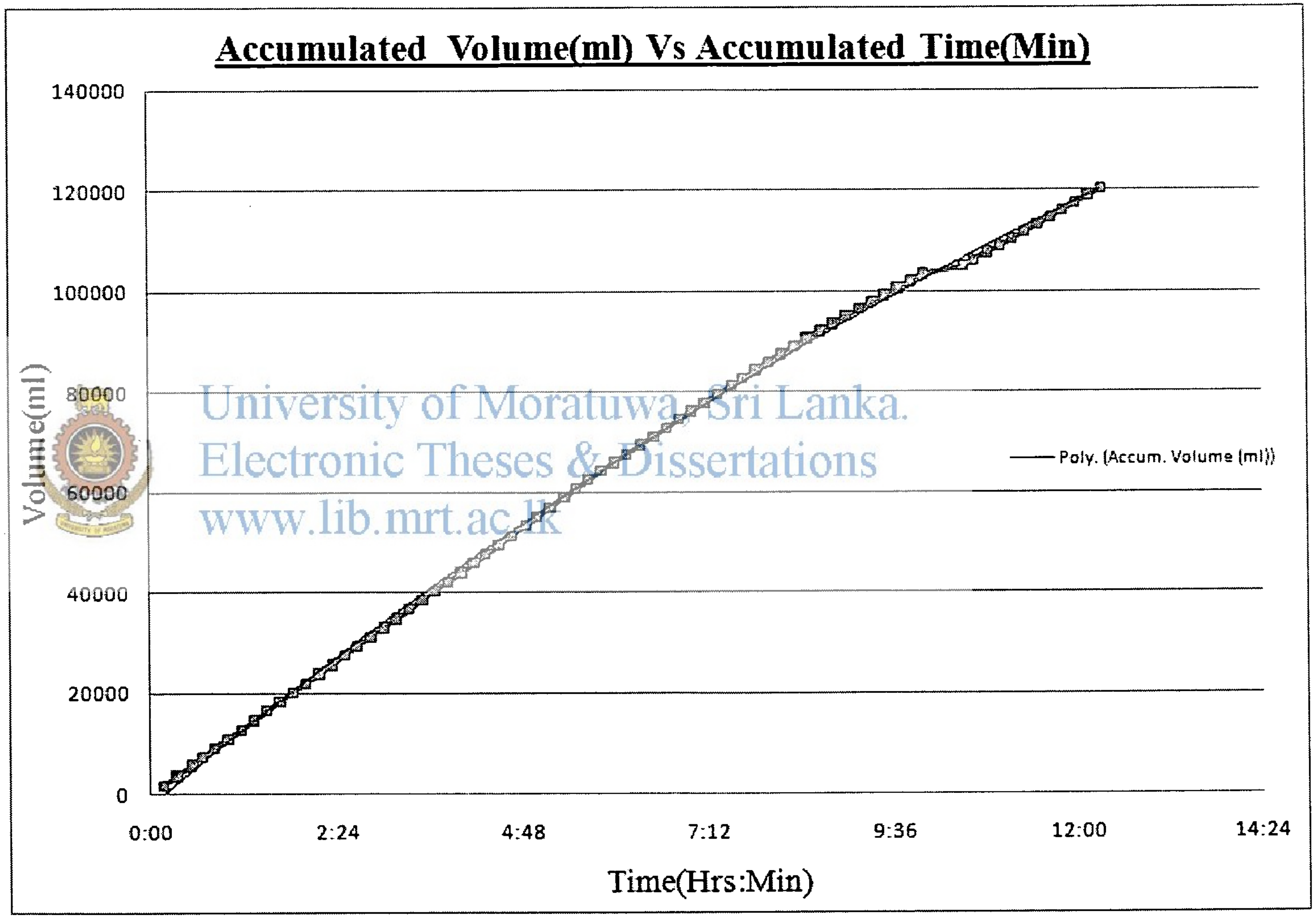
Data Collection Sheet - Test No 01

Date:	2008 / 04 / 12		Removed water volume			
Time period	Time Gap (min)	Accum. Time (Min)	Volume (ml)	Accum. Volume (ml)	weight of water (kg) Calculated	Weight of tank (kg) calculated
14:00 - 14:10	0:10	0:10	1830	1830	1.830	120.220
14:10 - 14:20	0:10	0:20	1850	3680	3.680	118.390
14:20 - 14:32	0:12	0:32	2130	5810	5.810	116.540
14:32 - 14:40	0:08	0:40	1520	7330	7.330	114.410
14:40 - 14:50	0:10	0:50	1810	9140	9.140	112.890
14:50 - 15:00	0:10	1:00	1850	10990	10.990	111.080
15:00 - 15:10	0:10	1:10	1850	12840	12.840	109.230
15:10 - 15:20	0:10	1:20	1835	14675	14.675	107.380
15:20 - 15:30	0:10	1:30	1840	16515	16.515	105.545
15:30 - 15:40	0:10	1:40	1825	18340	18.340	103.705
15:40 - 15:50	0:10	1:50	1840	20180	20.180	101.880
15:50 - 16:00	0:10	2:00	1840	22020	22.020	100.040
16:00 - 16:10	0:10	2:10	1835	23855	23.855	98.200
16:10 - 16:20	0:10	2:20	1840	25695	25.695	96.365
16:20 - 16:30	0:10	2:30	1860	27555	27.555	94.525
16:30 - 16:40	0:10	2:40	1800	29355	29.355	92.665
16:40 - 16:50	0:10	2:50	1840	31195	31.195	90.865
16:50 - 17:00	0:10	3:00	1830	33025	33.025	89.025
7:45 - 7:55	0:10	3:10	1830	34855	34.855	87.195
7:55 - 8:05	0:10	3:20	1840	36695	36.695	85.365
8:05 - 8:15	0:10	3:30	1840	38535	38.535	83.525
8:15 - 8:25	0:10	3:40	1850	40385	40.385	81.685
8:25 - 8:35	0:10	3:50	1830	42215	42.215	79.835
8:35 - 8:45	0:10	4:00	1840	44055	44.055	78.005
8:45 - 8:55	0:10	4:10	1850	45905	45.905	76.165
8:55 - 9:04	0:09	4:19	1770	47675	47.675	74.315
9:04 - 9:14	0:10	4:29	1825	49500	49.500	72.545
9:14 - 9:24	0:10	4:39	1850	51350	51.350	70.720
9:24 - 9:35	0:11	4:50	2000	53350	53.350	68.870
9:35 - 9:44	0:09	4:59	1800	55150	55.150	66.870
9:44 - 9:54	0:10	5:09	1870	57020	57.020	65.070
9:54 - 10:05	0:11	5:20	2010	59030	59.030	63.200
10:05 - 10:14	0:09	5:29	1750	60780	60.780	61.190
10:14 - 10:24	0:10	5:39	1800	62580	62.580	59.440
10:24 - 10:34	0:10	5:49	1700	64280	64.280	57.640
10:34 - 10:44	0:10	5:59	1700	65980	65.980	55.940

Data Collection Sheet - Test No 01

cont..

10:44	-	10:54	0:10	6:09	1700	67680	67.680	54.240
10:54	-	11:05	0:11	6:20	1800	69480	69.480	52.540
11:05	-	11:15	0:10	6:30	1680	71160	71.160	50.740
11:15	-	11:25	0:10	6:40	1690	72850	72.850	49.060
11:25	-	11:35	0:10	6:50	1690	74540	74.540	47.370
11:35	-	11:45	0:10	7:00	1680	76220	76.220	45.680
14:40	-	14:50	0:10	7:10	1650	77870	77.870	44.000
14:50	-	15:00	0:10	7:20	1640	79510	79.510	42.350
15:00	-	15:11	0:11	7:31	1730	81240	81.240	40.710
15:11	-	15:20	0:09	7:40	1570	82810	82.810	38.980
15:20	-	15:30	0:10	7:50	1620	84430	84.430	37.410
15:30	-	15:40	0:10	8:00	1600	86030	86.030	35.790
15:40	-	15:50	0:10	8:10	1580	87610	87.610	34.190
15:50	-	16:00	0:10	8:20	1560	89170	89.170	32.610
16:00	-	16:10	0:10	8:30	1540	90710	90.710	31.050
16:10	-	16:20	0:10	8:40	1450	92160	92.160	29.510
16:20	-	16:30	0:10	8:50	1450	93610	93.610	28.060
16:30	-	16:40	0:10	9:00	1440	95050	95.050	26.610
16:40	-	16:50	0:10	9:10	1430	96480	96.480	25.170
16:50	-	17:00	0:10	9:20	1400	97880	97.880	23.740
17:00	-	17:10	0:10	9:30	1410	99290	99.290	22.340
17:10	-	17:20	0:10	9:40	1400	100690	100.690	20.930
17:20	-	17:30	0:10	9:50	1400	102090	102.090	19.530
17:30	-	17:40	0:10	10:00	1390	103480	103.480	18.130
6:30	-	7:02	0:32	10:32	1510	104990	104.990	16.740
7:02	-	7:10	0:08	10:40	1230	106220	106.220	15.230
7:10	-	7:21	0:11	10:51	1480	107700	107.700	14.000
7:21	-	7:30	0:09	11:00	1350	109050	109.050	12.520
7:30	-	7:40	0:10	11:10	1400	110450	110.450	11.170
7:40	-	7:50	0:10	11:20	1400	111850	111.850	9.770
7:50	-	8:00	0:10	11:30	1400	113250	113.250	8.370
8:00	-	8:10	0:10	11:40	1400	114650	114.650	6.970
8:10	-	8:20	0:10	11:50	1400	116050	116.050	5.570
8:20	-	8:30	0:10	12:00	1380	117430	117.430	4.170
8:30	-	8:40	0:10	12:10	1400	118830	118.830	2.790
8:40	-	8:50	0:10	12:20	1390	120220	120.220	1.390


Accumulated Volume(ml) Vs Accumulated Time(Min)
140000
120000
100000
80000
60000
40000
20000
0
Volume(ml)
0:00
2:24
4:48
7:12
9:36
12:00
14:24
Time(Hrs:Min)
Poly. (Accum. Volume (ml))

Data Collection Sheet - Test No 02

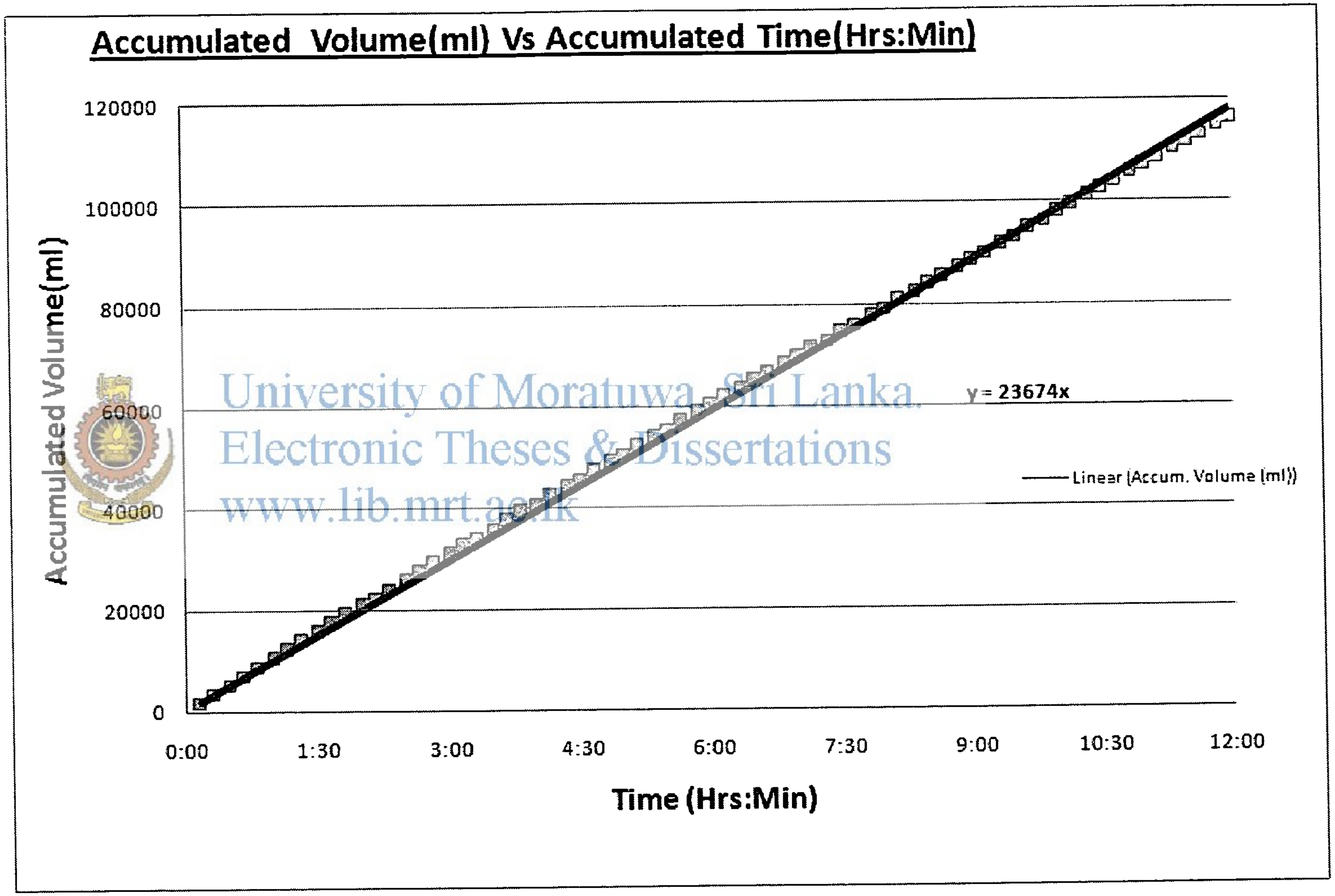
Date: 2008 / 05 / 03

Time period	Time Gap (min)	Accum. Time (Min)	Removed water volume: Volume (ml)	Accum. Volume (ml)	weight of water (kg) Calculated	Weight of tank (kg) calculated
9:00 - 9:10	0:10	0:10	1730	1730	1.730	116.240
9:10 - 9:20	0:10	0:20	1750	3480	3.480	114.51
9:20 - 9:30	0:10	0:30	1740	5220	5.220	112.76
9:30 - 9:40	0:10	0:40	1730	6950	6.950	111.02
9:40 - 9:50	0:10	0:50	1720	8670	8.670	109.29
9:50 - 10:00	0:10	1:00	1720	10390	10.390	107.57
10:00 - 10:10	0:10	1:10	1720	12110	12.110	105.85
10:10 - 10:20	0:10	1:20	1720	13830	13.830	104.13
10:20 - 10:30	0:10	1:30	1720	15550	15.550	102.41
10:30 - 10:40	0:10	1:40	1720	17270	17.270	100.69
10:40 - 10:50	0:10	1:50	1700	18970	18.970	98.97
10:50 - 11:00	0:10	2:00	1720	20690	20.690	97.27
11:00 - 11:10	0:10	2:10	1680	22370	22.370	95.55
11:10 - 11:20	0:10	2:20	1700	24070	24.070	93.87
11:20 - 11:30	0:10	2:30	1700	25770	25.770	92.17
11:30 - 11:40	0:10	2:40	1700	27470	27.470	90.47
11:40 - 11:50	0:10	2:50	1700	29170	29.170	88.77
11:50 - 12:00	0:10	3:00	1690	30860	30.860	87.07
12:00 - 12:10	0:10	3:10	1700	32560	32.560	85.38
12:10 - 12:20	0:10	3:20	1690	34250	34.250	83.68
12:20 - 12:30	0:10	3:30	1700	35950	35.950	81.99
14:00 - 14:10	0:10	3:40	1650	37600	37.600	80.29
14:10 - 14:20	0:10	3:50	1650	39250	39.250	78.64
14:20 - 14:30	0:10	4:00	1640	40890	40.890	76.99
14:30 - 14:40	0:10	4:10	1640	42530	42.530	75.35
14:40 - 14:50	0:10	4:20	1630	44160	44.160	73.71
14:50 - 15:00	0:10	4:30	1650	45810	45.810	72.08
15:00 - 15:10	0:10	4:40	1640	47450	47.450	70.43
15:10 - 15:20	0:10	4:50	1640	49090	49.090	68.79
15:20 - 15:30	0:10	5:00	1640	50730	50.730	67.15
15:30 - 15:40	0:10	5:10	1630	52360	52.360	65.51
15:40 - 15:50	0:10	5:20	1600	53960	53.960	63.88
15:50 - 16:00	0:10	5:30	1610	55570	55.570	62.28
9:15 - 9:25	0:10	5:40	1630	57200	57.200	60.67
9:25 - 9:35	0:10	5:50	1600	58800	58.800	59.04
9:35 - 9:45	0:10	6:00	1600	60400	60.400	57.44

Data Collection Sheet - Test No 02

cont..

9:45	-	9:55	0:10	6:10	1600	62000	62.000	55.84
9:55	-	10:05	0:10	6:20	1550	63550	63.550	54.24
10:05	-	10:15	0:10	6:30	1580	65130	65.130	52.69
10:15	-	10:25	0:10	6:40	1580	66710	66.710	51.11
10:25	-	10:35	0:10	6:50	1580	68290	68.290	49.53
10:35	-	10:45	0:10	7:00	1560	69850	69.850	47.95
10:45	-	10:55	0:10	7:10	1580	71430	71.430	46.39
10:55	-	11:05	0:10	7:20	1580	73010	73.010	44.81
11:05	-	11:15	0:10	7:30	1580	74590	74.590	43.23
11:15	-	11:25	0:10	7:40	1580	76170	76.170	41.65
11:25	-	11:35	0:10	7:50	1560	77730	77.730	40.07
11:35	-	11:45	0:10	8:00	1570	79300	79.300	38.51
11:45	-	11:55	0:10	8:10	1570	80870	80.870	36.94
11:55	-	12:05	0:10	8:20	1570	82440	82.440	35.37
12:05	-	12:15	0:10	8:30	1550	83990	83.990	33.8
13:50	-	14:00	0:10	8:40	1560	85550	85.550	32.25
14:00	-	14:10	0:10	8:50	1560	87110	87.110	30.69
14:10	-	14:20	0:10	9:00	1570	88680	88.680	29.13
14:20	-	14:30	0:10	9:10	1570	90250	90.250	27.56
14:30	-	14:40	0:10	9:20	1560	91810	91.810	25.99
14:40	-	14:50	0:10	9:30	1550	93360	93.360	24.43
14:50	-	15:00	0:10	9:40	1550	94910	94.910	22.88
15:00	-	15:10	0:10	9:50	1550	96460	96.460	21.33
15:10	-	15:20	0:10	10:00	1550	98010	98.010	19.78
15:20	-	15:30	0:10	10:10	1550	99560	99.560	18.23
15:30	-	15:40	0:10	10:20	1550	101110	101.110	16.68
15:40	-	15:50	0:10	10:30	1550	102660	102.660	15.13
15:50	-	16:00	0:10	10:40	1540	104200	104.200	13.58
16:00	-	16:10	0:10	10:50	1520	105720	105.720	12.04
16:10	-	16:20	0:10	11:00	1520	107240	107.240	10.52
16:20	-	16:30	0:10	11:10	1500	108740	108.740	9
16:30	-	16:40	0:10	11:20	1500	110240	110.240	7.5
16:40	-	16:50	0:10	11:30	1500	111740	111.740	6
16:50	-	17:00	0:10	11:40	1500	113240	113.240	4.5
17:00	-	17:10	0:10	11:50	1500	114740	114.740	3
17:10	-	17:20	0:10	12:00	1500	116240	116.240	1.5

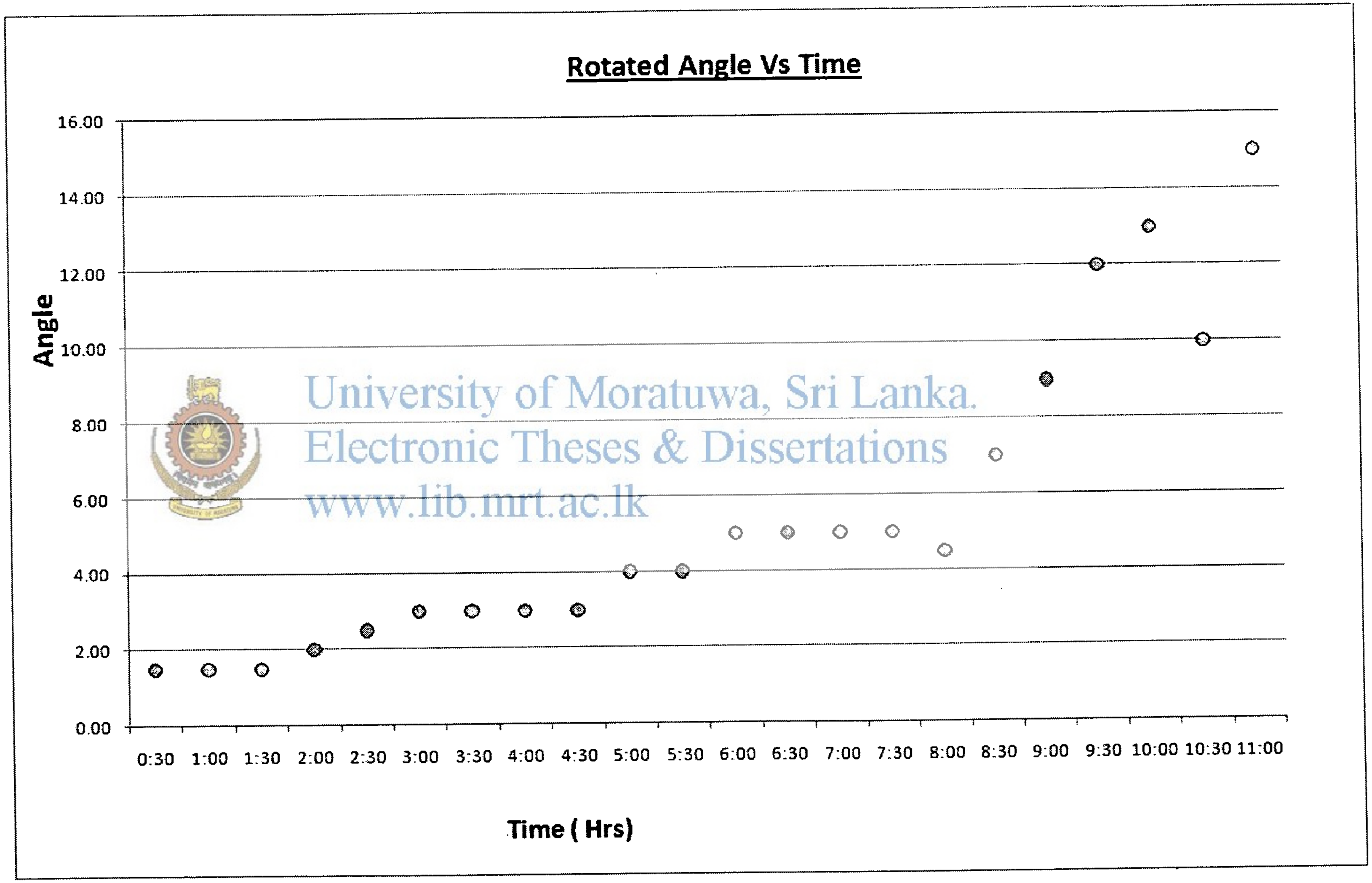

Accumulated Volume(ml) Vs Accumulated Time(Hrs:Min)
Accumulated Volume(ml)
120000
100000
80000
60000
40000
20000
0
0:00
1:30
3:00
4:30
6:00
7:30
9:00
10:30
12:00
Time (Hrs:Min)
y = 23674x
Linear (Accum. Volume (ml))

Data Collection Sheet - Test No 03

Date: 2008 / 07 / 20

Time period	Time Gap(min)	Accumulated Time (Min)	Rotate Angle°	Total rotation deg
8:00 - 8:30	0:30	0:30	1.50	0
8:30 - 9:00	0:30	1:00	1.50	1.50
9:00 - 9:30	0:30	1:30	1.50	3.00
9:30 - 10:00	0:30	2:00	2.00	5.00
10:00 - 10:30	0:30	2:30	2.50	7.50
10:30 - 11:00	0:30	3:00	3.00	10.50
11:00 - 11:30	0:30	3:30	3.00	13.50
11:30 - 12:00	0:30	4:00	3.00	16.50
12:00 - 12:30	0:30	4:30	3.00	19.50
12:30 - 13:00	0:30	5:00	4.00	23.50
13:00 - 13:30	0:30	5:30	4.00	27.50
13:30 - 14:00	0:30	6:00	5.00	32.50
14:00 - 14:30	0:30	6:30	5.00	37.50
14:30 - 15:00	0:30	7:00	5.00	42.50
15:00 - 15:30	0:30	7:30	5.00	47.50
15:30 - 16:00	0:30	8:00	4.50	52.00
16:00 - 16:30	0:30	8:30	7.00	59.00
16:30 - 17:00	0:30	9:00	9.00	68.00
17:00 - 17:30	0:30	9:30	12.00	80.00
17:30 - 18:00	0:30	10:00	13.00	93.00
18:00 - 18:30	0:30	10:30	10.00	103.00
18:30 - 19:00	0:30	11:00	15.00	118.00

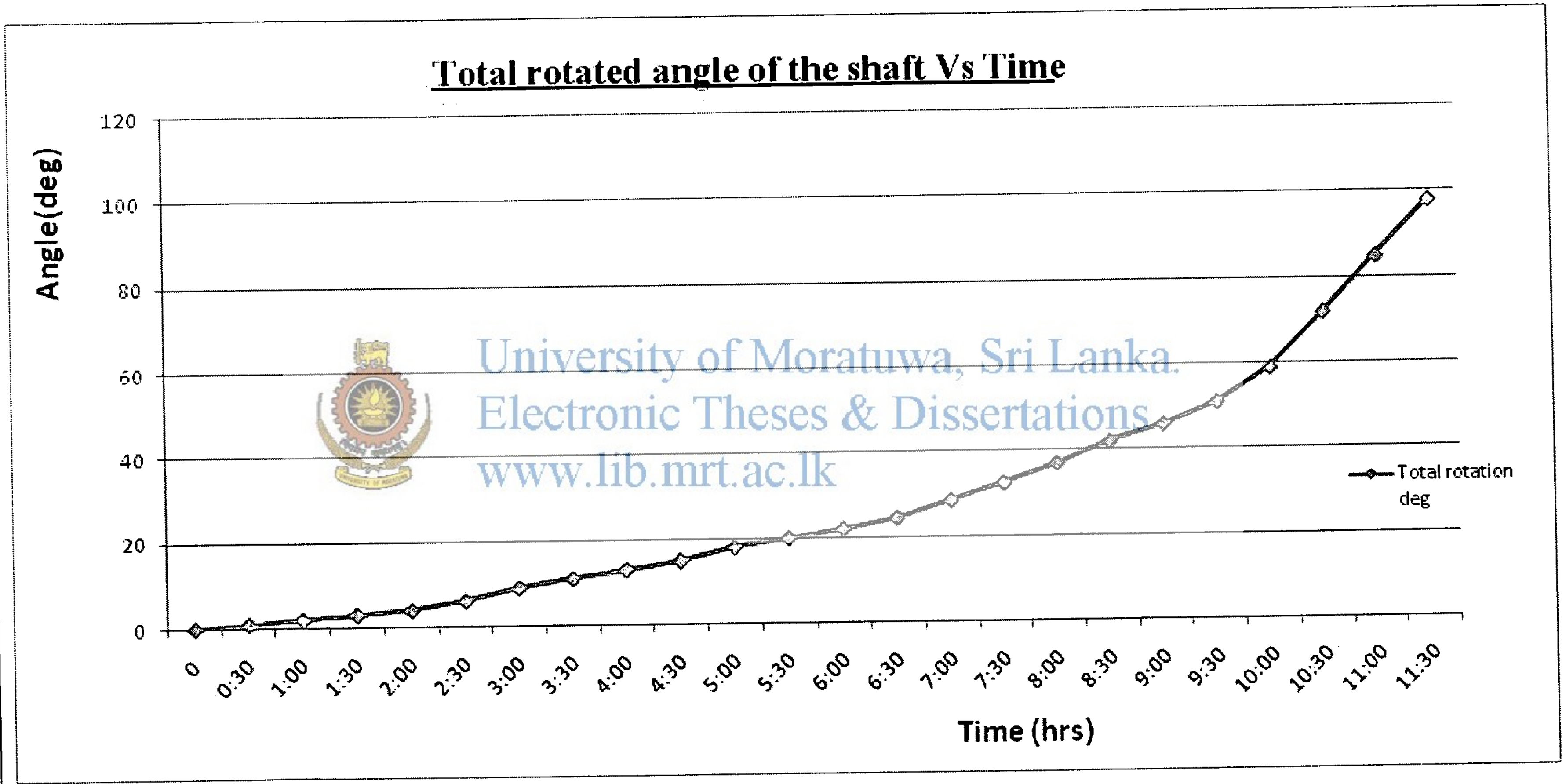
Weight of counter mass = 156 kg
Initial weight of water tank = 86.3 kg
Final weight of water tank = 30.8 kg


Rotated Angle Vs Time
Angle
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
0:30
1:00
1:30
2:00
2:30
3:00
3:30
4:00
4:30
5:00
5:30
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
10:30
11:00
Time (Hrs)

Data Collection Sheet - Test No 04

Date: 2008 / 08 / 06

Time period	Time Gap(min)	Accumulated Time (Min)	Rotate Angle°	Total rotation deg
	0	0	0	0
8:00 - 8:30	0:30	0:30	1.00	1.00
8:30 - 9:00	0:30	1:00	1.00	2.00
9:00 - 9:30	0:30	1:30	1.00	3.00
9:30 - 10:00	0:30	2:00	1.00	4.00
10:00 - 10:30	0:30	2:30	2.00	6.00
10:30 - 11:00	0:30	3:00	3.00	9.00
11:00 - 11:30	0:30	3:30	2.00	11.00
11:30 - 12:00	0:30	4:00	2.00	13.00
12:00 - 12:30	0:30	4:30	2.00	15.00
12:30 - 13:00	0:30	5:00	3.00	18.00
13:00 - 13:30	0:30	5:30	2.00	20.00
13:30 - 14:00	0:30	6:00	2.00	22.00
14:00 - 14:30	0:30	6:30	2.50	24.50
14:30 - 15:00	0:30	7:00	4.00	28.50
15:00 - 15:30	0:30	7:30	4.00	32.50
15:30 - 16:00	0:30	8:00	4.50	37.00
16:00 - 16:30	0:30	8:30	5.00	42.00
16:30 - 17:00	0:30	9:00	4.00	46.00
17:00 - 17:30	0:30	9:30	5.00	51.00
17:30 - 18:00	0:30	10:00	8.00	59.00
18:00 - 18:30	0:30	10:30	13.00	72.00
18:30 - 19:00	0:30	11:00	13.00	85.00
19:00 - 19:30	0:30	11:30	13.00	98.00


Total rotated angle of the shaft Vs Time
Angle(deg)
120
100
80
60
40
20
0
0
0:30
1:00
1:30
2:00
2:30
3:00
3:30
4:00
4:30
5:00
5:30
6:00
6:30
7:00
7:30
8:00
8:30
9:00
9:30
10:00
10:30
11:00
11:30
Time (hrs)
Total rotation deg

Appendix –C

Table- Comparison of energy output at fix positioning and single axis tracking

Time	Yearly Average (W)	Panel out put(W)	Incidence Angle	rad (θ)	cos (θ)	Gain@ fixed tilt (W)	loss of energy due to non track (W)	Tracker operating Time	Energy Whrs	Loss energy (Whrs)
8.00-9.00	228.50	10.05	60	1.05	0.50	5.03	5.03	18.00	72.00	18097
9.00-10.00	440.18	19.37	45	0.79	0.71	13.70	5.67	12.00	48.00	204212
10.00-11.00	584.25	25.71	30	0.52	0.87	22.26	3.44	7.00	28.00	12399
11.00-12.00	718.51	31.61	15	0.26	0.97	30.54	1.08	2.00	8.00	3878
12.00-13.00	794.47	34.96	0	0.00	1.00	34.96	0.00	3.00	12.00	0
13.00-14.00	815.25	35.87	15	0.26	0.97	34.65	1.22	8.00	32.00	4400
14.00-15.00	720.71	31.71	30	0.52	0.87	27.46	4.25	10.00	40.00	15295
15.00-16.00	575.80	25.34	45	0.79	0.71	17.91	7.42	6.00	24.00	26714

Appendix –D

Optimum operational time decision

Gather data for the year 2005 and average calculates for each hour concern for the all days of month, neglect data with some abnormal variations.

Table -Annual Average insolation at Colombo

Time	Daily average insolation (W/m^2) at Colombo-											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
6.00-7.00	2	1	0	2	4	3	6	5	6	2	4	1
7.00-8.00	52	46	65	70	76	74	86	96	92	79	54	52
8.00-9.00	212	197	236	222	247	231	250	244	248	226	219	210
9.00-10.00	400	381	423	398	449	421	482	504	510	491	420	403
10.00-11.00	563	519	481	532	614	608	651	669	657	604	543	571
11.00-12.00	676	642	703	650	740	704	775	825	796	759	654	697
12.00-13.00	729	708	801	737	828	781	857	904	894	865	688	742
13.00-14.00	717	701	774	716	882	827	921	977	968	858	719	722
14.00-15.00	634	633	679	636	720	768	828	865	858	766	621	642
15.00-16.00	509	531	559	504	586	566	626	687	663	587	559	534
16.00-17.00	338	362	420	407	466	421	494	537	518	459	346	348
17.00-18.00	153	180	231	210	225	213	271	320	295	232	172	141
18.00-19.00	49	48	51	45	39	34	43	54	49	38	37	34

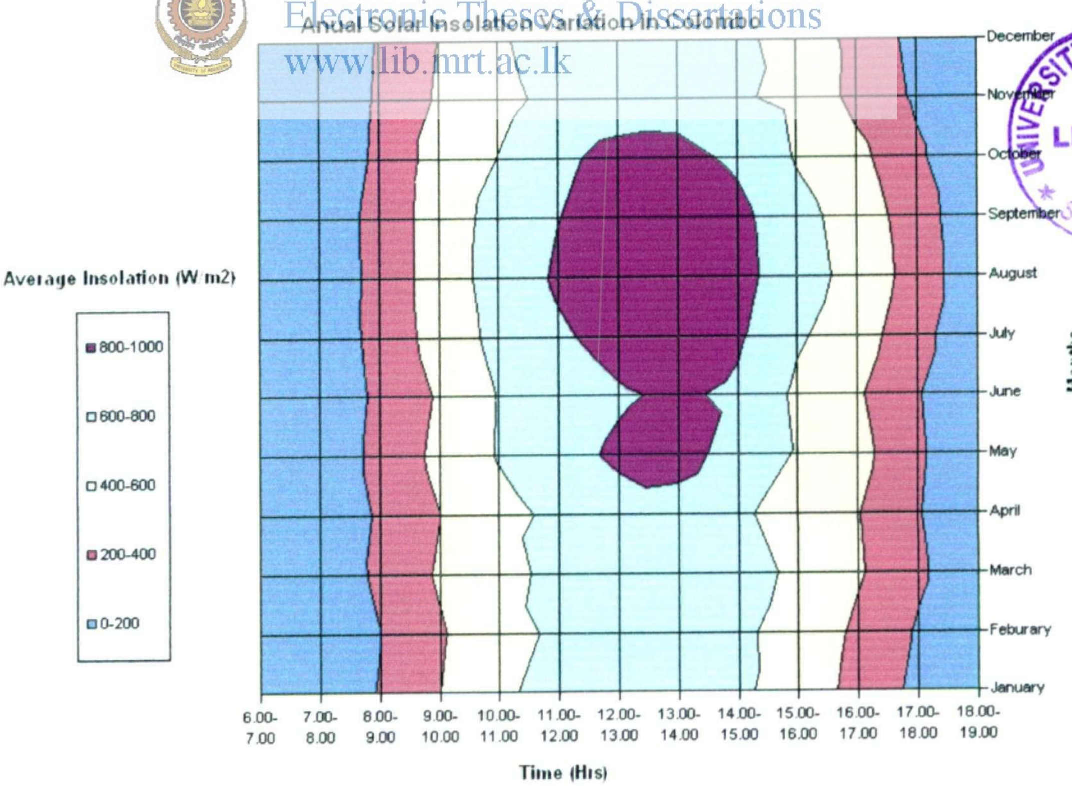


Figure -Annual Average insolation at Colombo

Appendix - E

Bill of Quantities for the Construction

Srl No	Qty	Unit	Description	Unit Price (Rs.)	Total Price(Rs.)
1	1	Nos	Plastic Water Tank 120 ltr	450.00	450.00
2	10	Meters	Iron L-angles 40x40x3mm	450.00	4,500.00
3	7.5	Meters	Galvanized tubes 50mm Med Duty	420.00	3,150.00
4	2	Nos	Ball Bearing	800.00	1,600.00
5	1	Kg	Welding rods No 10	150.00	150.00
6	0.25	Litters	Anti Corrosives paint	400.00	100.00
7	2	Nos	Bicycle Sprocket wheel	370.00	740.00
8	2	Nos	Bicycle Chain	140.00	280.00
			Sub Total		10,970.00

Total Material cost (Rs.)	10,970.00
Total Labour cost (Rs.)	1,200.00
Other cost (Rs.)	500.00
Total cost of construction (Approx) (Rs.)	12,670.00