LIFE TIME ENERGY EFFICIENCY OF PHOTOVOLTAIC POWER MODULE

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree

of

MASTER OF TECHNOLOGY

in

WATER RESOURCES DEVELOPMENT

By

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STUDENT'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled, "**Life Time Energy Efficiency of Photovoltaic Power Module**", in partial fulfillment of the requirements for the award of degree of **Master of Technology** in **Water Resources Development** in Water Resources Development and Management (WRD&M) of **Indian Institute of Technology, Roorkee** is a authentic record of my own work carried out during the period from June, 2012 to June, 2013 under the supervision of Prof. Devadutta Das (Professor), WRD&M. The matter embodied in this dissertation has not been submitted by me for the award of any other degree.

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CERTIFICATE

This is to certify that the statement made by the candidate is correct and true to the best of my knowledge.

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ABSTRACT

Photovoltaic systems are the most important, reliable, eco-friendly and promising technologies for energy conversion, which will play a major role in sustainable energy system. Most of the Indian Territory receive adequate amount of solar radiation, which is necessary for the development of solar photovoltaic (PV) systems for power generation. Photovoltaic system must be energy efficient and reliable if they are to replace conventional energy sources.

Life time Energy Analysis plays a major role in the advancement of PV Technologies and their application in the field of energy efficiency. It includes the total lifetime of the PV system, encompassing raw material production, manufacturing, use, and maintenance and end-of-life management. This thesis analyses the Energy Payback Period and Life Time Energy Efficiency of Photovoltaic Module for major cities of India. . For this purpose, Energy consumption required for making different component of PV module, annual energy available from PV module and output energy of module in its lifetime is calculated. Each of the energies required for manufacturing, material production, use and distribution of the system have been taken into account to determine the embodied energy of the PV module.

The amount of solar radiation incident on a solar panel is affected by the local climatology, orientation and tilt angle with the horizontal plane and the ground reflectance properties. This thesis also analyses theoretical aspects of choosing solar panel tilt angle used at different locations of India. Finally a comparison of received energy is made while optimizing the tilt angle monthly, seasonally and annually.

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CHAPTER 1

INTRODUCTION

1.1 General

The sharp rise in demand being experienced throughout the world in the past few years has resulted in exploration and utilization of different renewable energy sources. Fast diminishing conventional or fossil fuel energy resources coupled with sharp rise in their prices has further lead to the development of eco-friendly options which are found abundant in nature.

Nuclear energy, biomass, fuel cell and solar energy are some of the promising alternative energy sources in the future. Among these options, solar energy technology is being aggressively developed. Advantages of Solar energy that it is freely available, found in abundance, sustainable and environmental friendly. Use of solar energy will help preserve conventional energy sources. Therefore solar energy power plants will play a major role in meeting world energy demands and keeping the environment pollution free.

If renewable energy resources like Photovoltaic (PV) systems are to replace conventional energy sources as major electricity producers, they should be reliable and energy efficient. Therefore Lifetime energy analysis plays an important role in the advancement of PV technologies and guiding their application in the field of energy efficiency.

Conversion efficiency is defined as the amount of solar energy that can be converted to electricity. It does not give the overall performance of the photovoltaic system. It only gives the operational energy efficiency of solar cell. For much extensive analysis Life time energy analysis is used. It covers raw material production, maintenance, use, total life time of PV module and finally its end-of- life management

1.2 World Energy Scenario

International Energy Agency (IEA) and Energy Information Administration (EIA) publish data annually about the energy consumption pattern, their environmental impact and give a probable solution of it. IEA has noted that energy consumption in G20 has slowed down to 2% (October 2012) due to economic crisis. For many years world energy demand is characterized by Indian and Chinese markets. As on 2007 energy consumption pattern, non OECD members have surpassed the OECD members. China and India are the two countries that are least affected by the global recession. It is estimated that current and predicted world energy consumption will increase at a rate of about 1.4% till 2035(fig1). As on 2012 EIA data energy supply by power source was oil (32.4%), coal (27.3%), natural gas (21.4%), Hydro 2.3 %, nuclear 5.7%, bio fuels and waste 10% and others 0.9%.

Since 1990, energy consumption has increased incomparably in India and China. Together they shared for approximately 10 % of the world's total energy consumption in 1990 and 20 % in 2007. Both countries have high economic growth over the period. It is expected that total energy share of these countries would reach to 30% in 2035. In opposite to this, US share of world energy consumption is likely to reduce from 21 % in 2007 to16 % in 2035.

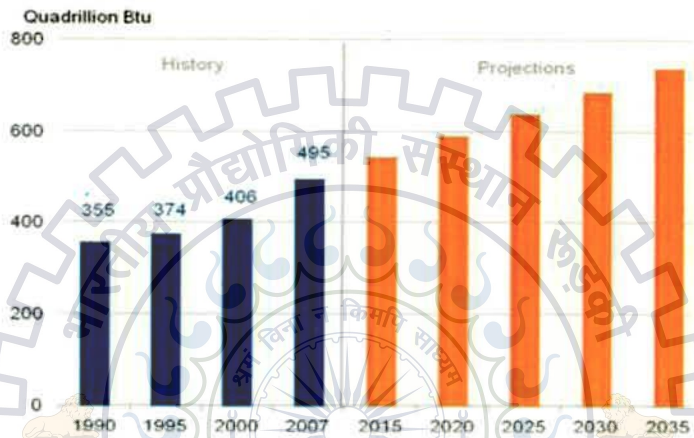


Fig.1.1: World Energy Scenario

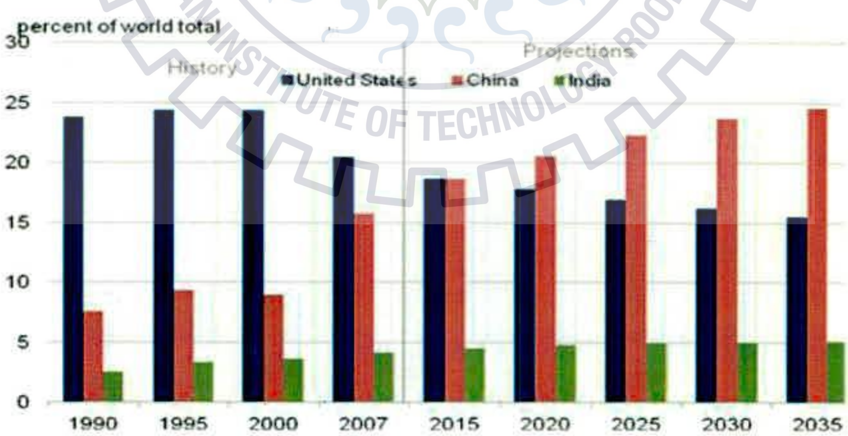


Fig.1.2: US, India and China Energy consumption percentage

1.3 India Energy Scenarios

The all India installed power generation capacity as on 30.04.2013 was 223636 MW comprising of 151620 MW thermal, 39291 MW hydro, 4780 MW nuclear and 27542 MW Renewable energy Sources. Indian economy is growing at great pace and scarcity of power is increasing day by day. Therefore it is a great challenge to us to balance the demand supply chain. In India, increment rate in demand for power is greater than its GDP.

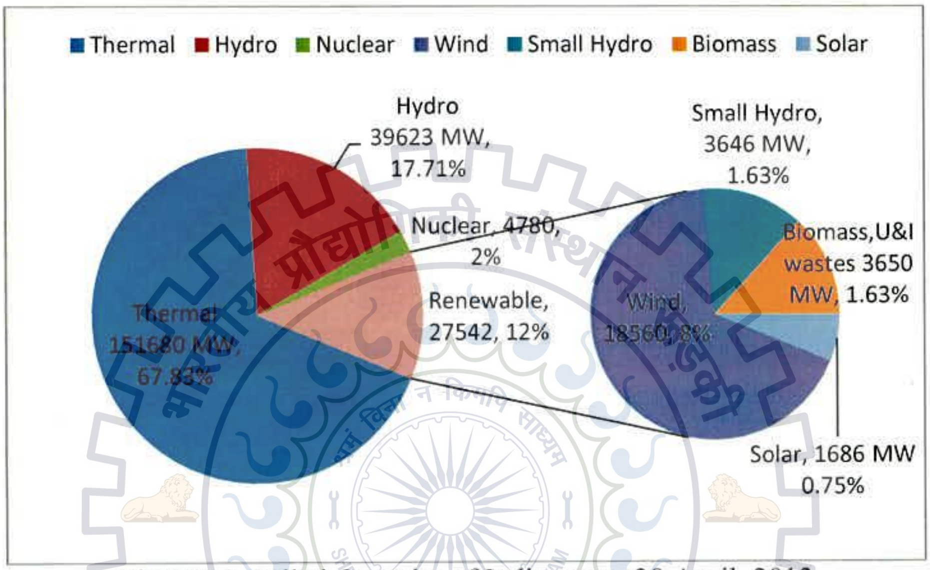


Fig.1.3: Installed Capacity of India as on 30 April, 2013

1.4 Need for Renewable Energy Sources

The gradually increasing demand of energy had put burden on the conventional energy sources. As the fossil fuels are depleting day by day and causing many environmental issues, a substitute method must be explored for sustained energy supply. Fossil fuels emit green house gases which results in global warming of the earth. As a result of global warming, dubious changes in weather pattern will come and low lying area will be submerged due to melting of ice at the poles. Fig.1.4 shows the rise in CO2 concentration over the last 50 years.

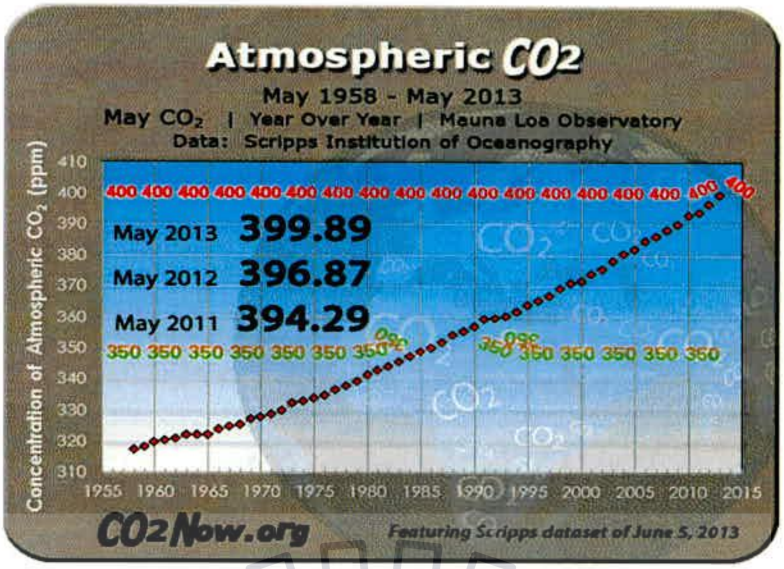


Fig. 1.4: Concentration of Atmospheric CO_2

The current CO2 concentration level is about 399.89 ppm (in May 2013) and scientists have claimed that this value must be dropped to 340 ppm or otherwise it may lead to inevitable calamitous effects.

1.5 Challenges For Solar Energy

Challenges for the PV technologies ahead:

1. **Costly:**

   The per unit cost of solar energy system in India is 12-15 rupees while for the conventional energy sources is 3-8 rupees. For economically viable its cost should be as par the conventional energy sources. Continuous efforts are going on to keep the material and its processing cost low.

2. **Load Fluctuation**:

   In case of conventional energy sources, the power companies can reserve their sources to meet the demand during peak hours but it is not easily possible as in case of solar energy sources due to instantaneous availability of solar energy. A thorough study of energy generation overtime and efficient storage must be implemented for this.

3. **Huge Investment Requirements**:

Solar energy technologies are emerging, these don't have the technology and infrastructures as the developed fossil fuel have. So a strong financial support and awareness is needed to develop this technology. In view of this, India has launched JNNSM which provide financial support to the new players at 12% interest. Banking sectors must come forward for financially support such projects.

4. **Lesser expertise**:

There is shortage of expertise in rural areas for photovoltaic application. In rural areas, rigorous training and education structures should be implemented in this field.

1.6 Objectives of the Study

- To find the embodied energy, energy payback time, Lifetime Energy Efficiency of a Photovoltaic Power Module.
- To find the optimum tilt angle of a solar panel.

CHAPTER 2

LITERATURE REVIEW

Photovoltaic system must be energy efficient as well as cost efficient with conventional energy sources. Life Time Energy analysis is an important means in navigating the photovoltaic technology. Life Time Energy analysis results for a Photovoltaic System directly depend on the boundaries of the system under consideration. Many authors have investigated the energy metrics for different photovoltaic module using different set of model equations and boundary conditions.

A lot of life cycle assessment and various studies have been done to quantify the energy consumed in producing photovoltaic module. (Hagedorm, 1989; Phylipsean and Alsena, 1995; Nieuwlar et al, 1996; Kato et al.,1998;GEMIS 2004; Kaarl and Therese,2003; Gagnone et al, 2003;R Kannan et al.,2005; Arvind Tiwari et al.,2009; Majid Jamil et al.,2012)

Arvind Tiwari et al.(2009) in his paper "Energy metrics analysis of hybrid- photovoltaic (PV) modules" has discussed about electricity production efficiency, EPBT and lifetime conversion efficiency of hybrid PV/T module. He has setup his experiment in Solar Energy Park, IIT Delhi. A well set computative equation have been used to figure out the energy parameters. All the primary and secondary production process and energy consumption in the utility are taken into consideration for evaluating PV/T module's embodied energy. Further EPBT of PV/T module is calculated using module annual output and its total embodied energy. Two mono crystalline PV modules connected in series and mounted on a structure at an inclination of 30^0. Working fluid is allowed to pass through the air duct. To induce the flow of air below the duct to fans of capacity 12 W were provided at the inlet. It helps in extracting the thermal energy that is available at the back of the photovoltaic module. It is worth noting that EPBT gets significantly reduced if photovoltaic and photo thermal system are used combinely. Based on the observations for the period 2004-2007, EPBT are 12.57 and 3.23 years if the annual output is taken as electrical energy and thermal energy respectively. In case of hybrid PV/T module EPBT is about 1.99 years with balance of system component and under standard test conditions. Under standard test conditions electricity production factor values are .50 for PV module and .63 for Hybrid PV module with balance of system components .EPF reduces to .24 and .31 for PV and Hybrid PV respectively with outdoor conditions.

R. Kannan et al.(2005) have presented a paper on "Life cycle assessment study of solar PV systems" taking a 2.7 kWp distributed solar photovoltaic system as an example in Singapore. The objective of this paper is to find the EPBT for above mentioned PV system and make a comparison between the steam power plant and PV system. This study also includes the reduction of CO_2 emission in case of PV system. The annual solar insolation of Singapore is 1638 kWh/m^2. There is limitation of space in Singapore so solar energy production for huge scale cannot be done. So, small PV system is taken for distributed power generation. EPBT for the 270 MW comes out to be 6.19 years and that of 2.7 kWp solar plant is 6.74 years. Considering the 4% transmission and distribution losses in Singapore, EPBT reduces to 5.87 years for a T& loss alone system. The emission of green house gases comes out to be 218 g-CO2/kWh$_e$ for solar photovoltaic plant and for steam power plant including T&D loss is about 976 g-CO2/kWh$_e$. Author has reported that by the improvement in PV manufacturing technology and mass production EPBT can be reduced to 3.5 years and GHG emissions to about 129 g-CO2/kWh$_e$. It is also estimated that if the usage of supporting structure of PV panel aluminium is reduced to 10% and using concrete structure, EPBT can be reduced to 4.8 years and GHG emissions to about 177 g-CO2/kWhe. It is seen that for per unit ^{0}C rise in solar cell temperature, the output of the PV reduces by approximately 0.5%. . Authors have suggested that by using natural cooling PV system efficiency can be increased to about 10.8%.

Gregary A. Keolian and Geoffray McD. Lewis(1997) in this paper highlights results from a combined life-cycle analysis between the United Solar Systems Corporation and University of Michigan. Energy efficiency of PV system is done using a set of model equation and compared it with other electric generating sources. The whole PV life cycle cover raw material production, maintenance, use, total life time of PV module and finally its end-of- life management. UPM- 880 is used as a sample and solar insolation data of three places namely Detroit, Phoenix and Boulder are used in this study. The life cycle energy analysis indicates that balance of system, aluminium frame play a vital role in the total energy investment in the UPM-880 module. These energy metrics were calculated for a module life of 25 years and conversion efficiency of 9%.

Table 2.1: Energy Payback Time & Electricity Production Efficiency

Location & Insolation	**Energy generated in lifetime**	**Energy Payback Time**		**Electricity Production Efficiency**	
		Standard	**Frameless**	**Standard**	**Frameless**
Detroit, 1202 kWh/m^2/year	558.3	4.1	2.5	3.36	5.48
Boulder 1974 kWh/m^2/year	917.0	2.5	1.5	5.52	9.00
Phoenix 2480 kWh/m^2/year	1152.0	2.0	1.2	6.94	11.31

E.A Alsema and G.J.M. Phylipsen (1997) categorize their study as worst, base and best case. These cases are taken as present technology, future probable technology and future optimistic technology respectively. According to these cases EPBT and environmental life assessment of multi-crystalline silicon solar module have been discussed separately. Authors have suggested various methods to deduce embodied energy of the PV module such as: use of thinner silicon wafers with larger area, use of secondary aluminium for supporting structure, optimization and monitoring of cell and module making processes with respect to energy utilization. The energy pay-back time of a frameless module under Dutch isolations conditions comes out to be 3.8 years, 1.3 years and 0.5 years for the worst, base and best case respectively.

M. Benghanem (2010) in his article analyzes the best choice of tilt angle for Madinah, Saudi Arabia. The previous year's monthly daily global and diffuse insolation data of Madinah site is taken in the calculation. Here Sky diffuse radiation and isotropic models are used to find the diffuse solar radiation. . Calculation for beam and ground reflected radiation is same for each model. It is found that if the solar panels tilt are allowed to change monthly, then it will extract maximum energy. This study also suggests that yearly fixed optimum angle is approximately equal to the latitude of the Madinah site. The result of this study shows that best choice of tilt angle for winter months is 37^0 and for summer it is 12^0. When monthly optimum tilt angle is used, net profit of energy is about 8% as compared to the yearly fixed angle. It is suggested here that at least tilt angle should be changed seasonally for higher efficiency if we are not able to do on monthly basis.

Jamil Ahmad and Gopal Nath Tiwari have examined the analytical approach of selecting the tilt angle for solar flat- plate collectors. Authors have selected eight individual sites in the world. They have shown by what amount the collected solar energy will increase by changing the tilt angle. For Indian locations, measured values of the monthly mean daily global and diffuse solar radiation on a horizontal surface are used in calculations. For other stations, the monthly average daily global solar radiation and monthly average clearness index on a horizontal surface are used in calculations. Different equations of Isotropic and Anisotropic models are used to compute the total solar radiation falling on a tilted surface of solar panel.

They have plotted graphs between tilt angle ($0\text{-}90^0$) and total solar radiation for each month of the year and for each location. In this paper, authors have shown that all eight diffuse radiation models yields approximately same optimum tilt. The result of this study shows that best choice of tilt angle at New Delhi station for winter months is 47.5^0 and for summer it is 13^0. Authors have finally suggested that tilt angle must be changed seasonally if monthly is not possible for higher efficiency.

Murat Kacira et al.(2004) have conducted an experiment at Photovoltaic Research Centre in Sanliurfla. The aim of the experiment was to make a comparison between the performance of two axis tracking system and monthly varying tilt angle system. During the experiment, they have mounted a solar panel at angle of 14^0 , another is seasonally varied and at third panel two axis tracking system is installed. . Maximum radiation was observed when tilt angle is $30\text{-}40\text{-}50^0$ from January to march,$0\text{-}10\text{-}20^0$ from April to August and $40\text{-}50\text{-}60^0$ from September to December. Authors have calculated that compared to the fixed tilt angle of 14^0 south, 29.3% more solar radiation and 34.6% more power can be generated in the case of two axis tracking system but this is not always feasible and practical.

Arbi Gharakhani Siraki , Pragasen Pillay (2012) have proposed a modified sky model to calculate the optimum PV installation angle for urban applications. For an urban application, surrounding obstacles, shading and sky blocking effects play a vital role in energy production. The amount of solar radiation receives under these conditions have been discussed in this paper. For normal solar panel applications HDKR model is generally used method and it gives better result. Authors have introduced a shading coefficient K_{sh} to take into account for the effect of shading caused by surrounding obstacles. K_{sh} can be calculated for different hours of an average day from the outlines of the obstacles plotted in the solar position plane. Author have calculated and discussed the sky view factor accurately with a program. Calculations have been done to find the impact of the ground reflectance ratio on the yearly optimum tilt angle. Finally authors have suggested that while choosing the installation angles surrounding obstacles should be taken into consideration.

Kadir Bakirci (2012) has found the optimum tilt angle for eight locations in Turkey using measured solar radiation. He was varying the tilt angle from 0^0 to 90^0 in steps of 1^0 and finding the tilt value at which received solar energy is maximum.

Coorelations methods were used to calculate the optimum tilt and accuracy of result are found by of Root Mean Square Error (RMSE). The yearly average optimum tilt angle for a south-facing solar collector were 31.21^0, 32.71^0, 32.61^0, 34.31^0, 32.61^0, 32.81^0 and 33.21^0 in Adana, Ankara, Diyabakir, Erezurum, Istanbul, Izmirh, Samsun and Traabzon respectively.

CHAPTER 3

SOLAR ENERGY SYSTEMS

3.1 Solar thermal system

Solar thermal system is a technology for harnessing solar energy for thermal energy. Solar collectors capture the energy of the sun and convert it into heat. Solar energy is passed through a layer of glazed glass and heat is extracted by the concealed material. Due to the glazing of glass, solar collectors effectually absorb the heat. The glazing of the glass prevents heat from escaping, thereby effectively capturing the heat.

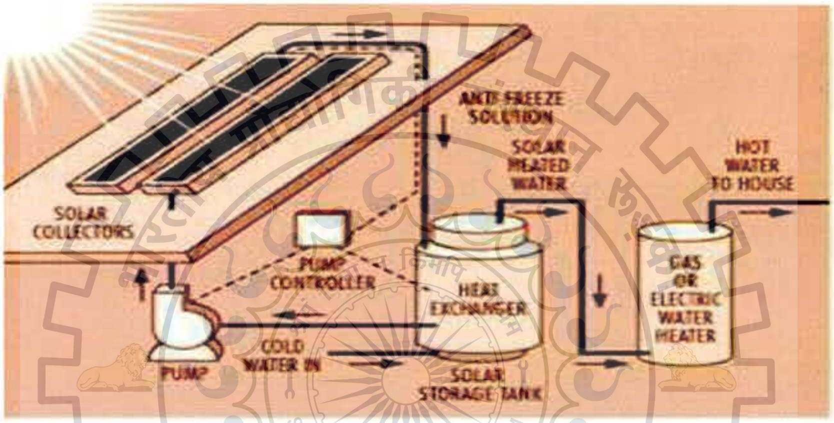


Fig.3.1: Solar Water Heater

Solar collectors are found in three categories depending upon their usage. Low temperature collectors are used to heat the swimming pool and they are usually flat plate collector. Medium collectors are used for heating air or water for commercial and residential usage. The applications include solar drying and distillation. High-temperature collectors concentrate sunlight using mirrors or lenses and are generally used for electric power production.

3.2 Solar thermal system

Solar photovoltaic system uses the photovoltaic effect of the semiconductor materials to generate electrical power by converting solar radiation into direct current.

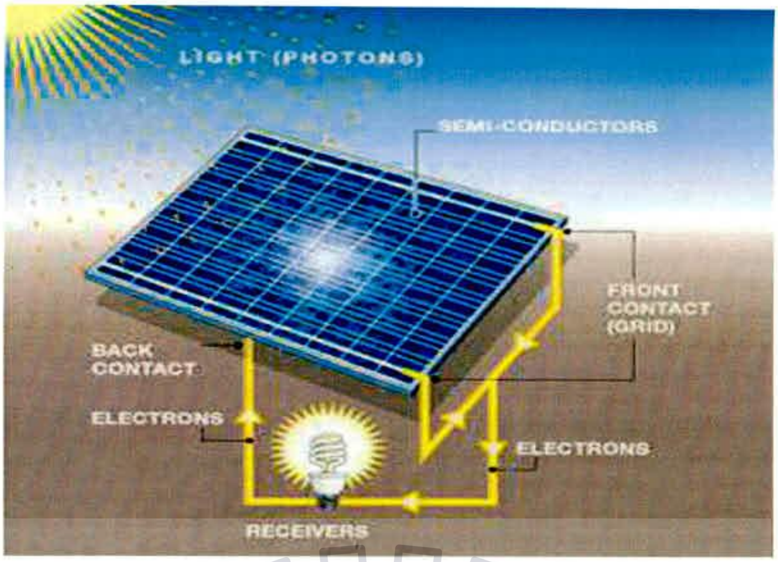


Fig.3.2: Solar Photovoltaic Method

3.3 Solar Cell

A solar cell is an electrical device that converts the energy of light directly into electricity. It works on the principle of photovoltaic effect.

3.3.1 Photovoltaic Effect

Photovoltaic effect is the creation of electric field among two dissimilar semiconductor materials.

Semiconductor Si has 4 e^{-}s in its valence bond and it is covalently bonded in its pure form. This bond can be broken by applying energy greater than its energy gap (Eg). For Si, Eg=1.12 eV, this value lies between conductor and insulator. Electron jumps from valence band to the conduction band if it extracts energy greater than energy gap. As a result it leaves a hole behind which is filled by nearby e^{-}s. In this way hole behave as a positively charged mobile particle. So electrical properties of Si can be changed by introducing the impurities and the process is called doping. Doping can be done to the elements of group III and group V of the periodic table. Same as if group V element such as P is added as impurities, a free electron is available and it jumps to the conduction band with a lower energy. In this way P becomes the donor element.

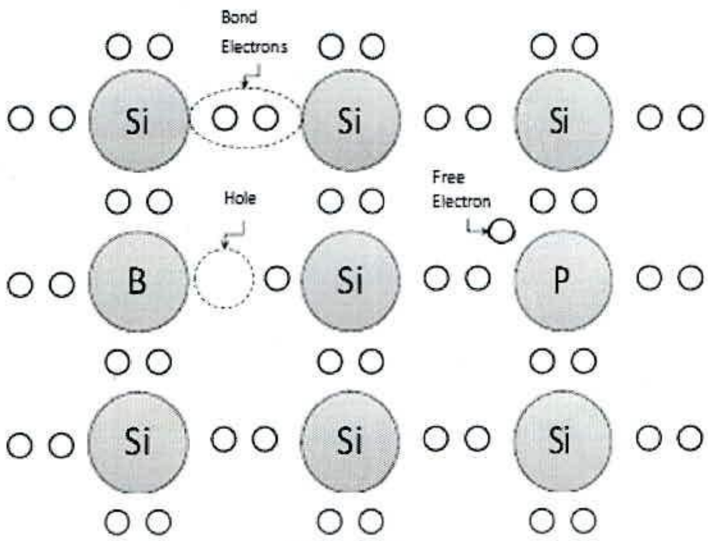


Fig.3.3: Photovoltaic Effect

Photovoltaic cell is a p-n junction having metal contacts on its both sides. There is high density of e⁻s in n junction and holes in p junction. Holes and electrons can easily move in their respective reasons. These junction results in an electric field which drive the e⁻s to move onto front surface and holes to its back surface. If e⁻s survive their movement upto cell thickness then electricity can be collected at the appliances. Afterwards e⁻s re-enter the PV cell at the back contact and recumbent with holes and the process goes on.

3.4 Photovoltaic system components

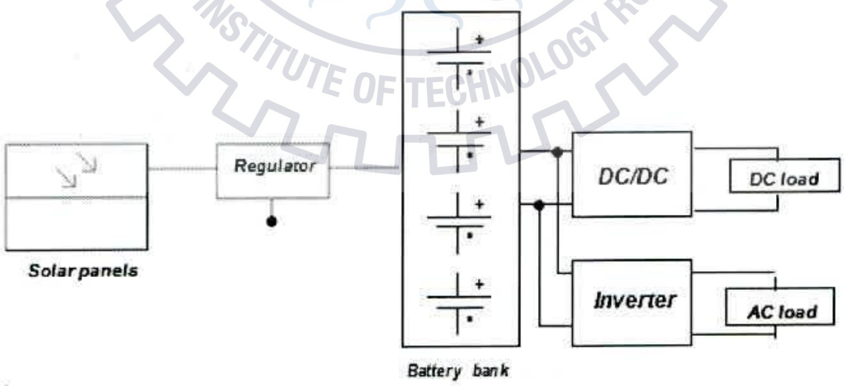


Fig.3.4: PV system Components

3.4.1 The Solar Panel

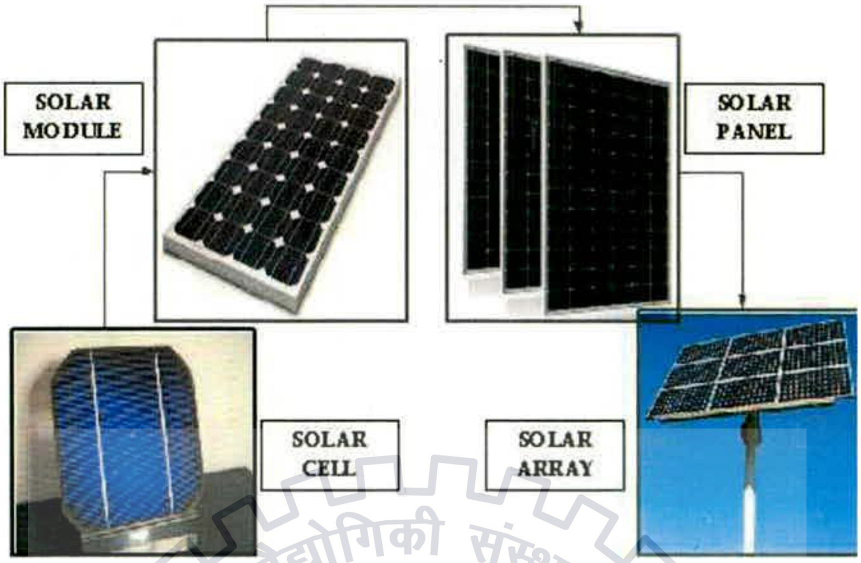


Fig.3.5: Photovoltaic cell to Photovoltaic Array

Solar Module:

These are combination of solar cells connected in either series or parallel according to the voltage and current requirements. Generally solar modules consist of 36 or 72 solar cells. All the cells are of equal rating, size, and type and further wired in series. These are encapsulated to protect it from mechanical and environmental damages.

When the solar panel are in partial shadow, hot-spots occur which ultimately damages the PV cell. To avoid this by-pass diodes are used in parallel to cells.

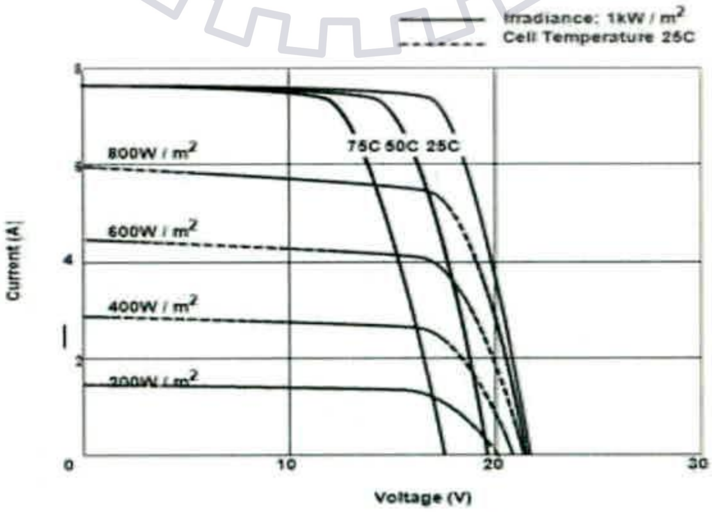


Fig.3.6: I-V Characteristics of Solar Cell

Each solar cell has its own electrical characteristics. These characteristics depend on the amount of solar radiation received and the temperature of that cell. These represent the generation of voltage for a concerned solar radiation and based on it how much electric current flow. The current generated in a solar cell is directly proportional to the amount of solar radiation. Voltage reduces slightly with the rise of temperature. To maximize the solar output, the operating point should be so chosen that the product of voltage and current is maximum.

Interconnection of Solar panels

Solar panel are electrically interconnected to form an array and supported on a structure. The number of panel interconnected depends on the voltage and current rating of batteries. Panels are connected in series to increase the current value and in parallel to increase its voltage. It is desirable condition that all panels have identical operating characteristics.

3.4.2 Battery bank

The function of the battery is to store the energy when panel output is not consumed immediately by the load and deliver it when there is demand for it. In case of charging electrical energy is converted into chemical energy and vice versa. Most batteries have 2 V electrical potential differences between the electrodes. For PV uses 12 or 24 V batteries are used.

Two types of batteries are generally used in Photovoltaic applications:

i. Lead Acid Batteries
ii. Nickel Cadmium Batteries

i. Lead Acid Batteries

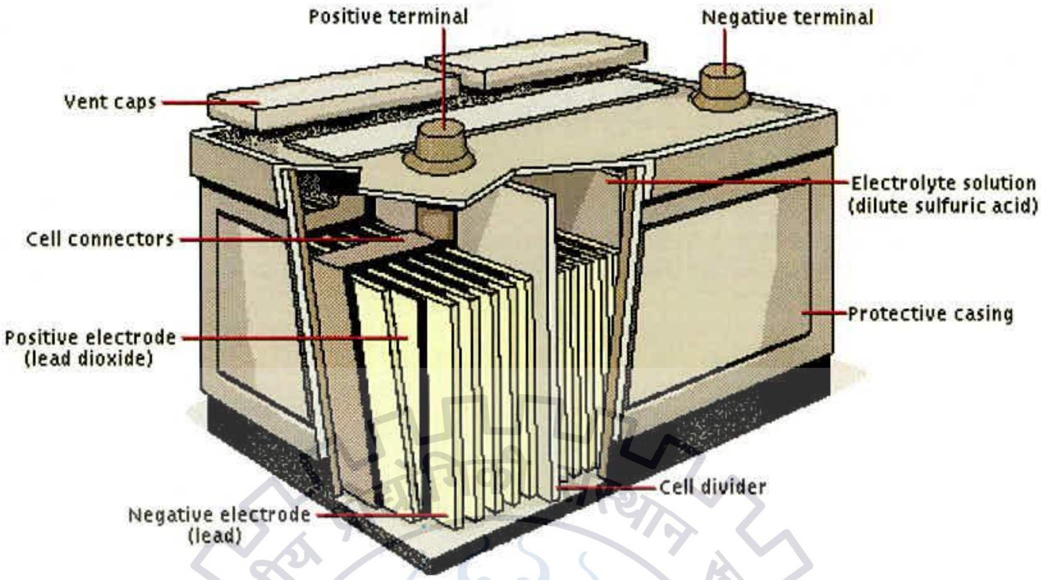


Fig.3.7: A Lead Acid Battery

1. Discharging Process

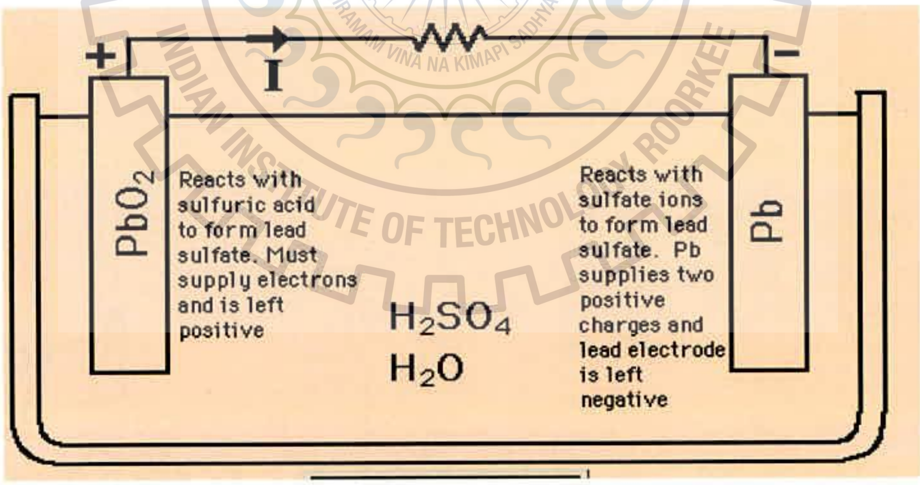


Fig.3.8: Lead Acid Battery discharging process

2. Charging Process

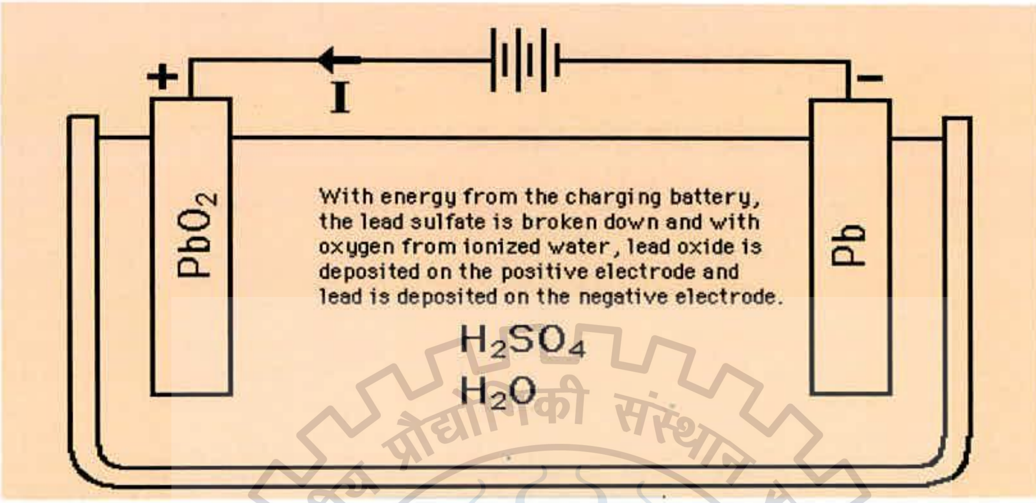


Fig.3.9: Lead Acid Battery Charging Process

ii. Nickel Cadmium Battery

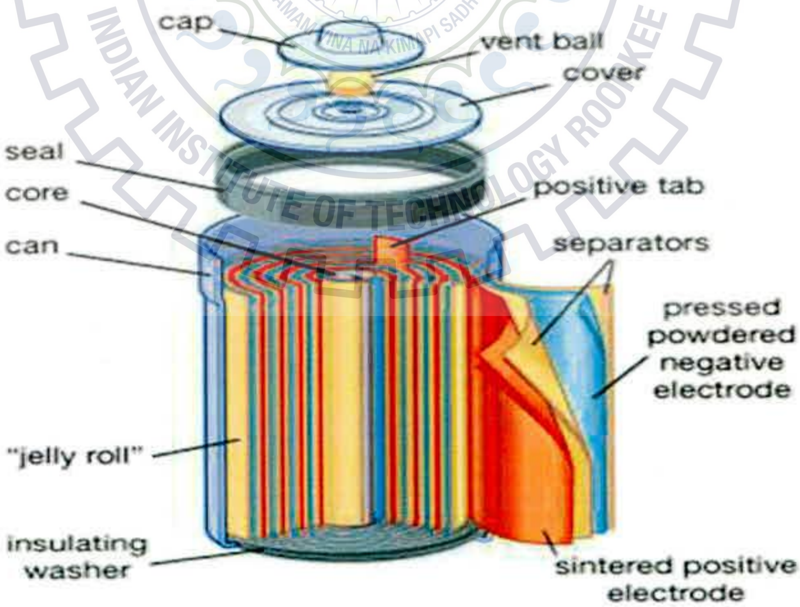


Fig.3.10: Nickel Cadmium Battery

The Nickel- Cadmiun is the rechargeable battery and following reaction takes place during discharge process:

$$Cd + 2H_2O + 2NiOOH \longrightarrow 2Ni(OH)_2 + Cd(OH)_2$$

3.4.3 The Regulator

The solar power charge regulator ensures that panel and battery are working together in an appropriate condition. It prevents overcharging or over discharging the battery, both of which are detrimental to the life of the battery.

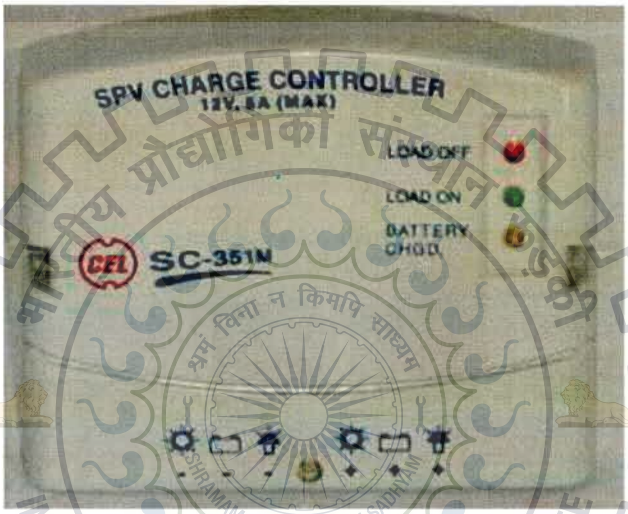


Fig.3.11: Charge Controller

3.4.4 Inverter

Inverters convert the DC voltage to AC or DC at desired frequency level and higher voltage level. The output of the PV panel is fixed DC and may not match with the output of the load so inverters are connected between them.

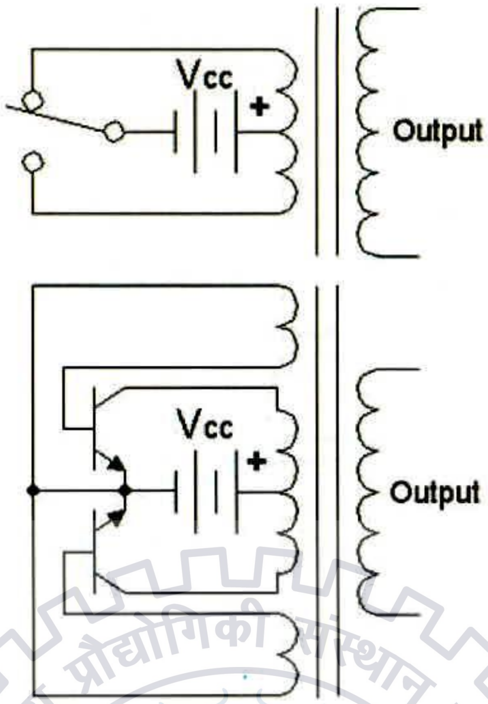


Fig.3.12: Working principle of Inverter

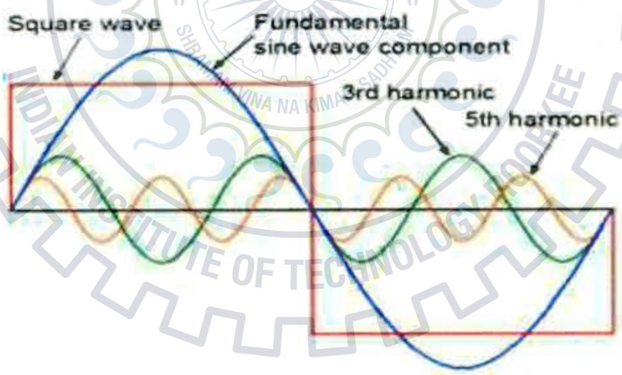


Fig.3.13: The output achieved from the inverter

3.4.5 The Load

The load is the equipment that consumes the power generated by photovoltaic system. The load may include wireless communication equipment, router, workstation, lamp, TV set, etc. Generally it is suitable for lightning purpose. Estimation has to be done in advance about the maximum consumption while designing the PV system.

3.5 Types of Solar Cell

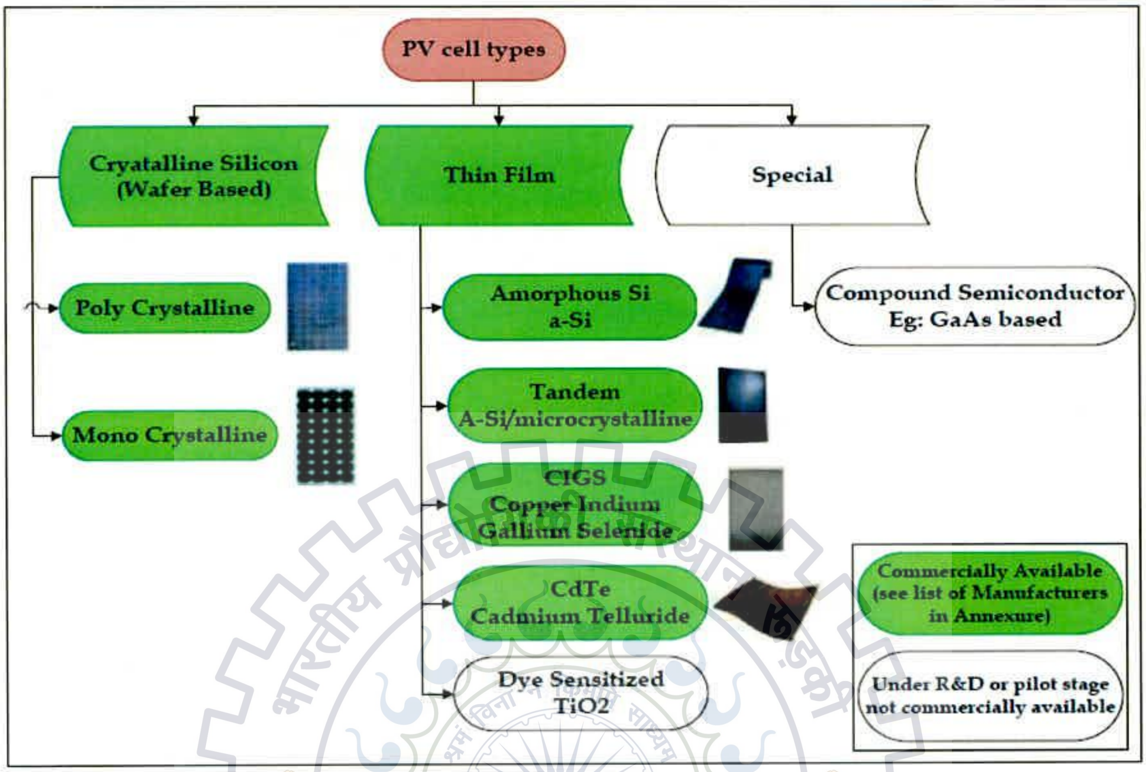


Fig.3.14: Types of Solar Cell

Crystalline Silicon Technologies:

Crystalline Silicon is the widely used technology in today's world covering the entire solar market. This is due to its trustworthy and proven technology. Also it is available in profound amount in nature. It manufacturing involves making of silicon ingots and slicing them to wafers of silicon. Further the process is same as other technologies. Its efficiency lies between 14 to 20 % and likely to improve upto 25% by 2020.

Thin Film Technologies:

This technology involves deposition of a very thin layer of light sensitive material to the glass or plastic. Higher efficiency can be achieved by combining layer of microcrystalline and amorphous silicon. Advantages of thin film solar cells are their high efficiency, low material usage and insensitivity to temperature and overheating.

CHAPTER 4

MANUFACTURING PROCESS OF SOLAR CELL

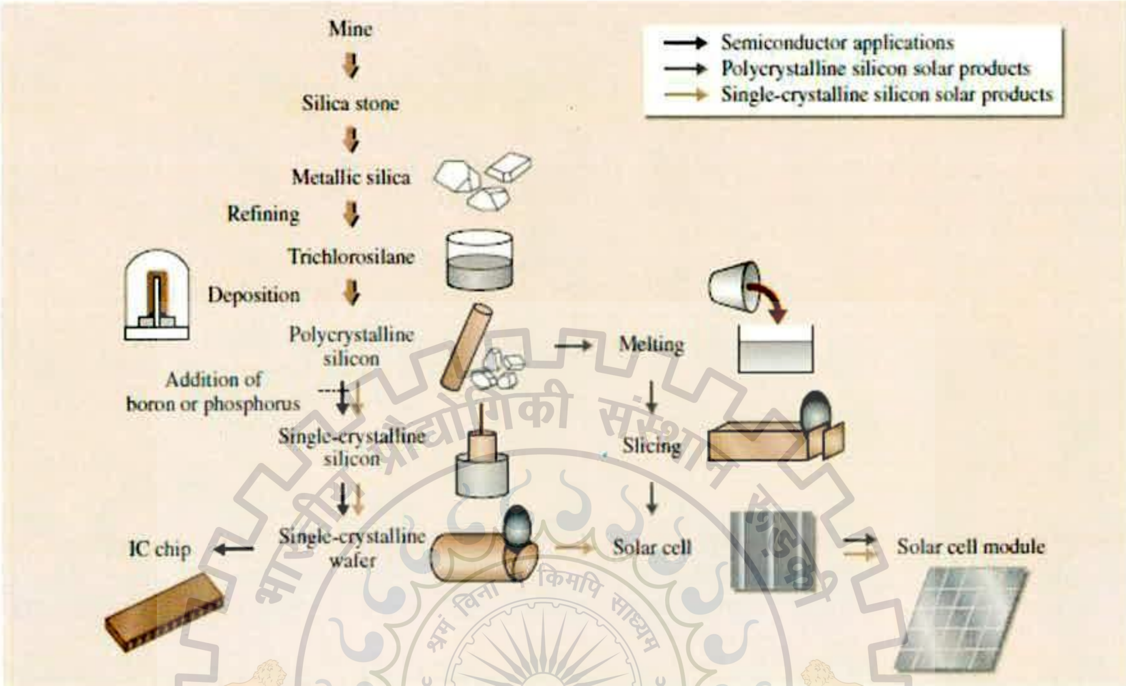


Fig.4.1: Manufacturing Process of Solar Module

Manufacturing Process of Photovoltaic Cell involved following Stages:

1. Reduction of sand to metallurgical- grade silicon.
2. Purification of metallurgical -grade silicon to semiconductor- grade silicon.
3. Conversion of semiconductor- grade silicon to single-crystal silicon wafers into solar cells.
4. Processing of single-crystal silicon wafers into solar cells.
5. Solar cell encapsulation into weatherproof solar cell modules.

4.1 Sand to Metallurgical-Grade Silicon

Silicon is available in copious amount in earth's crust. The source material for the extraction of silicon (Si) is silicon dioxide (SiO_2), the major constituent of sand. However, in the present commercial extraction process, the crystalline form of silicon dioxide, quartzite, is used. This material is reduced in large arc furnaces by carbon to produce silicon according to the reaction-

$SiO_2 + 2C$ ----> $Si + 2CO$

Silicon is repeatedly thronged from the furnace. After that it is blown with oxygen or oxygen mixtures to further purify it. It is then thronge into shallow troughs which solidifies and is afterwards broken into chunks. Metallurgical-grade silicon (MG-Si) is generally 98 to 99% pure , with the major impurities being iron and aluminium. Silicon must be much lucid than metallurgical grade silicon for use in solar cell applications..

4.2 Conversion of MG- Si to Semiconductor- Grade Silicon

The standard approach to purify MG-Si is known as Siemens Process. The MG-Si is converted to a volatile compound that is condensed and refined by fractional distillation. The detailed processing sequence is that in the presence of a Cu catalyst, a bed of fine MG-Si particles is fluidized with HCl to promote the following reaction:

$Si + 3HCl$ ---> $SiHCl_3 + H_2$

The emitted gases are passed through a condenser. The remaining liquid is subjugated to multiple fractional distillations to get SeG-$SiHCl_3$ (tricholosilane). To extract SeG-Si, the SeG-$SiHCl_3$ is reduced by hydrogen when mixtures of the gases are heated. Silicon is deposited in a fine grained with polycrystalline form onto an electrically heated silicon rod according to the reaction

$SiHCl_3 + H_2$ ----> $Si + 3 HCl$

4.3 Semiconductor- Grade Polysilicon to Single- Crystal Wafers

For the solar cell , silicon must be very pure and there must be zero defects in the crystal structure .The Czochralski process is the pronounced method to produce such material for commercial purpose. The SeG polycrystalline silicon is liquefied in a crucible with pinch amount of one of the dopants required in the completed device added. Boron is generally used as p-type dopant for solar cell applications. In this process minute temperature control is done to pull pure crystal from large crystal of silicon. Crystals of diameter in excess of 12.5 cm and 1 to 2 m in length are routinely grown in this manner.

Silicon solar cells need only be 100 μm or more to absorb radiation in sunlight. Therefore,larger single crystal is sliced up into wafers are as thin as possible. With present wafering technology it is difficult to cut wafers which are thinner than 300 μm. More than half the silicon is wasted as kerf or cutting losses in the process. The low overall yield in going from SeG-Si to single- crystal wafer is major weak link in the standard technology.

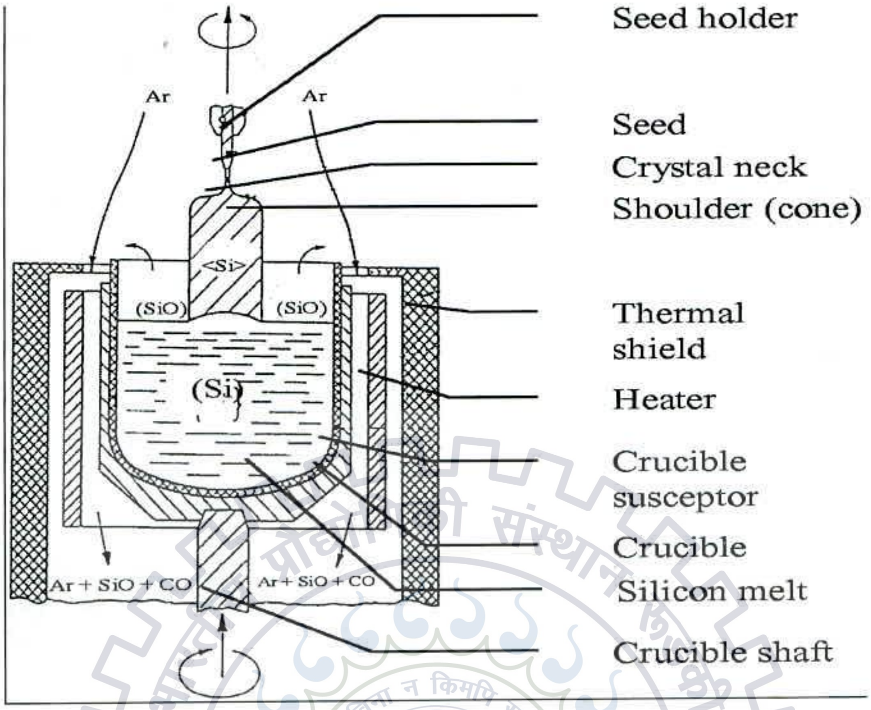


Fig.4.2: Czochralski process

4.4 Solar Cells from Single-Crystal Wafers

After etching silicon wafers and cleaning them, additional impurities are introduced into the cell in a controlled manner by a high-temperature impurity diffusion process.

In the Czochralski process, Boron element is generally mixed to the melt which the result in p-type silicon wafers. N-type impurities must be added to get a p-n junction. For this purpose P element is mostly used. A carrier gas is passed through ($POCl_3$) which results in the formation of oxide layer on the wafer surface. At higher temperature P diffuse from its oxide to Si. Afterwards oxide layer is removed from its surface.

Metal contacts are then attached to both the n-type and the p-type regions .Back metal contact is generally formed over the whole back surface, while top contact is required in the form of a grid.

The contact is usually made up of three separate layers of metal. For good adherence, a thin bed of Ti in the bottom side and for good solderability and low resistance Ag layer is used in the bottom side. Finally , a thin antireflection coating is deposited on the top of the cell by the vaccum evaporation process.

4.5 Solar Cells to Solar Cell Modules

Encapsulation is provided in the solar cells to protect it from mechanical damage, chemical reactions and as electrical isolation. It also serves as support to cells and provide rigidity to them. Encapsulation protects metallic contacts and interconnections from corrosive elements in the atmosphere. Finally, it provides electrical isolation of the voltages generated by the panel. These may reach voltages as high as 1500 V above ground in some systems. The durability of the encapsulation will determine the ultimate operating life of the module, which ideally should be 20 years or more.

Structure layer approach is used in module design to provide rigidity. This layer can be either at the back or front of the module. Cells can be bonded directly to this layer and encapsulated in a flexible potant or enclosed in a laminate supported by it. The final layer, if at the rear of the module, acts as a moisture barrier. If at the top, it has the additional duties of implanting self-cleaning properties and improving impact resistance.

For structural back configuration anodized aluminium, porcelainized steel, epoxy board are used and for structural front configuration glass is used.

Another impotant area of module design concerns the interconnections between the cells. It is common practice to use multiple interconnects for redundancy. This increases the module tolerance to interconnect failure (by corrosion or fatigue) as well as to cracked cells. Cyclic stresses are set up in the interconnects due to differentials in temperature expansion coefficients and wind loading. A stress-relief loop is generally required in the interconnect.

4.6 Module Circuit Design

The electrical circuit aspects of the way solar cells are interconnected within solar modules can have a substantial effect on the field performance and operating life of the modules.

When solar cells are connected together, there is sometimes a mismatch in their operating characteristics .These mismatches indicate that output power of the PV module is less than the maximum output power. The difference, the mismatch loss, is the most significant for cells connected in series. Even more important than the loss in power is the potential for overheating in the poorest cell of a series string. Fig.4.2 shows the output characteristics of the lowest current output cell in a series string together with the combined output of the rest of the cells. The voltage across each of these components must be equal and opposite in sign when the module is short-circuited. The module short-circuit current can be found by reflecting one of the curves in the current axis as shown and finding its intercept with the other. In this connection, the poorest cell is reversed-biased and the power equal to the shaded area is dissipated in it. It is apparent from the fig.4.2 that power up to the maximum generating capability of the rest of the series string can be dissipated in the poorest cell under some conditions. Mismatching effect can result in extensive temperature increment in the poorest cell which ultimately leads to damage of the module.

Two techniques are available for reducing the severity of the foregoing effects. One is a technique known as series paralleling and the other by the use of bypass diodes. The by-pass diode becomes forward biased when a series block becomes reversed-biased. This limits the power dissipated in this block as well as providing a low-resistance path for the module or branch string current.

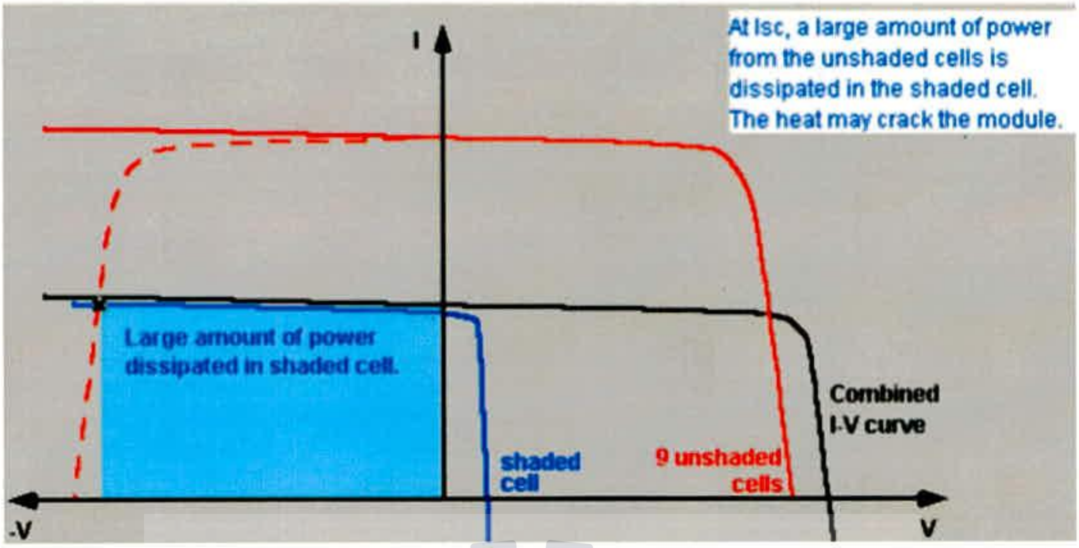


Fig. 4.3: Output Characteristics of Shaded Solar Cell

4.7 Progress in Manufacturing Solar Cell

Having Produced purified silicon, it is then necessary to convert it into the form of thin sheets about 100 micro meter or thick. In the past, the approach used has been to form a large single-crystal ingot using the Czochralski (CZ) process and then slice thin wafers from this ingot. In this process over half the silicon lost in sawing it into wafers but cutting limitations result in thicker wafers than essential. Also, the wafers are circular, which means that they cannot be packed very densely when encapsulated into solar modules unless trimmed to a square or hexagonal shape.

Galium Arsenide Solar Cell

Galium Arsenide (GaAs) is a compound semiconductor having direct band gap .In this material sunlight is very quickly absorbed after entering. Therefore only a few micron thick layer is required thus reducing material requirement. The processing sequence is to start with an n-type substrate of GaAs and epitaxially grow the overlying p-type $Ga_{1-x}Al_xAs$ layer from the liquid phase. The same processing step also dopes the top portion of the substrate p-type by the diffusion of p-type impurities. The large indirect band gap of AlAs causes it to act as a window layer, allowing most of the light to be absorbed well into the bulk of the solar cell.

CHAPTER 5

ENERGY ANALYSIS OF SOLAR MODULE

5.1 Embodied Energy

Embodied energy is new idea for the environmental analysis and lifetime energy calculations. Embodied energy is defined as: "the amount of energy consumed by all of the activities associated with a manufacturing process"[4]. It includes energy consumption in all the activities, energy used in making equipment. Overall it includes all the direct and indirect energy involved in the process.

The intention of embodied energy analysis in solar cell is to calculate the quantity used in manufacturing silicon material, its production process energy, its raw material extraction energy and energy used in its auxiliary components [5].

Embodied energy gives the indication of the amount of energy consumed in the process. The goal of the designer since several years is to make a better design of the material so that energy consumed is less [4]. The assessment of embodied energy was highly ignored due to lack of data and no clear methodology. There was a lack of understanding and common belief that study of energy portion for the embodied energy analysis is of no use.

From renewable technology perspective, study of embodied energy and its payback time is important to know to check its feasibility. There is no sense of using that technology that cannot payback embodied energy in its lifetime [12].

5.2 Energy Pay Back Time (EPBT)

The Energy Payback Time depends on the annual output of the system and the energy involved in making that system and its associated components. Energy densities of different material are needed to calculate the embodied energy of the system and its component.

Thus EPBT can be calculated by dividing the embodied energy by yearly output of the system and it is expressed [5] as:

$$EPBT = \frac{\text{Embodied Energy(Ein)}}{\text{Annual Energy Output(Eout)} - \text{Eom}}$$

Where,

E_{om}= Annual energy required for operation and maintenance of the module.

Ein= Embodied Energy of photovoltaic module

Eout= Annual Energy output of photovoltaic module

Annual energy generation from PV module, embodied energy of the PV module and competing energy sources from which solar PV system is compared are the functional parameters to calculate the EPBT.

The variation of Embodied energy is not much affected by the geographical area. The output of the photovoltaic module depends on the geographical area as ambient temperature and solar radiation varies with it.

5.3 Life time Energy Efficiency

The ratio of total energy output of the PV module in its lifetime to the energy used in making it, determine its Life time energy efficiency. Life time is used to determine the overall performance of the photovoltaic module system.

$$\acute{\O} (t) = (Eout*T) / Ein$$

Where,

Eout=Annual electrical output energy of a PV Module

Ein= Total Embodied Energy of a PV Module

T= Lifetime of PV Module

Life time energy analysis includes the identification of energy consumption in each step of manufacturing PV component and their total percentage contribution. First a method of desegregation is used to estimate the quantity of material used. Then decomposition is done to separate the materials from their primary material. To obtain the total energy requirements energy density of each material is multiplied by the quantity of that material used in that process and then all the products are aggregated.

There are several methods to carry out energy analysis including:

Process Analysis:

It is done by determining a system boundary around a individual process. Then all the direct and indirect energy associated with that process is calculated. These are done through the provision of other goods and services bypass the system definition and capital equipment. This process is largely dependent on selection of system boundary, different system boundaries of the process yields different output.

Input-Output Analysis:

It uses the economic flow of services and goods between different sectors of an economy. A list of sales and purchase in row and columns are done and energy intensities are calculated by dividing the purchase from the energy supply.

As the Input-Output Analysis is inherently unreliable, process analysis greatly reduces the error and more preferred for the embodied energy analysis.

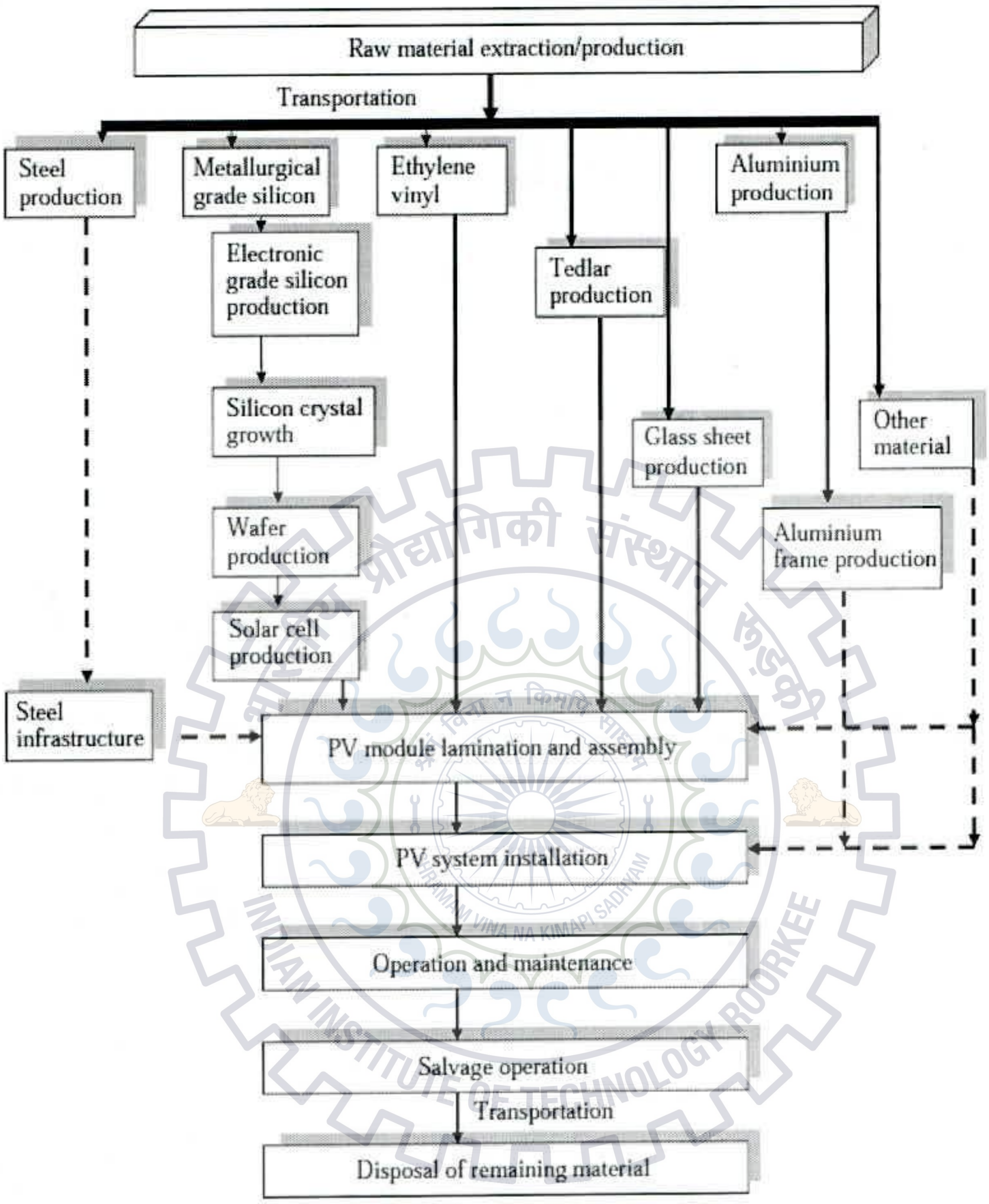


Fig.5.1: Processes to calculate embodied energy

Conversion efficiency only gives the operational energy efficiency of PV cell. For much extensive analysis Life time energy analysis is used. It covers raw material production, maintenance, use, total life time of PV module and finally its end-of- life management.

Table 5.1: Specification of a PV module

Size of PV Module	$1.20*0.55*0.01\ m^3$
Effective area of PV Module	$.60534\ m^2$
Area of a Cell	$.0139\ m^2$
Thickness of Cell	.00035 m
Density of Silicon	$2.3*10^3\ Kg/m^3$
Mass of a Single PV Cell	$11.2*10^{-3}$ Kg
Fill Factor of a Cell	0.72
Solar Cell Efficiency	15%
No. of Cell in PV Module	36
Total Mass of Cells	0.4032 Kg
Module Efficiency	12%
Packing Factor of PV Module	83%

Table 5.2 Energy requirement in different processes for production of a PV module

Process	**Energy Requirement**
Silicon Purification & Processing	
Metallurgical Grade Silicon Production From SiO_2	20 KWh per Kg of MG-Silicon
Electronic grade Silicon from MG-Si	100 KWh per Kg of EG-Silicon
Cz-Si from EG-Si	210 KWh per Kg of EG-Silicon
Solar Cell Fabrication	120 KWh per m^2 of silicon cell
PV Module Assembly	190 KWh per m^2 of PV Module
Roof-top Integrated PV Cell	200 KWh per m^2 of PV Module
PV Installation Support Structure	350 KWh per m^2 of PV Module
Balance of System	46 KWh per m^2 of PV Module
Operation & Maintenance	82 KWh per m^2 of PV Module
Transportation	53.5 KWh per m^2 of PV Module
Administration	10 KWh per m^2 of PV Module

The total embodied energy required for making individual components of the PV module is shown in Fig.5.1, with their manufacturing energy needs to be evaluated. The specification and design data of a PV module (glass-to-glass) are given in Table3. reported that 2.4 kg of MG-Si and 2.3 kg of EG-Si are required for 0.729 kg of solar cells. Therefore 0.4032 kg of solar cells requires 1.327 kg of MG-Si and 1.273 kg of EG-Si.

5.4 Calculations for Embodied Energy

The embodied energy of a PV module (glass-to-glass) can be derived in the following steps:

i. Silicon purification and processing
   (a) Production of 1.327 kg of MG-Si= 1.327 *20= 26.54 kWh
   (b) Production of 1.273 kg of EG-Si= 1.273 *100= 127.30 kWh
   (c) Production of 1.273 kg of EG-Si for Cz-Si= 1.273*210= 267.33 kWh
ii. Solar cell fabrication=120 * (0.60534 *0.83) = 60.29 kWh
iii. PV Module assembly=190 * 0.66= 125.40 kWh
iv. Assuming that the energy required for assembly of a glass-to-tedlar PV module and a glass-to-glass PV module is approximately the same).
v. Installation/integration= 200 *0.66= 132 kWh

Hence, the total embodied energy required for installation/integration of a PV

Module =739 kWh

For Open- Field Installation, Embodied Energy of a PV Module= 964.25 KWh

India is enriched with sumptuous amount of solar energy resource. India is situated in the equatorial sun belt of the earth. The reception of solar power in India is about 5000 trillion kWh / year. Its daily average solar energy incident varies from 4 to 7 Kwh/m2 with about 2,300–3,200 sunshine hours and approximately 300 sunny days in a year, depending upon geographical location.

Table 5.3: Average Solar Radiation for different cities

Place	Avg. Daily Solar Radiation (KWh/m^2)
Delhi	5.34
Kolkata	4.50
Ahmadabad	5.76
Hyderabad	5.18
Bangalore	5.26
Roorkee	5.27
Dehradun	5.15

5.5 Calculation for EPBT and Life time Energy Efficiency

Annual Energy Generated by a PV Module= $\eta \times A \times I(t) \times t_o$ =0.12×.6×5.34×300= 115.34 KWh

η= Conversion Efficiency of PV Module

A= Effective area of PV Module

I(t)= Average daily solar radiation

t_o= No. of clear days in a year

Energy Payback Period= Embodied Energy/ Annual Energy Output

= 964.25/115.34= 8.35 Years

Output Energy of a PV Module in its Lifetime

For a 25 years life of a module, degradation of 10% is taken in first 10 years and degradation of 10% in another 15 years, so

Degradation factor = (10×.95+15×.85) / (10+15) = 0 .89

Output Energy in Lifetime = 115.34×0.89×25 = 2566.315 KWh

Lifetime energy efficiency = Output Energy of a Module in its Lifetime / Embodied Energy

=2566.315 / 964.25 = 2.66 = 266%

5.6 Results and Discussions for EPBT and Life Time Energy Efficiency

From the calculations mentioned in section 5.4 and 5.5 (Calculation of Embodied energy, EPBT and Life Time Energy Efficiency), the total embodied energy associated with a mono-crystalline PV module in the process of material production, distribution, fabrication, component manufacturing, assembly and its installation is 964.25 KWh for Open- Field Installation and 739 kWh for building integrated photovoltaic module. For a mono-crystalline solar module having conversion efficiency of 12% and using the present technology of manufacturing photovoltaic module, the calculated energy payback period and life time Energy Efficiency is tabulated in Table 5.4.

Table 5.4.: EPBT and Lifetime Energy Efficiency of PV module

City	Energy Payback Period (Years)	Lifetime Energy Efficiency (%)
Delhi	8.77	266
Kolkata	9.92	224
Ahmedabad	7.75	287
Hyderabad	8.47	258
Banglore	8.66	262
Roorkee	8.47	263
Dehradun	8.67	257

CHAPTER 6

OPTIMUM TILT ANGLE OF PV CELL

6.1 Introduction

Solar energy is one of the abundantly available renewable energy sources available. Solar cells are the clean energy devices that convert the received solar energy into electrical output. It does not emit any harmful pollutants to the environment and so received much attention. Continuous efforts are going on to improve its production cost and improve its efficiency. These are important if the photovoltaic system is to be globally established as a power generating system. It is important to know the performance of the photovoltaic system at the installation site. For any solar panel, the more it is exposed to sunlight, the electricity it will generate. For that solar panel should be positioned in such a manner that it will extract maximum sunlight.

The local climatology, tilt angle of the solar panel and the ground reflectance properties are the various factors which affect the amount of solar radiation extraction on a solar panel. Optimum tilt angle is a important factor to be noted which affect the total output of solar panel largely. This tilt angle changes according to the latitude of the site, air pollution, , distribution of clear sunny days and clearness index.

Many researchers have given their model to calculate the solar radiation on tilted surfaces since last few years. Different method uses different methodology and they have their own limitations. There are many similarity methods to calculate the beam and ground reflection radiation on a inclined surface of PV module. The only difference comes in the case of diffuse radiation calculations. The approximation generally used for evaluating the diffuse component for a horizontal surface. It is found that sky radiance should be treated as anisotropic. It has large effect of aerosols. Many researchers have recommended different models for the year round application.

Use of tracking system is the best method to extract the maximum energy. A tracker follows the direction of the sun across the sky on its daily sweep. As the trackers are costly and it also need energy for its own operation so it is not widely applicable. The appropriate solution to this is to change the tilt angle on monthly or seasonally basis.

The estimation of tilt angle for Indian locations are based upon the data of monthly mean daily global and diffuse solar radiation on a horizontal surface. It is found that for the northern hemisphere orientation of solar panel should be south facing and its tilt angle will depend on the latitude of that location.

6.2 Solar radiation basic

The earth's axis is inclined about 23.45^0 with respect to the earth's orbit around the sun. The declination of the sun is the angle between a plane perpendicular to a line between the earth and the sun and the earth's axis. The declination of the sun is formulated as shown below [5]:

$$\delta = \frac{23.45\pi}{180} Sin\left(\frac{2\pi(284+n)}{365}\right)$$

Where,

n is the nth day of the year.

(a) Zenith, azimuthal and hour angles

Zenith angle (θ) gives the sun's path across the sky and azimuthal angle (α) gives the sun's location with respect to the north-south axis and hour angle is measured in the plane of apparent orbit of the sun.

(b) Solar and local standard time

The local time is the equal in the whole time zone .The solar time varies with respect to the position of the sun and the observer.

To calculate solar time with $(Longlocal \times Longsm)/15$ are subtracted from local time.

Where,

Longlocal is longitude of the observer in degrees (^{0}) and

Longsm is longitude for the standard meridian for the observer's time zone.

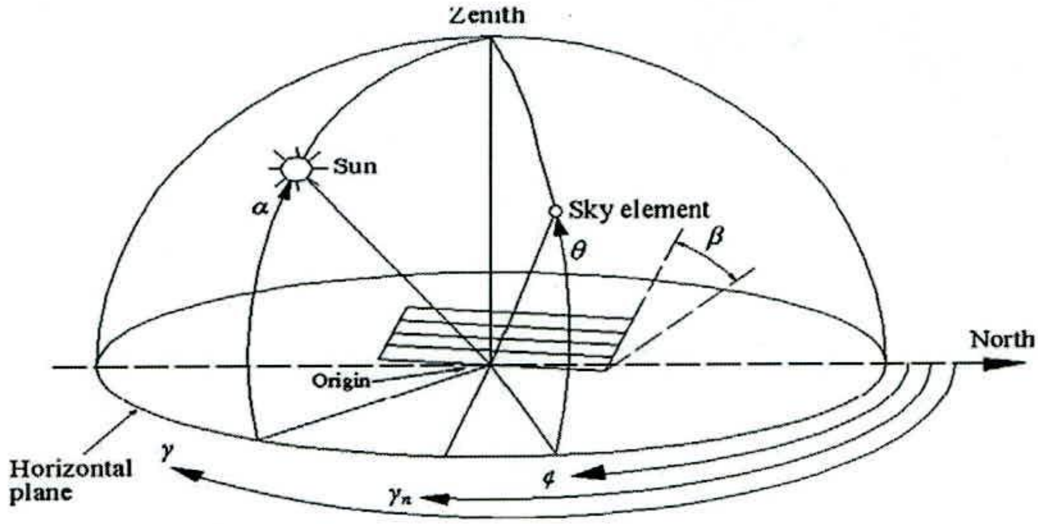


Fig. 6.1: Zenith, azimuthal, and hour angles

(c) Equation of time

The solar time changes somewhat less in reference to local standard time. This difference in time is regarded as Equation of time and its formula in minutes are depicted below [5]:

$$Eqt = -14.2\ Sin\ \left(\frac{\pi(7+n)}{111}\right)\quad for\ 1 \leq n \leq 106$$

$$Eqt = 4.0\ Sin\ \left(\frac{\pi(n-106)}{59}\right)\quad for\ 107 \leq n \leq 166$$

$$Eqt = -6.5\ Sin\ \left(\frac{\pi(n-166)}{80}\right)\quad for\ 167 \leq n \leq 246$$

$$Eqt = 16.4\ Sin\ \left(\frac{\pi(n-247)}{113}\right)\quad for\ 247 \leq n \leq 365$$

The solar time and local standard time can be related as follows [5]:

$$T_{Solar} = Tl_{ocal} + \frac{Eqt}{60} + \left(\frac{Long\ sm - Longlocal}{15}\right)$$

Where,

T_{solar} and Tl_{ocal} are in hours.

The hour angle ω is more relevant in calculation as it uses cosine and sine functions [5].

$$\omega = \pi \left(\frac{12 - Tsolar}{12}\right)$$

Unit of hour angle is radian.

(d) Sunrise and sunset times

When the sun is at horizon, cosine of the zenith angle is zero and sunrise or sunset happens at that time. Equating the cosine of zenith angle to zero, we get the relation as [7]:

$$\omega_{sr,ss} = \cos^{-1}(-\tan(\emptyset)\tan(\delta))$$

Where,

ωsr and ωss is the sunrise and sunset angle respectively.

(e) Global, diffuse and beam solar radiation

The beam solar radiation comes to the surface of earth without being dispersed. The sunlight that comes in the earth atmosphere is dispersed. The dispersed light that comes to the earth's surface are called diffuse radiation. The summation of these two direct beam and diffuse radiation is termed as Global radiation. Fig 6.2 shows the example of direct beam, diffuse and global radiation.

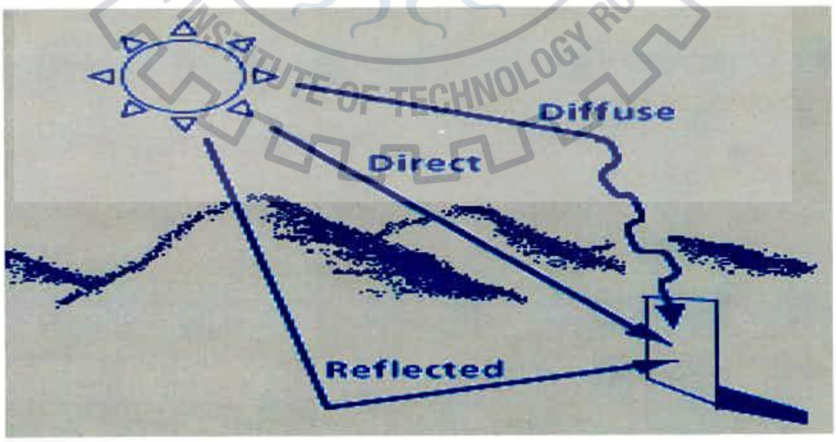


Fig. 6.2: Direct, diffuse and reflected radiation

(f) Modelling

In meteorological data, global and diffuse solar radiation is mentioned. The total radiations are obtained using various correlating mathematical models. The total mean monthly daily radiation on tilted surface are obtained by taking direct beam, diffuse radiation and reflected radiation independently.

The total radiation on a tilted surface can be written as follows [9]:

$$H_T = H_B + H_D + H_R$$

Researchers have given numerous methods to estimate the total radiation on a tilted surface of solar panel. The two models that are generally used are isotopic and anisotropic model.

The daily direct irradiation radiation extracted on an tilted surface can be given as [9]:

$$H_B = (H_g - H_d)R_b$$

Where,

H_d = monthly mean daily diffuse radiation on a horizontal surface

H_g = monthly mean daily global radiation on a horizontal surface

$$R_b = \frac{\text{average daily beam radiation on a tilted surface}}{\text{average daily beam radiation on a horizontal surface}}$$

The daily ground reflected radiation is given as:

$$H_R = H_g \rho \frac{(1-Cos\beta)}{2}$$

Where,

β= the tilt angle of the photovoltaic panel.

The equation of R_b in the case of northern hemisphere [9]:

$$R_b = \frac{cos(\emptyset-\beta)\cos\delta\sin\omega ss+\omega ss\sin(\emptyset-\beta)\sin\delta}{\cos\emptyset\cos\delta\sin\omega ss+\omega ss\sin\emptyset\sin\delta}$$

Where,

ωss= the sunset hour angle for the tilted PV panel

The equation of R_b in the case of northern hemisphere [9:

$$R_b = \frac{\cos(\emptyset+\beta)\cos\delta\sin\omega ss+\omega ss\sin(\emptyset+\beta)\sin\delta}{\cos\emptyset\cos\delta\sin\omega ss+\omega ss\sin\emptyset\sin\delta}$$

Where,

δ = the declination angle.

$\emptyset$ = latitude angle of the location.

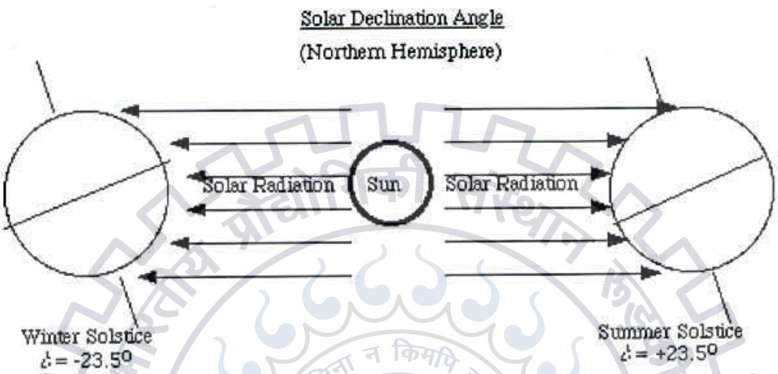


Fig. 6.3: Solar Declination Angle

The anisotropic and isotropic models are used to calculate R_b. Isotropic model regard diffuse radiation as evenly distributed in sky and anisotropic model takes it as circumsolar. The sky-diffuse radiation is represented as:

$$H_D = R_d H_d$$

$$R_d = \frac{\text{average daily diffuse radiation on a tilted surface}}{\text{average daily diffuse radiation on a horizontal surface}}$$

Models for Diffuse Radiation

The following models have been developed by various researchers. These can be classified into two distinct categories namely,(1) Isotropic models and (2) Anisotropic models

The anisotropic and isotropic models are used to calculate R_d.

Isotropic models

Isotropic model regard diffuse radiation as evenly distributed in sky. Different isotopic models [9] that are used for the calculation of R_d is tabulated below in Table 6.1.

Table 6.1: Different Isotropic models and their equations

Model Name	Model Equation
Badesecu model	$R_d = \frac{3+cos(2\beta)}{4}$
Tiane et al. model	$R_d = 1 - \frac{\beta}{180}$
Koronoakis et.al, model	$R_d = 1/3[2 + cos(\beta)]$
Liu and Jordan model	$R_d = \frac{1+cos(\beta)}{2}$

Anisotropic models

The anisotropic models assume the anisotropy of the diffuse sky radiation in the circumsolar region (sky near the solar disc) plus and isotropically distributed diffuse component from the rest of the sky dome. Different Anisotropic that are used for the calculation of R_d is tabulated below in Table 6.2.

Table 6.2: Different Anisotropic models and their equations

Anisotropic Model Name	**Model Equation**
Reindle model	$R_d = \frac{Hb}{Ho} Rb + \left(1 - \frac{Hb}{Ho}\right)\left(\frac{1+\cos\beta}{2}\right)(1 + \sqrt{\frac{Hb}{Hg}} \sin^3 (\frac{\beta}{2}))$
Olsethe and Skatveit model	$R_d = \frac{Hb}{Ho} Rb + \left(1 - \frac{Hb}{Ho} - \Omega\right)\left(\frac{1+\cos\beta}{2}\right) + \Omega \cos\beta$ Where, $\Omega = \{Max\ [0,(\ 0.3\text{-}2\times \frac{Hb}{Ho})]\}$
Stephen and Unworth model	$R_d = 0.51R_b + \left(\frac{1+\cos\beta}{2}\right) - \frac{1.74}{1.26\pi}[\sin\beta - (\beta \frac{\pi}{180}) \cos\beta - \pi \sin^2(\frac{\beta}{2})]$
Hay et,al. model	$R_d = \frac{Hb}{Ho} Rb + \left(1 - \frac{Hb}{Ho}\right)\left(\frac{1+\cos\beta}{2}\right)$

Out of different Isotropic and Anisotropic models mentioned in Table 6.1 and Table 6.2. Benghanem (2011) has reported that Liu and Jordon model of Isotropic models are most suitable for the calculation of R_d in India.

Total solar radiation on an inclined surface

Total solar radiation on an inclined surface is given as:

$$H_T = (H_g - H_d) + H_g \rho \frac{1-\cos(\beta)}{2} + H_d R_d$$

Where,

ρ is taken as 0.2.

6.3 Solar Radiation data of Different cities

Table.6.3: Monthly Mean Global radiation (MJ/m^2) data of different cities

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Delhi	13.33	16.42	20.65	24.08	24.42	22.56	19.09	17.79	18.9	16.8	14.13	11.93	18.25
Hyderaba	19.65	22.13	24.21	24.87	23.87	20.13	18.5	17.56	19.77	18.67	18.07	17.96	20.34
Banglore	20.42	23.35	23.7	23.64	22.88	17.71	16.71	16.16	18.89	18.42	17.45	17.35	19.7
Kolkata	13.52	15.68	18.98	21.07	20.64	17.17	15.09	15.57	14.9	15.27	13.85	12.68	16.17
Ahmedab	16.36	19.58	22.85	25.04	25.17	21.67	15.52	15.5	18.63	18.92	16.74	15.23	19.3
Roorkee	12.63	16.43	20.37	22.72	22.83	22.03	18.45	17.36	18.52	17.19	15.63	13.31	18.12
Dehradun	13.71	14.32	18.47	22.51	22.62	21.2	18.09	16.75	18.52	16.45	15.49	12.96	17.59

Table 6.4: Monthly Mean Diffuse radiation of different cities

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Delhi	5.21	6.22	7.56	8.83	10.68	11.66	11.83	10.27	8.27	6.37	4.92	4.87	7.82
Hyderaba	4.67	4.85	6.21	6.42	7.03	8.64	10.05	9.32	8.2	6.68	5.17	4.33	6.76
Banglore	5.65	4.67	6.12	7.37	8.66	10.8	10.68	11.12	10.23	8.45	7.1	6.17	7.83
Kolkata	5.92	6.77	7.72	9.27	10.67	10.67	10.28	9.76	8.68	7.37	5.94	5.37	8.19
Ahmedab	4.58	5.43	6.63	7.46	8.85	11.11	11.42	11.28	9.17	5.98	4.74	4.44	7.57
Roorkee	5.36	6.62	7.43	8.3	10.54	11.62	11.69	10.37	8.82	6.76	5.83	4.86	8.18
Dehradun	4.45	5.49	6.71	7.96	9.23	10.8	10.96	10.32	7.93	5.81	4.96	4.86	7.45

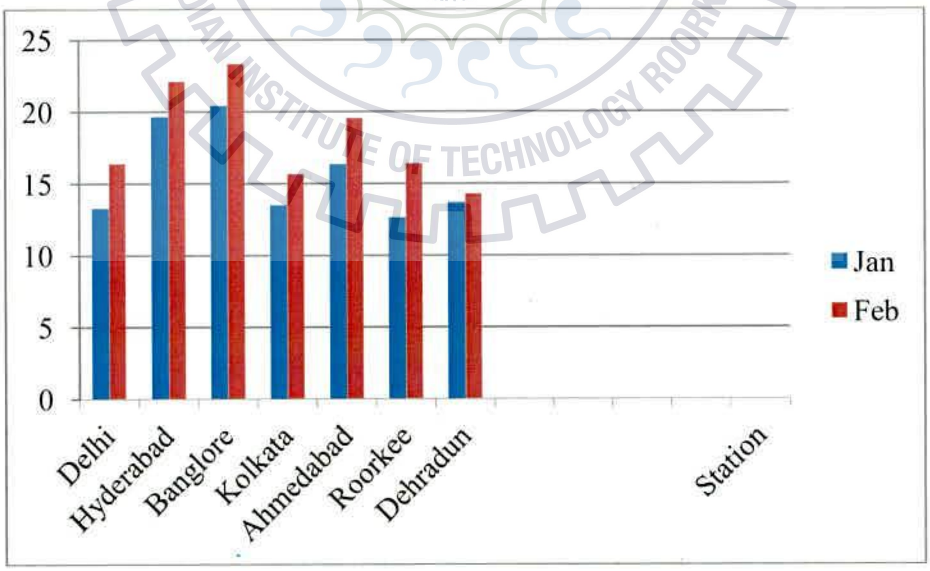


Fig. 6.4: Mean monthly global and diffuse solar radiation

6. 4 Matlab Program to find Monthly Optimum Tilt Angle

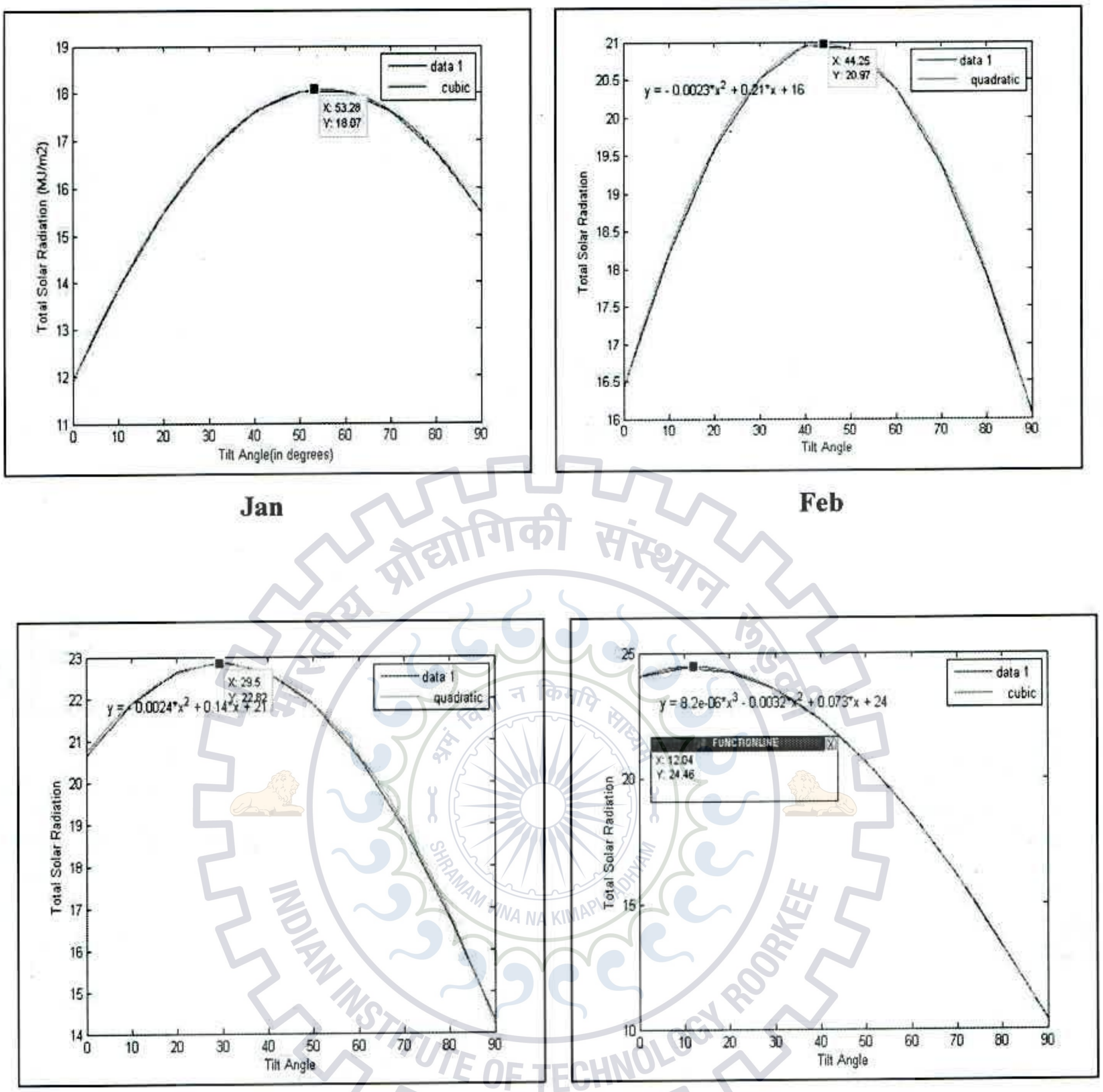
```
% solar program
Tlocal=11;
lngsm = 82.5;
longloc= long;
phi= (lat/360)*(2*pi);
n = [ 15 45 74 105 135 166 196 227 257 288 318 349];
Hg= [Hg1 Hg2 Hg3 Hg4 Hg5 Hg6 Hg7 Hg8 Hg9 Hg10 Hg11 Hg12];
Hd= [Hd1 Hd2 Hd3 Hd4 Hd5 Hd6 Hd7 Hd8 Hd9 Hd10 Hd11 Hd12];

for i=1:12
    del(i) = ((23.450*pi)*sin( (2*pi*(284 + n(i))/365)))/180;
    if n(i)>=1 && n(i)<106
        Eqt= -14.2* sin( pi*(n(i)+7)/111);
    else
        if n(i)>107 && n(i)<166
            Eqt= 4*sin( pi*(n(i)-106)/59);
        else
            if n(i)>=167 && n(i)<=246
                Eqt= -6.5*sin( pi*(n(i)-166)/80);
            else
                if n(i)>=247 && n(i)<=365
                        Eqt= 16.4*sin(pi*(n(i)-247)/113);
                end
            end
        end
    end

    Tsolar = Tlocal + (Eqt/60) + (lngsm - longloc)/15 ;
w = pi * (12- Tsolar)/12;
wss(i) = acos( -tan(phi) * tan(del(i)) );

for m=1:10
    beta(m)=(m-1)*10;
betar(m) = (beta(m)*pi)/180;
Rbnum1= cos(phi-betar(m))*cos(del(i))*sin(wss(i));
Rbnum2= wss(i)*sin(phi-betar(m))*sin(del(i));
Rbden1= cos(phi)*cos(del(i))*sin(wss(i));
Rbden2= wss(i)*sin(phi)*sin(del(i));
Rb(m)= (Rbnum1+Rbnum2)/(Rbden1+Rbden2);
Hb(m)= (Hg(i)-Hd(i))*Rb(m);
Hr(m)= Hg(i)*0.2*((1-cos(betar(m)))/2);
Rd(m) = (1+cos(betar(m)))/2;
HD(m)= Rd(m)*Hd(i);
Ht(m)= Hb(m)+HD(m)+Hr(m);

end

plot(beta,Ht);
```

By changing the input parameters such as long (longitude of the location), lat (latitude of the location) and mean monthly global and diffuse radiation, monthly tilt angle for each cities can be found. Mean monthly global and diffuse radiation for each city has been taken from Table 6.3 and Table 6.4 respectively. The input parameters values listed below in Table 6.5 has been used for each station to plot the graph between Total solar radiation and tilt angle on monthly basis. To avoid the repetition of the matlab program, one general program has been made in section 6.4. Monthly tilt angle for each station can be found by using the input parameters for that station. Monthly tilt angle has been found for each station and shown in figure 6.5 to figure 6.17.

Table 6.5: Longitude and Latitude of different cities

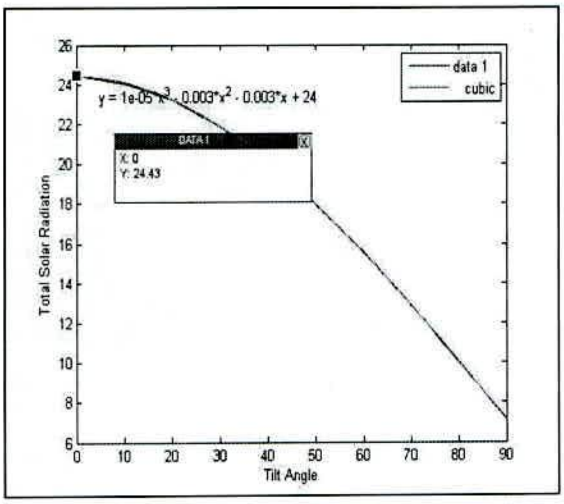
City	Longitude of the location	Latitude of the location
Delhi	77.2	22.58
Hyderabad	78.46	17.36
Bangalore	78.58	12.98
Kolkata	88.37	22.57
Ahmedabad	72.5	23.03
Roorkee	77.88	29.87
Dehradun	78.04	30.32

6.5 Monthly Optimum Tilt Angle of Delhi City

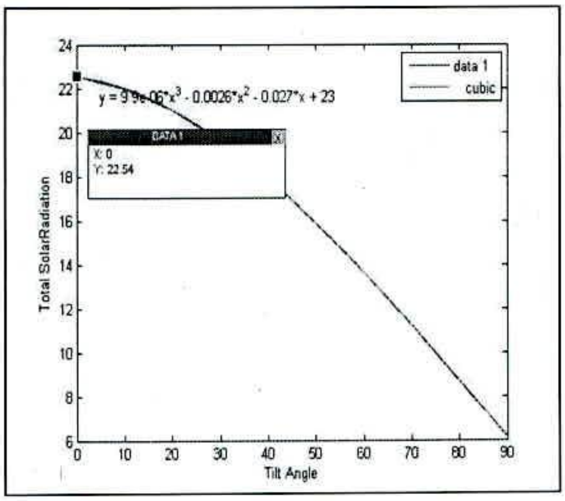


Mar **Apr**

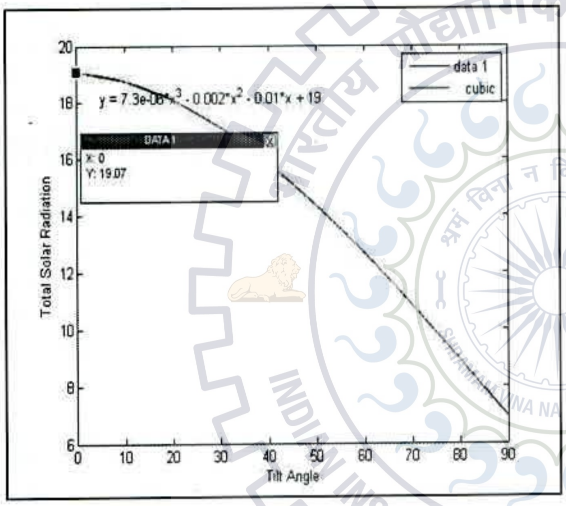
Fig. 6.5(a): Delhi Monthly Tilt Angle (January to April)



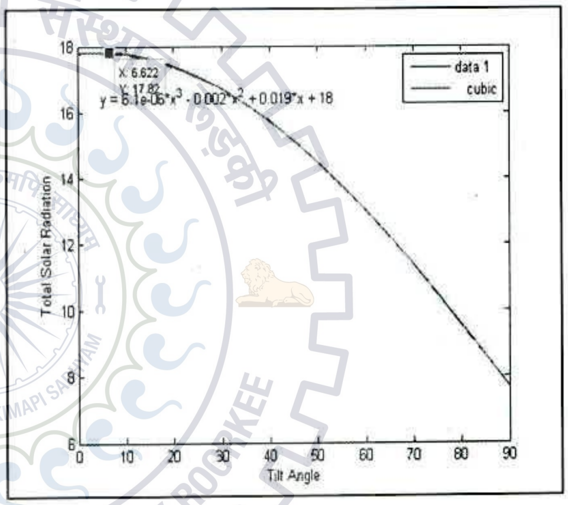
May



Jun

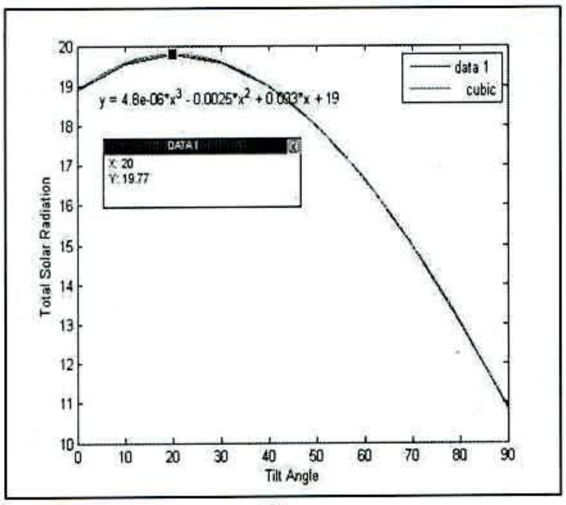


July

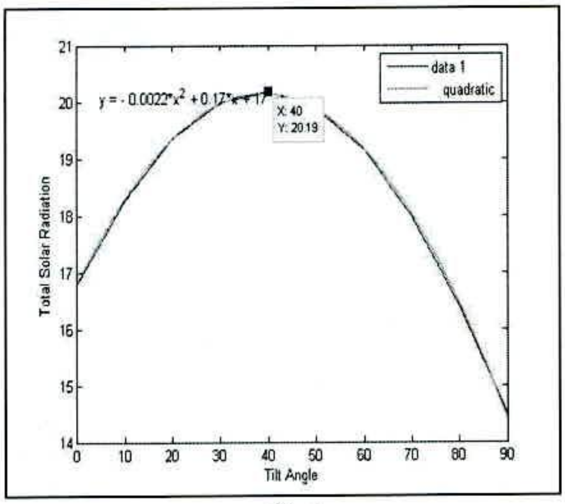


Aug

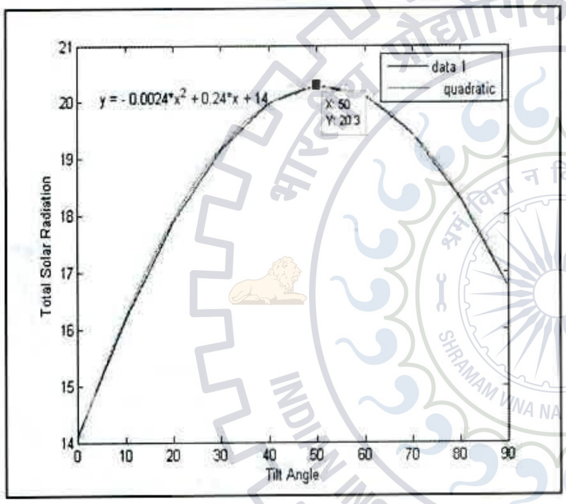
Fig. 6.5(b): Delhi Monthly Tilt Angle (May to August)



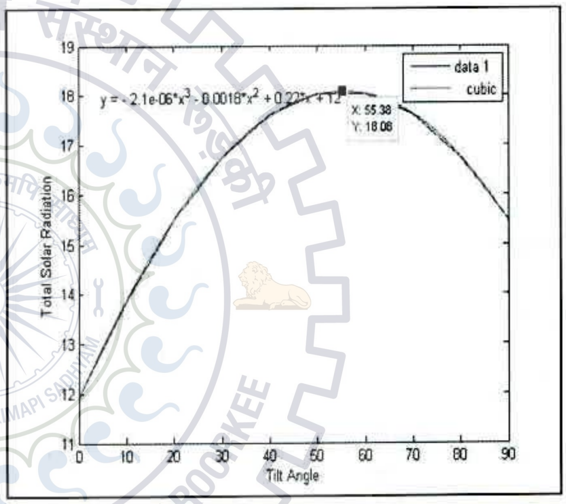
Sep



Oct



Nov



Dec

Fig. 6.5(c) : Delhi Monthly Tilt Angle (September to December)

Graphs 6.5(a) to 6.5(c) show the optimum monthly tilt angle of Delhi City. These monthly tilt angles are summarized in listed Figure 6.6.

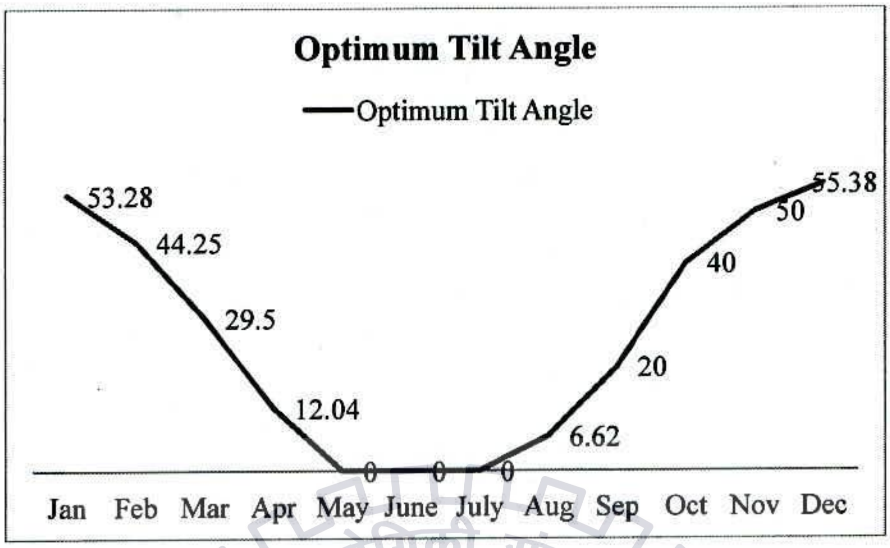
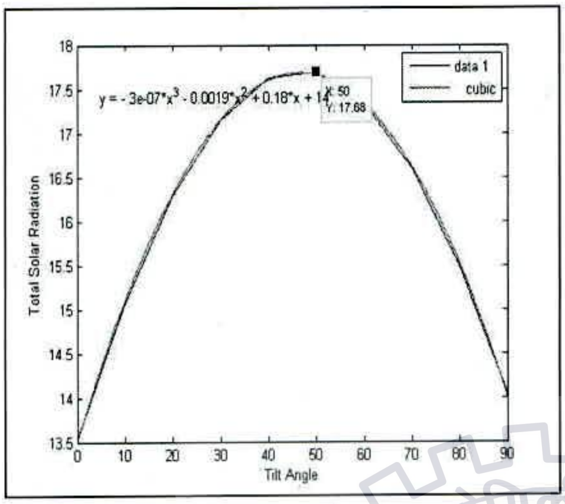
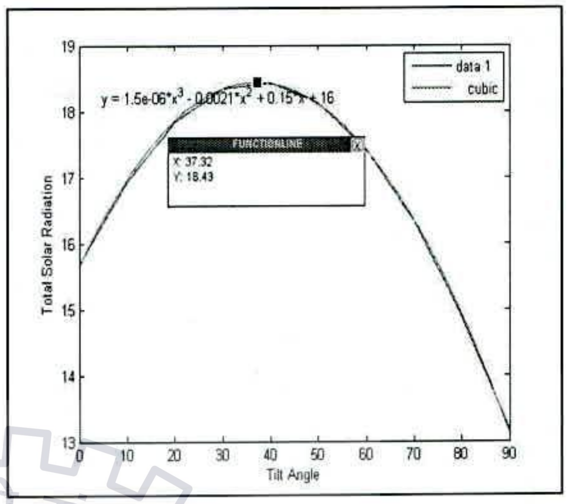


Figure 6.6: Monthly optimum tilt angle at Delhi station

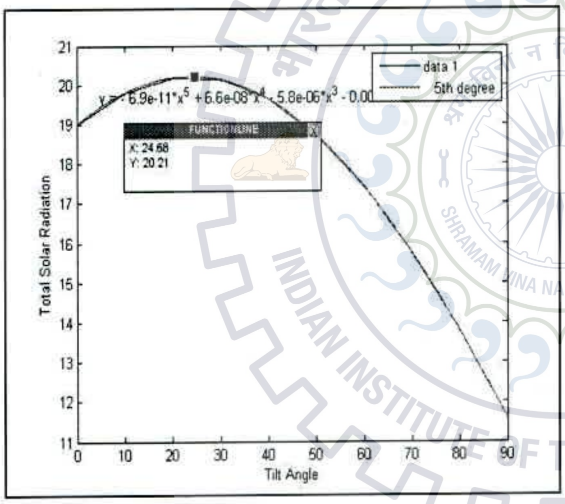
6. 6 Monthly Optimum Tilt Angle for Kolkata City



Jan



Feb



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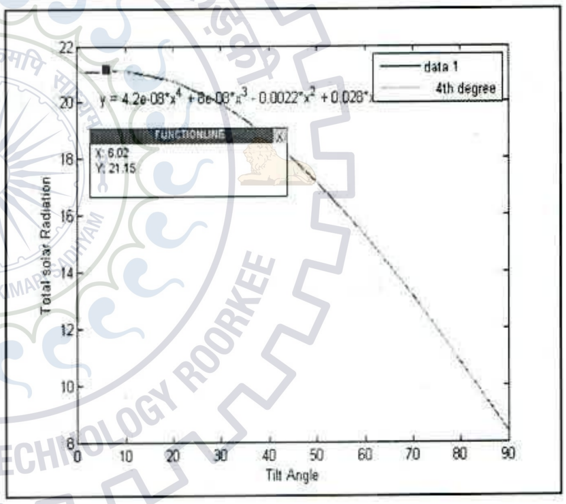


Apr

Fig. 6.7(a): Kolkata Monthly Tilt Angle (January to April)

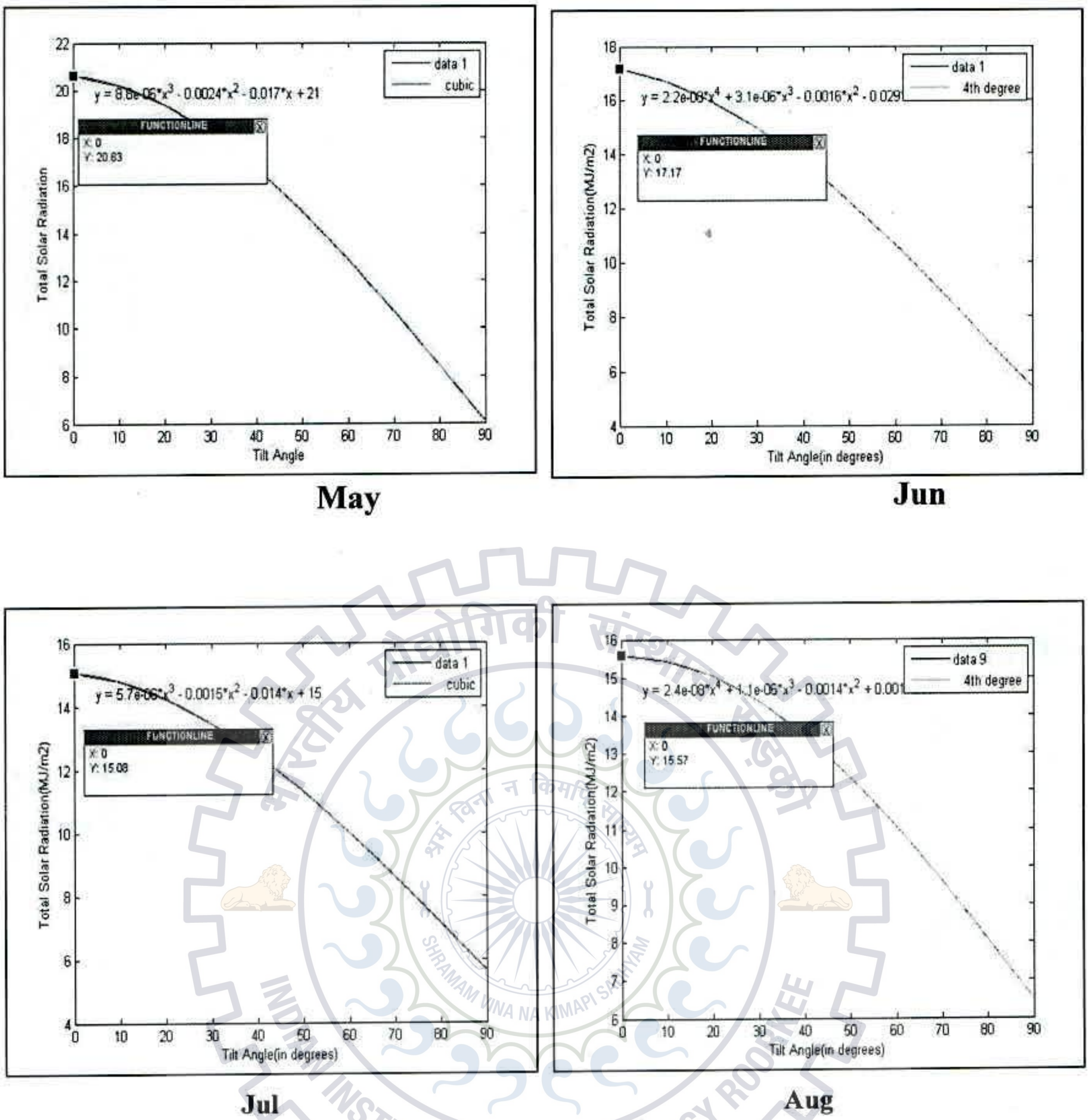
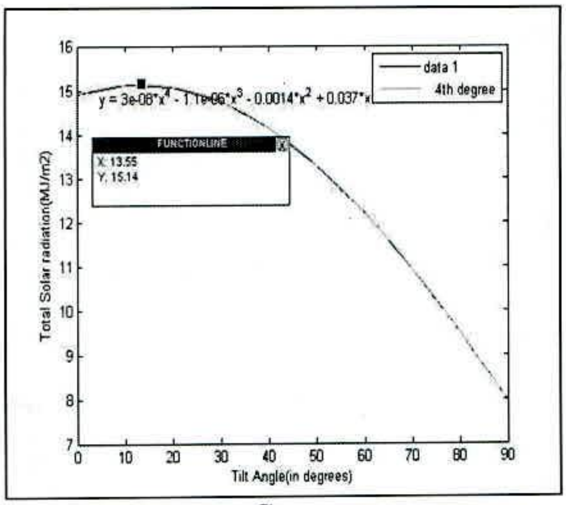
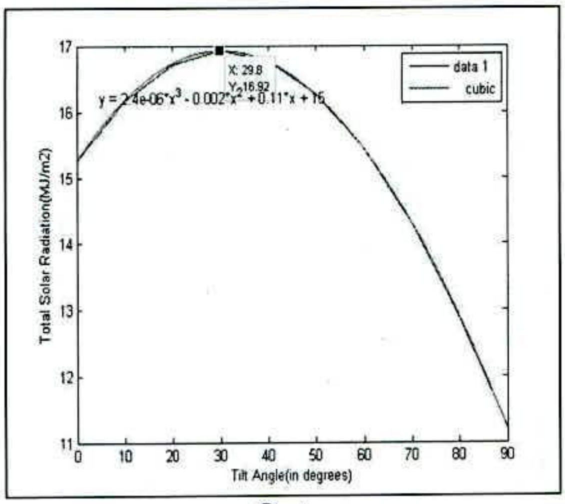


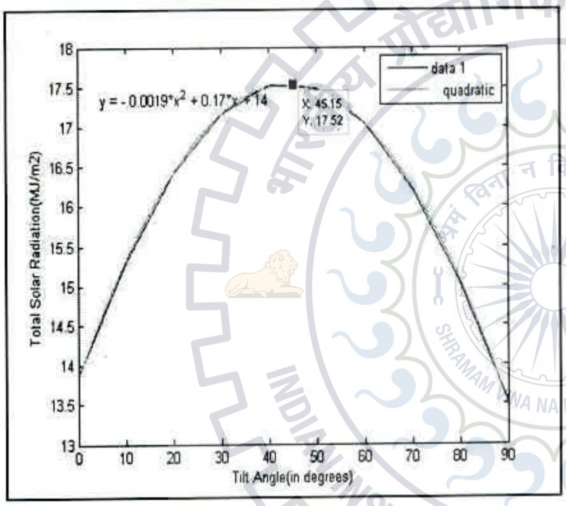
Fig. 6.7(b): Kolkata Monthly Tilt Angle (May to August)



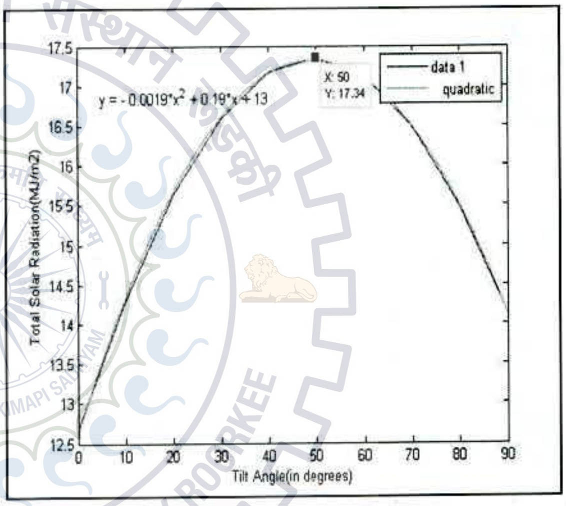
Sep



Oct



Nov



Dec

Fig. 6.7(c) : Kolkata Monthly Tilt Angle (September to December)

Graphs 6.7(a) to 6.7(c) show the optimum monthly tilt angle of Kolkata City. These monthly tilt angles are summarized in listed Figure 6.8.

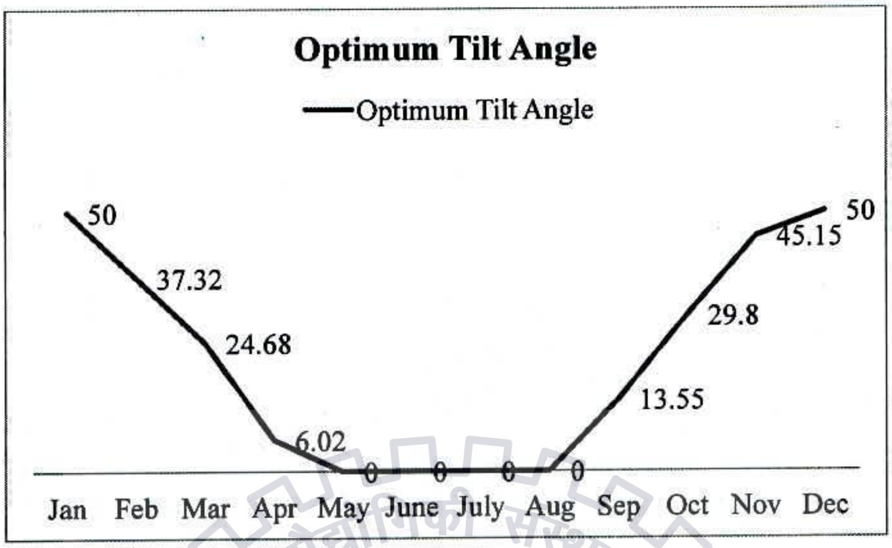
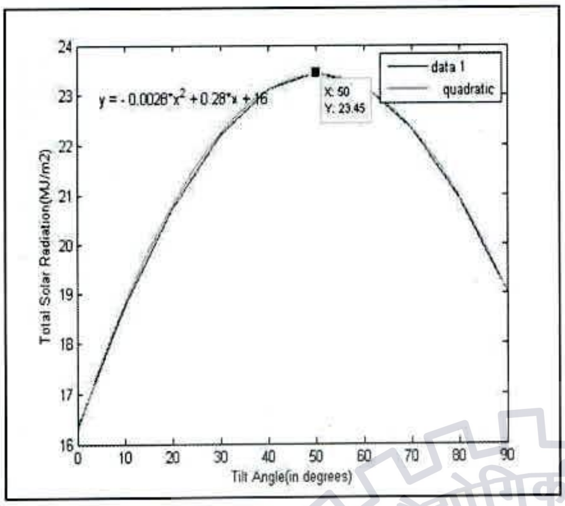
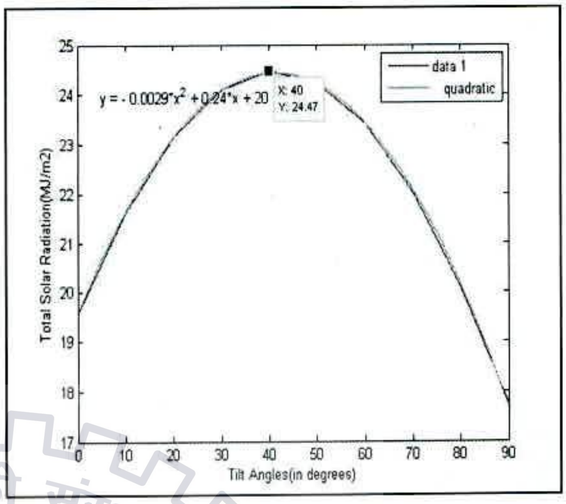


Figure 6.8: Monthly optimum tilt angle at Kolkata station

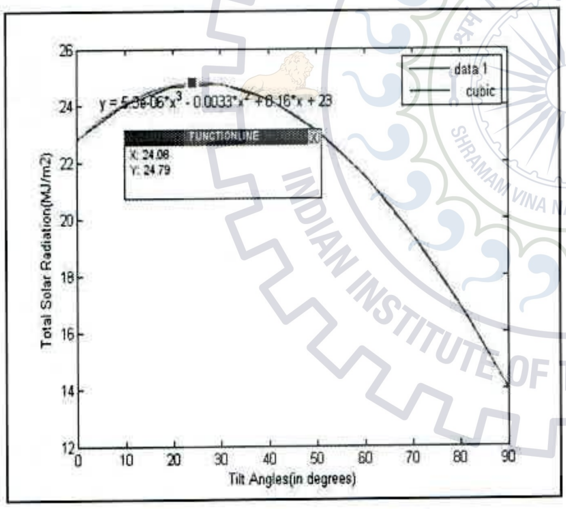
6. 7 Monthly Optimum Tilt Angle for Ahmedabad City



Jan



Feb



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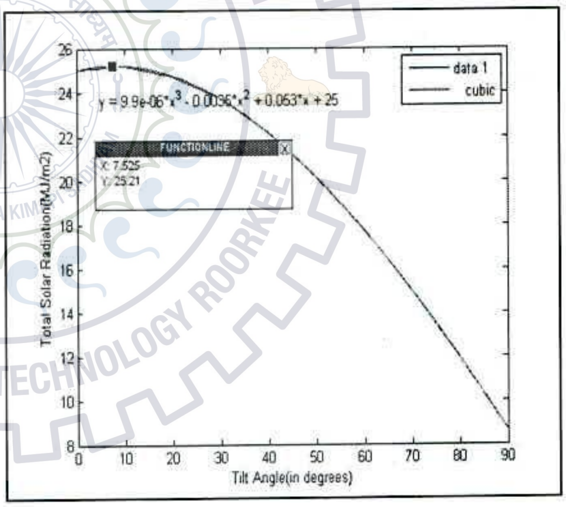
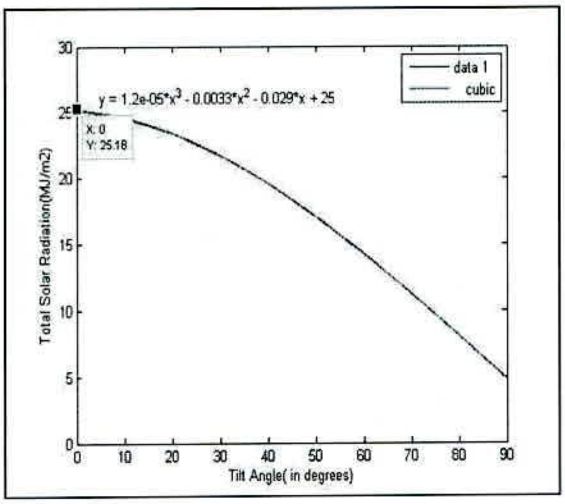
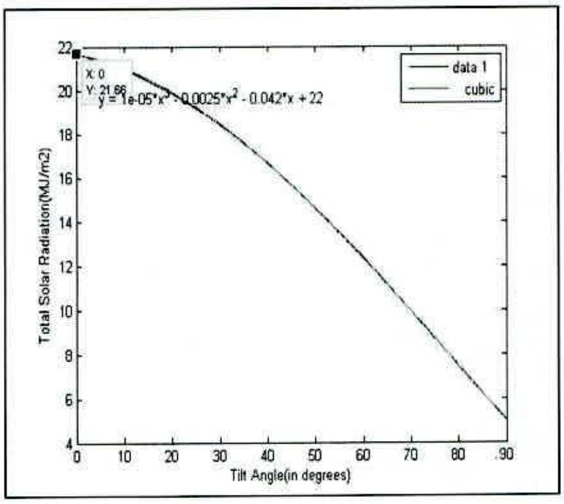


Apr

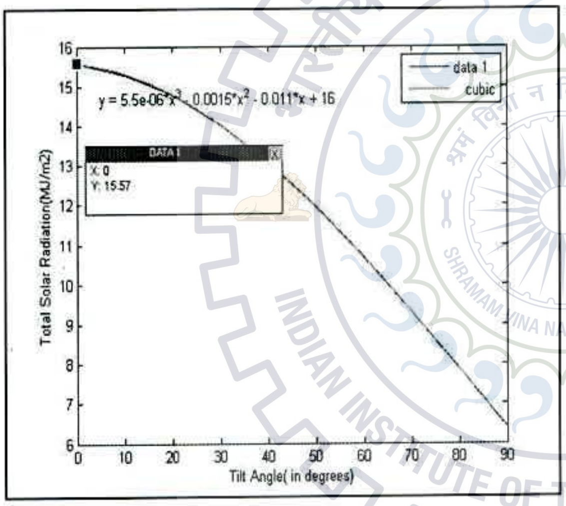
Fig. 6.9 (a): Ahmedabad Monthly Tilt Angle (January to April)



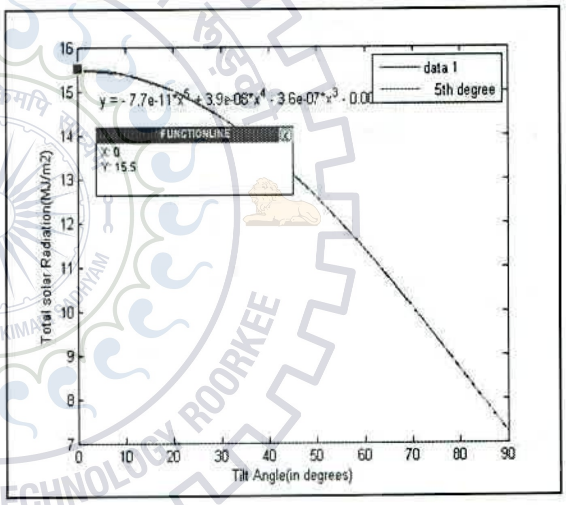
May



Jun

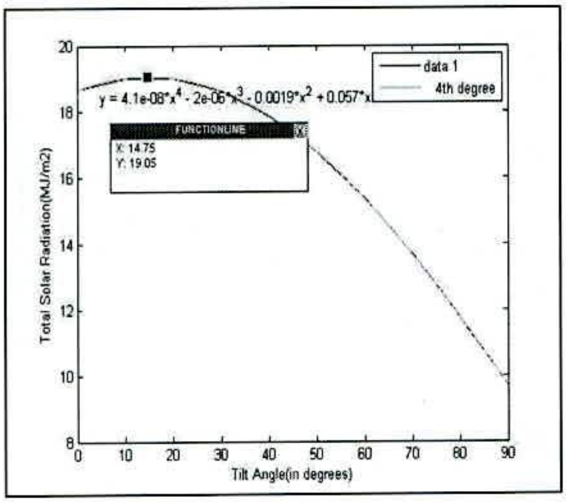


Jul

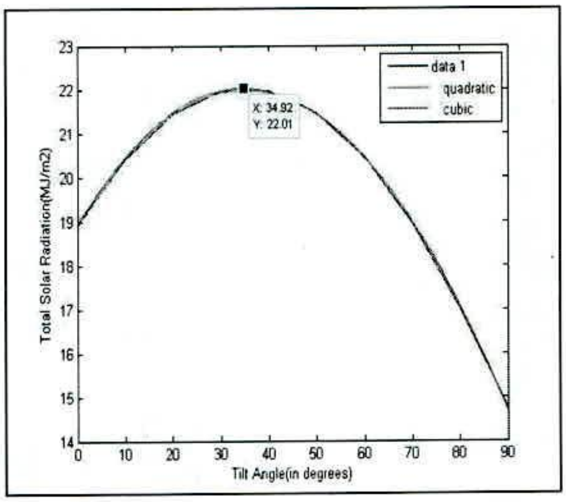


Aug

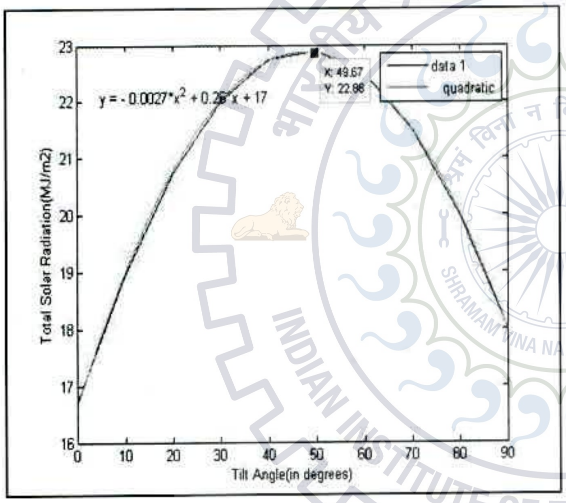
Fig. 6.9 (b): Ahmedabad Monthly Tilt Angle (May to August)



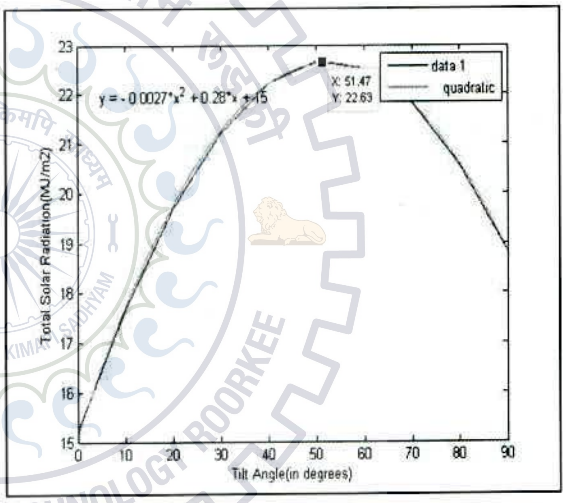
Sep



Oct



Nov



Dec

Fig. 6.9 (c) : Ahmedabad Monthly Tilt Angle (September to December)

Graphs 6.9(a) to 6.9(c) show the optimum monthly tilt angle of Ahmedabad City. These monthly tilt angles are summarized in listed Figure 6.10.

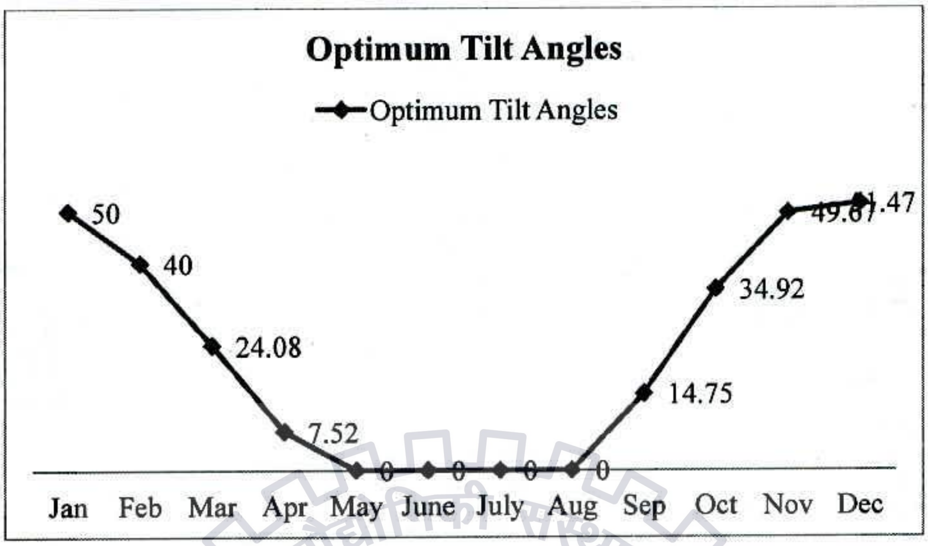
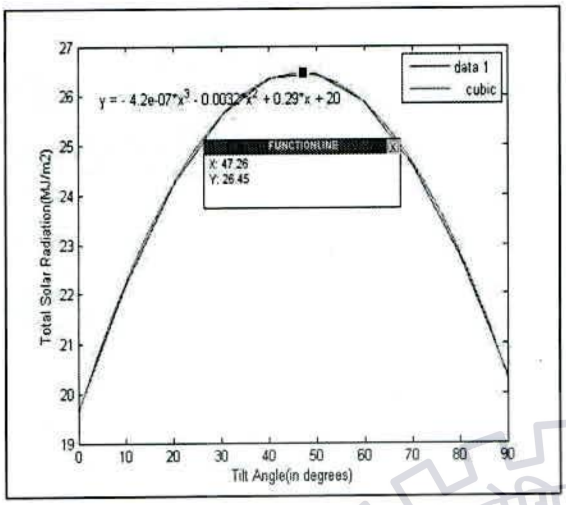
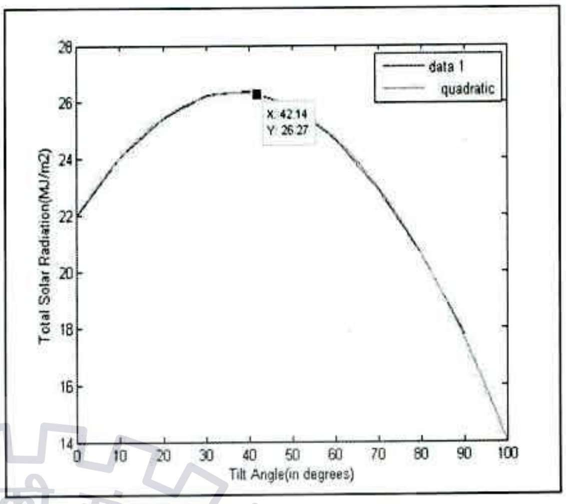


Figure 6.10: Monthly optimum tilt angle at Ahmedabad station

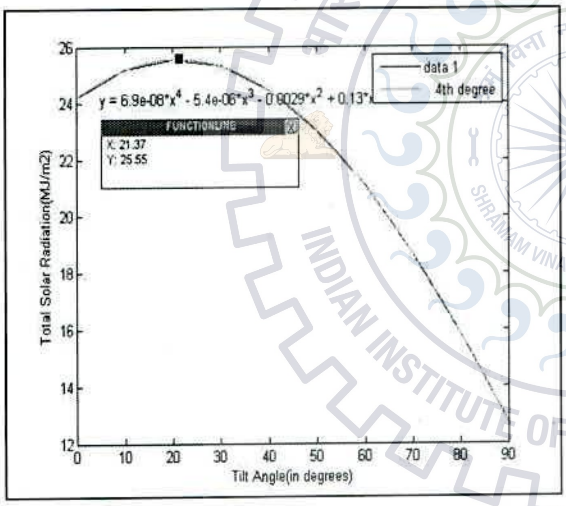
6. 8 Monthly Optimum Tilt Angle for Hyderabad City



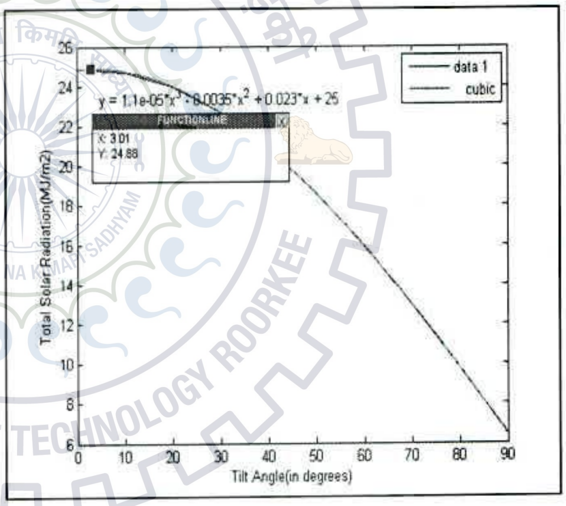
Jan



Feb

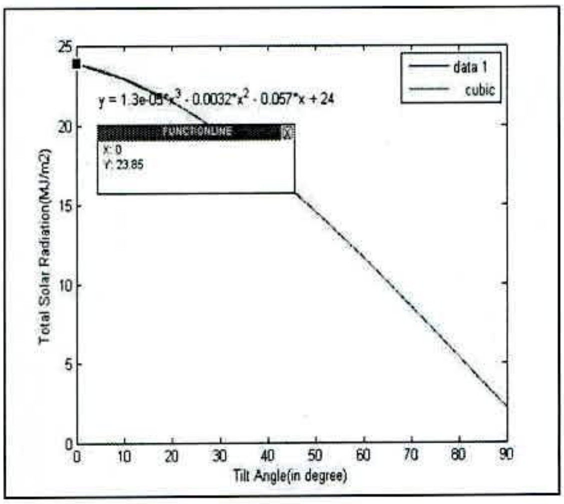


Mar

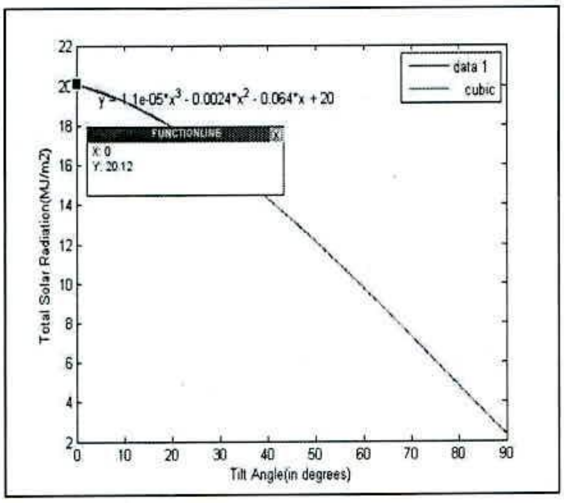


Apr

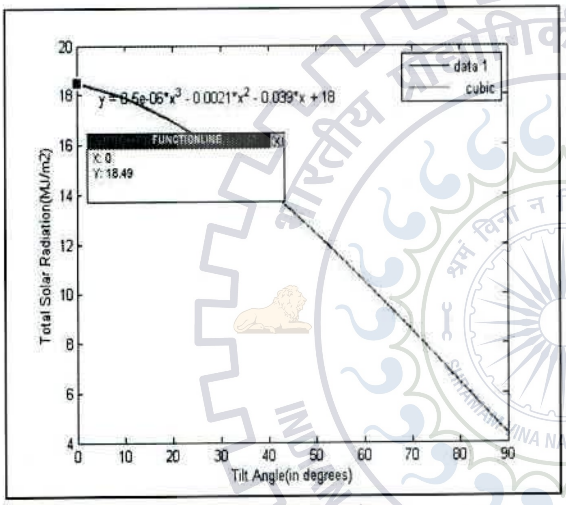
Fig. 6.11(a): Hyderabad Monthly Tilt Angle (January to April)



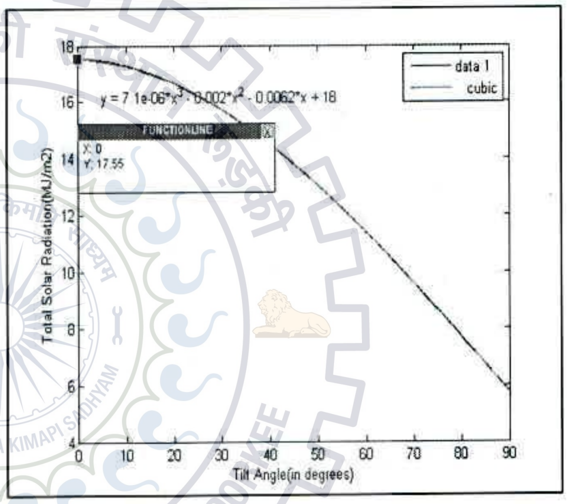
May



Jun

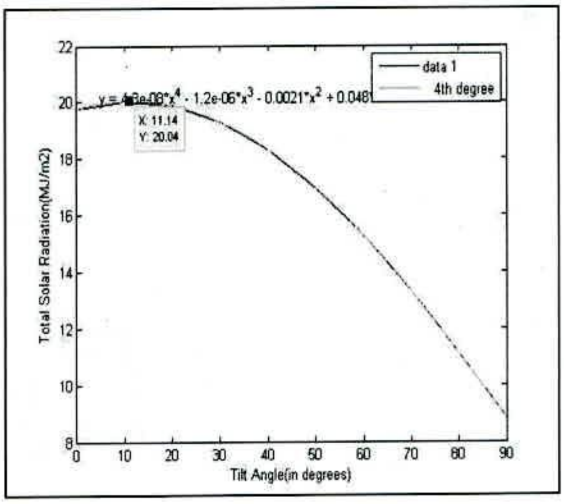


July

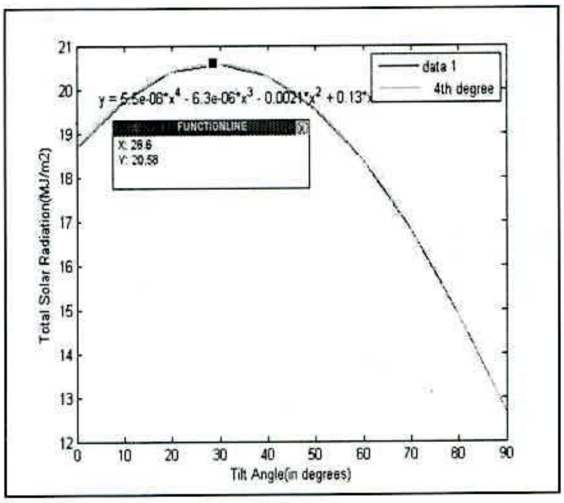


Aug

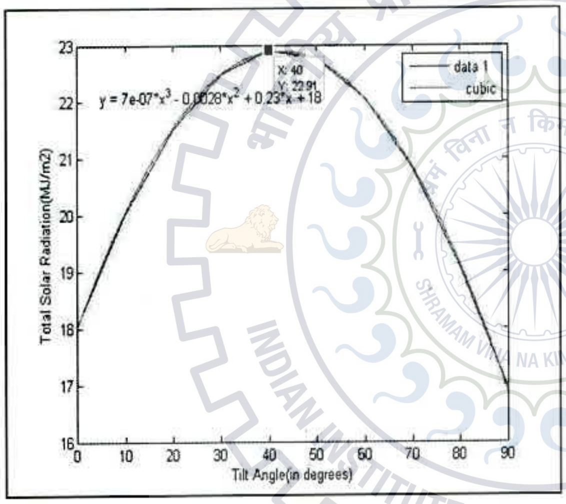
Fig. 6.11(b): Hyderabad Monthly Tilt Angle (May to August)



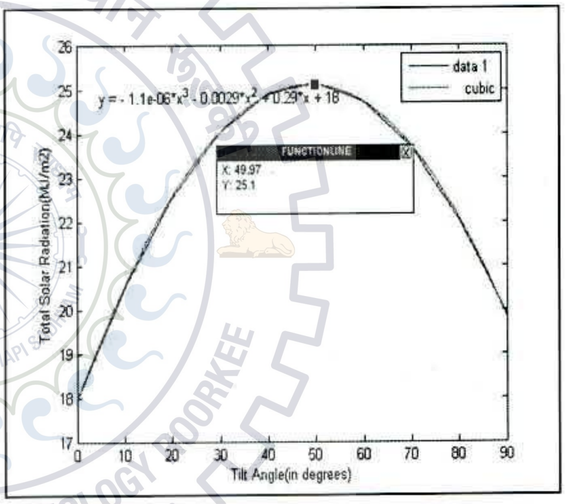
Sep



Oct



Nov



Dec

Fig. 6.11(c) : Hyderabad Monthly Tilt Angle (September to December)

Graphs 6.11(a) to 6.11(c) show the optimum monthly tilt angle of Hyderabad City. These monthly tilt angles are summarized in listed Figure 6.12.

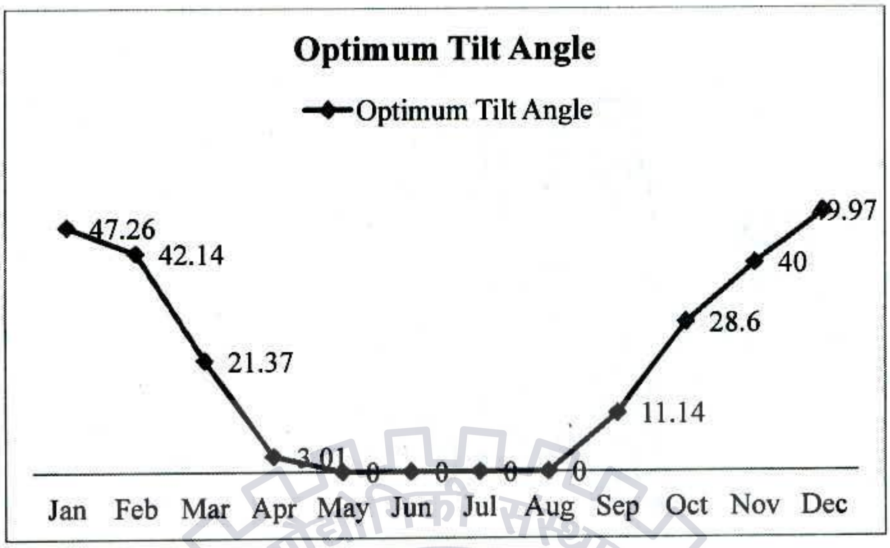


Figure 6.12: Monthly optimum tilt angle at Hyderabad station

6. 9 Monthly Optimum Tilt Angle for Banglore City

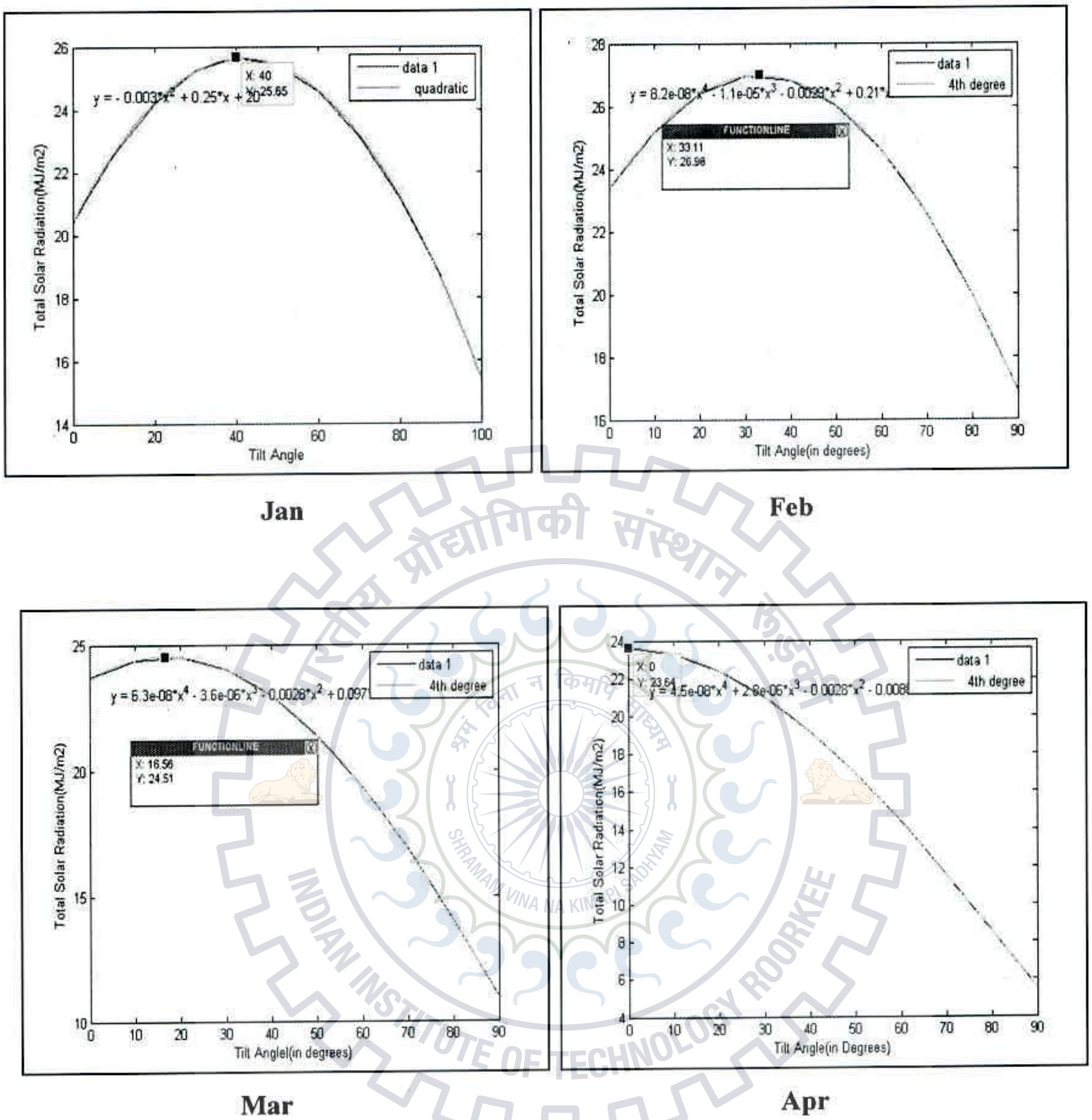
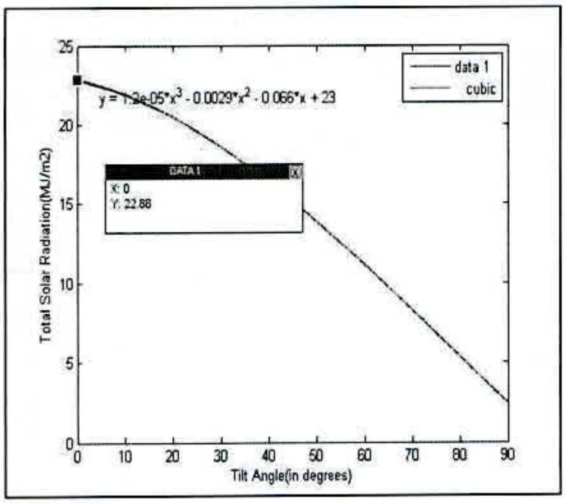
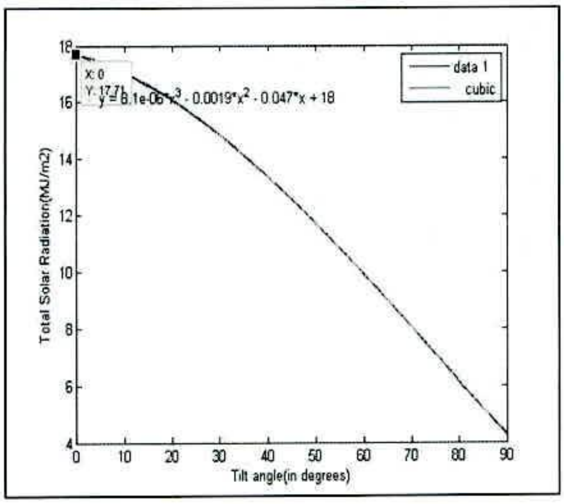


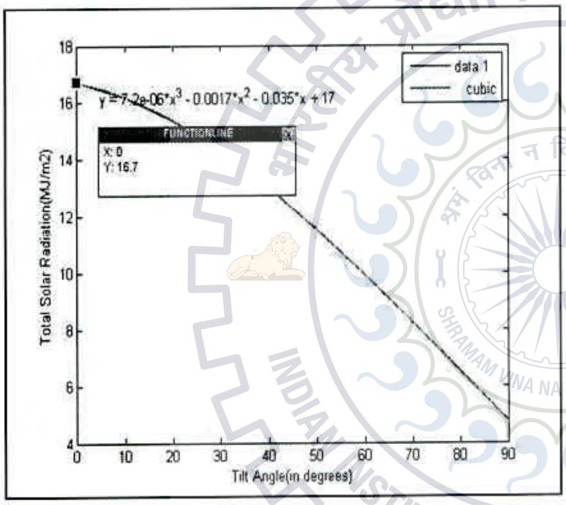
Fig. 6.13(a): Banglore Monthly Tilt Angle (January to April)



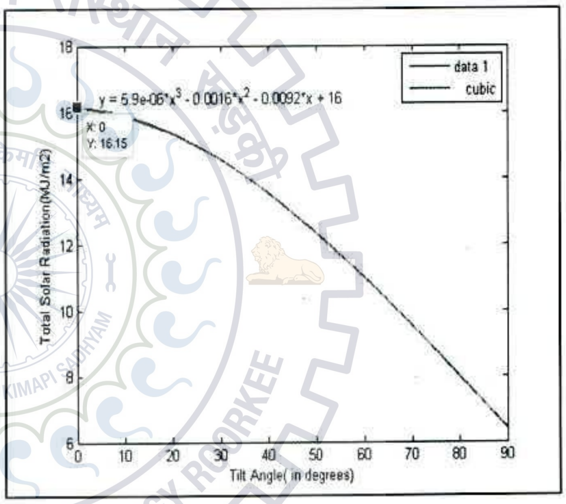
May



June

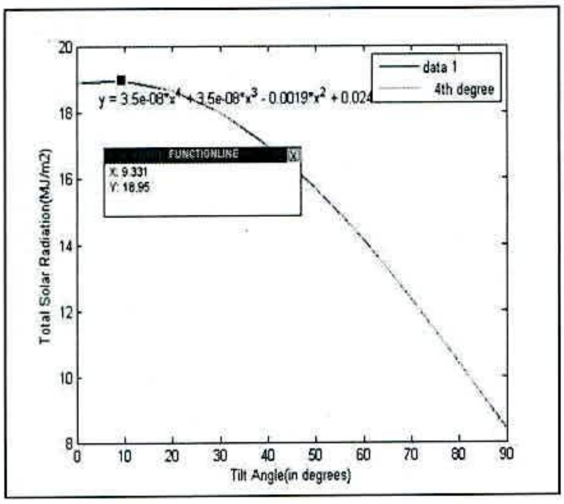


July

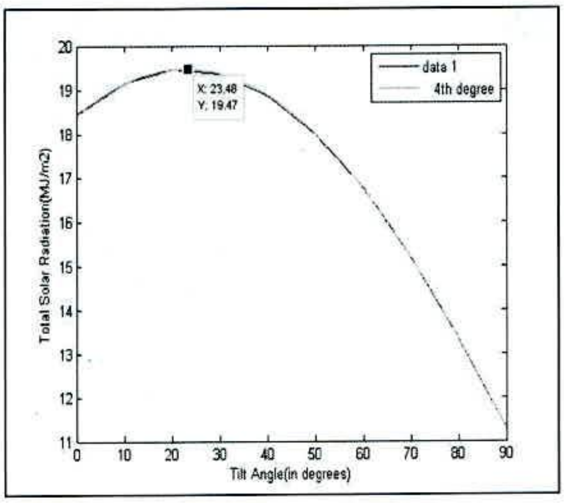


Aug

Fig. 6.13(b): Banglore Monthly Tilt Angle (May to August)



Sep



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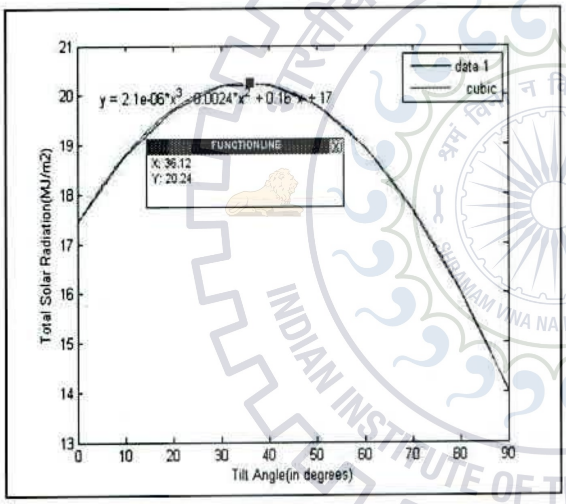

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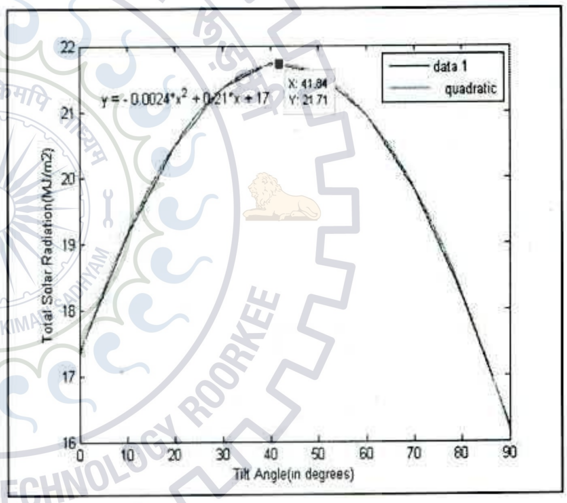


Dec

Fig. 6.13(c) : Banglore Monthly Tilt Angle (September to December)

Graphs 6.13(a) to 6.13(c) show the optimum monthly tilt angle of Banglore City. These monthly tilt angles are summarized in listed Figure 6.14.

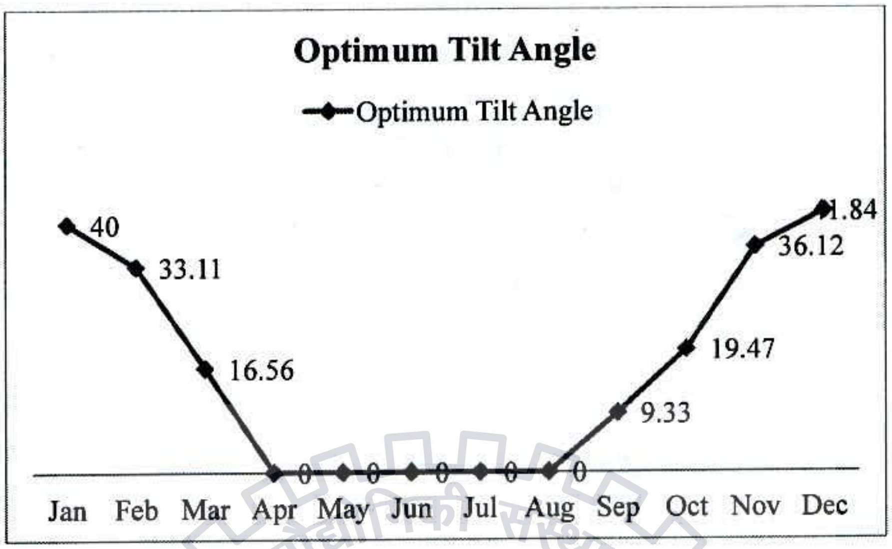
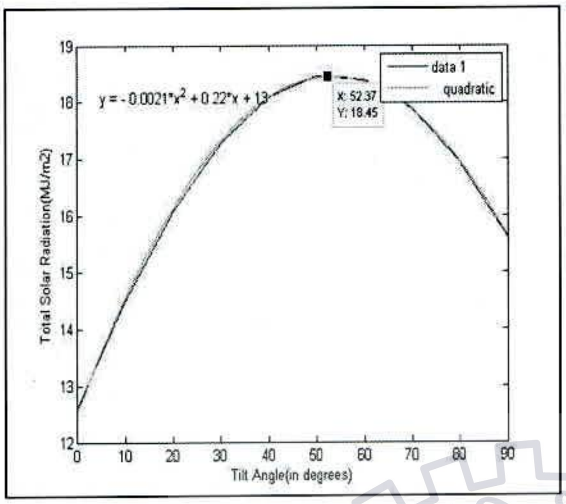


Figure 6.14: Monthly optimum tilt angle at Banglore station

6. 10 Monthly Optimum Tilt Angle for Roorkee City



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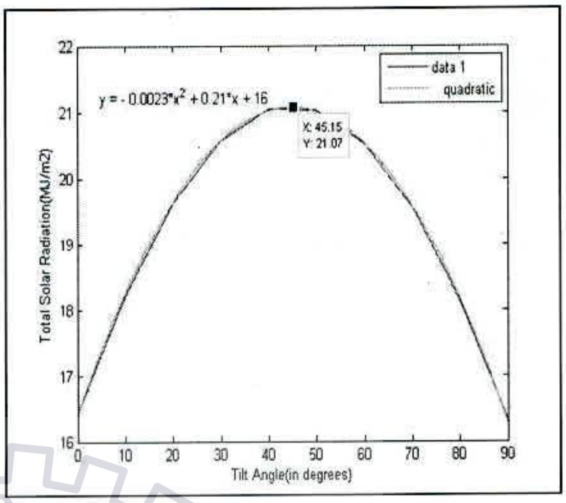
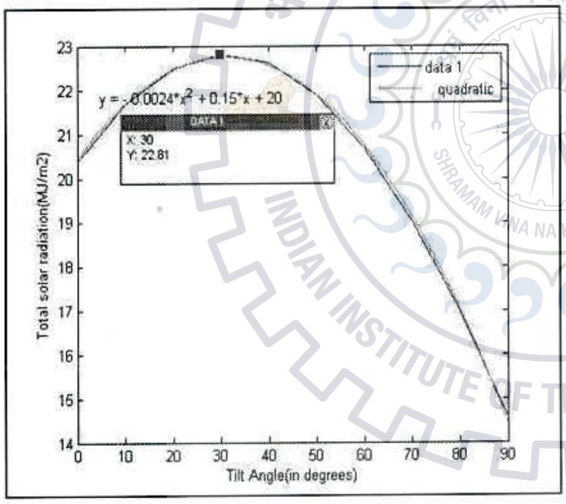
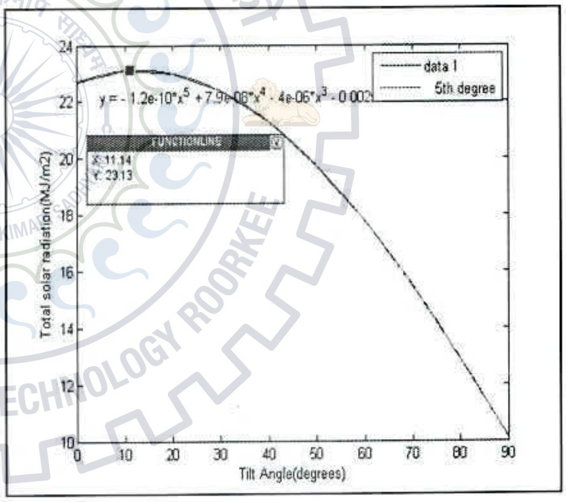


Feb

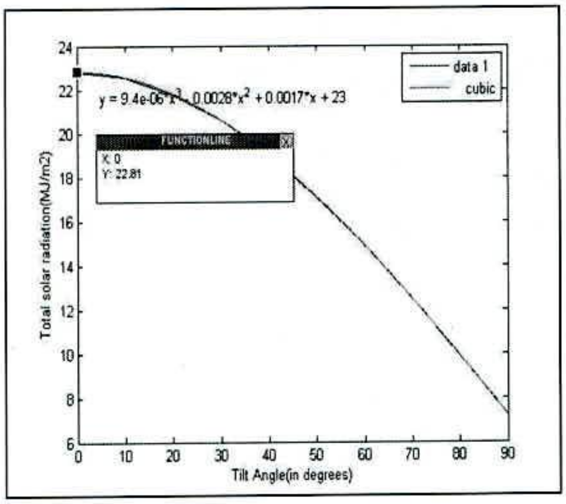


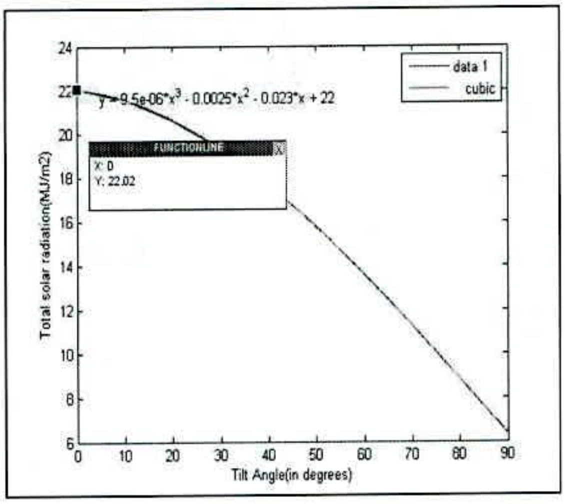
Mar



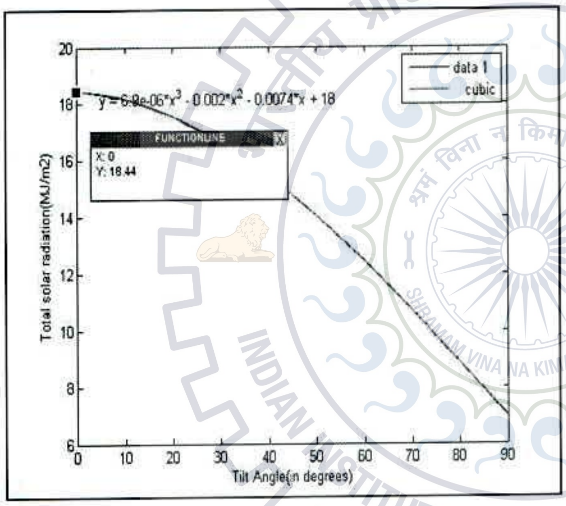
Apr

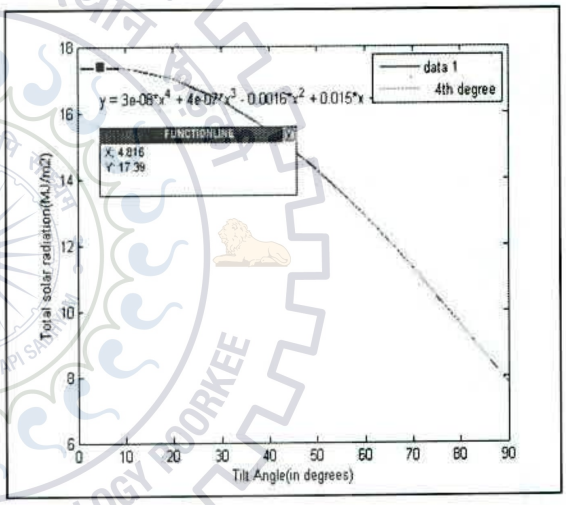
Fig. 6.15(a): Roorkee Monthly Tilt Angle (January to April)





May **June**





July **Aug**

Fig. 6.15(b): Roorkee Monthly Tilt Angle (May to August)

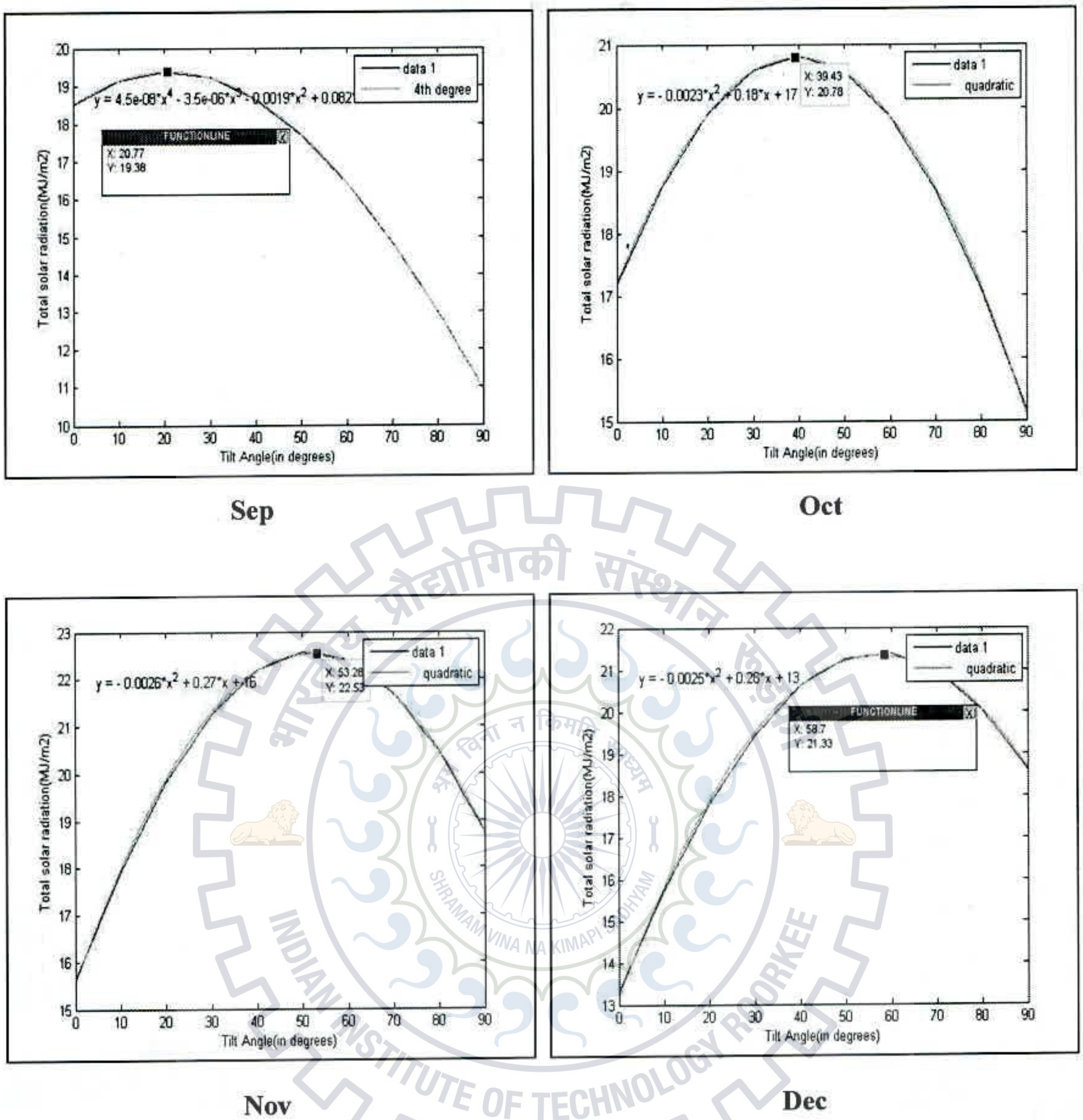


Fig. 6.15(c) : Roorkee Monthly Tilt Angle (September to December)

Graphs 6.15(a) to 6.15(c) show the optimum monthly tilt angle of Roorkee City. These monthly tilt angles are summarized in listed Figure 6.16.

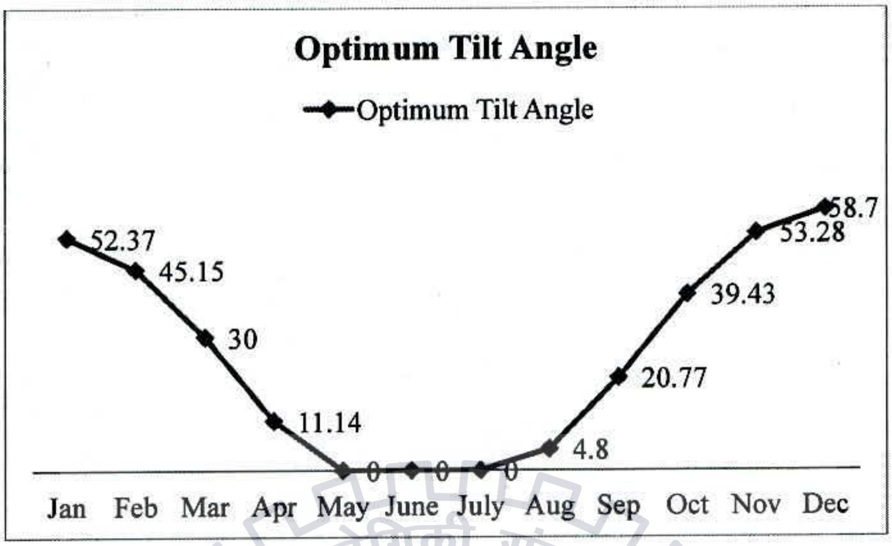


Figure 6.16: Monthly optimum tilt angle at Roorkee station

6. 11 Monthly Optimum Tilt Angle for Dehradun City

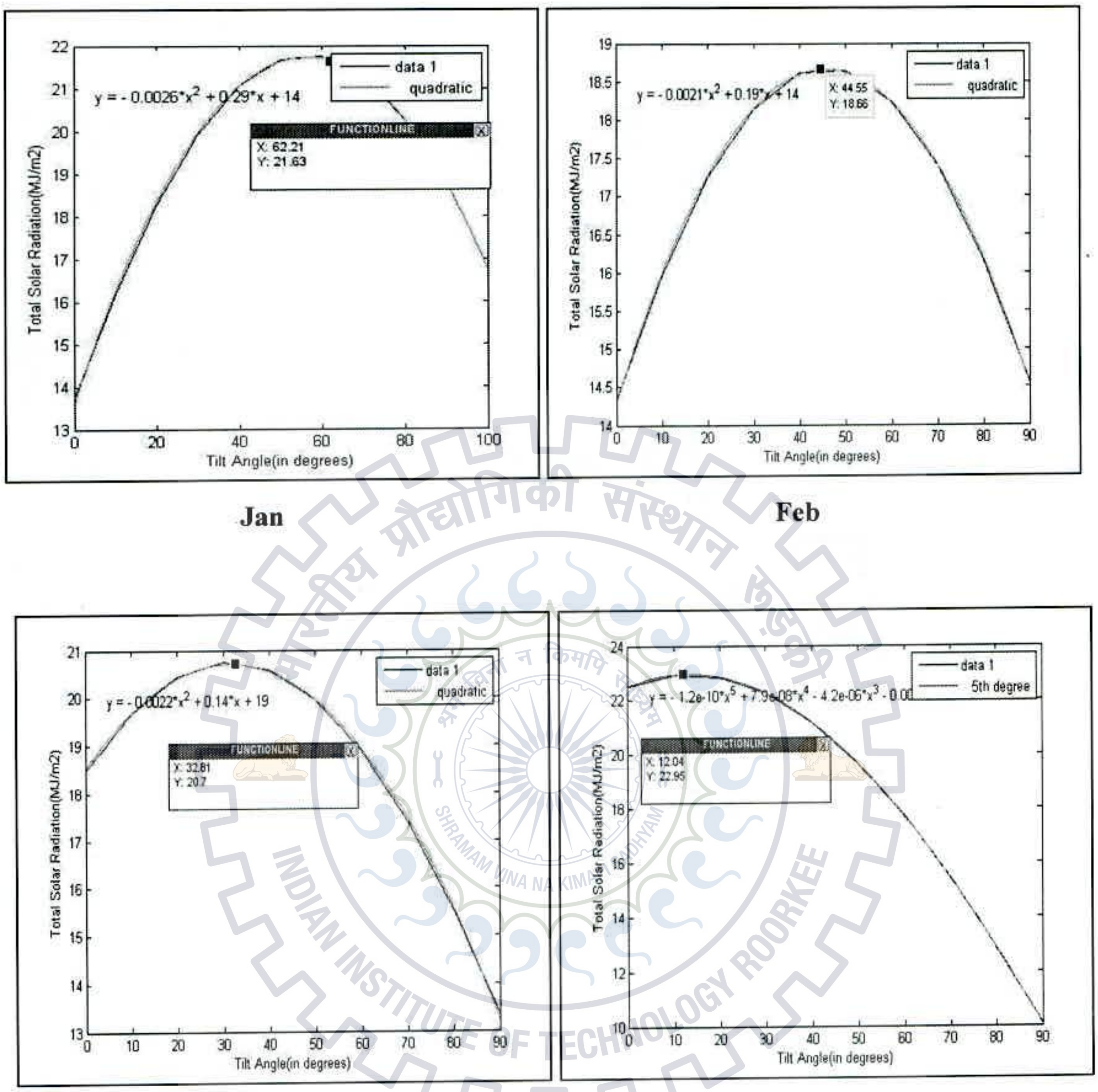
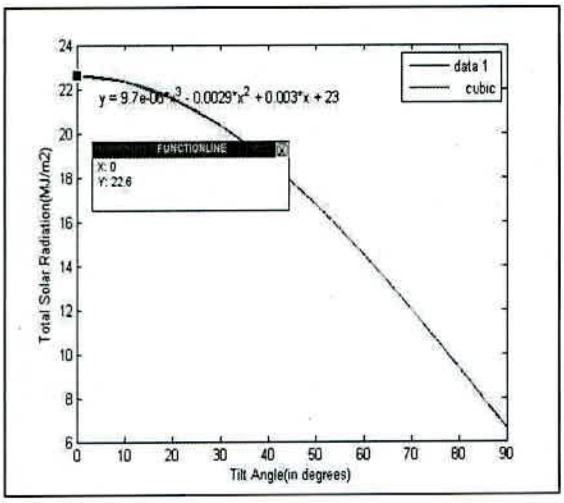
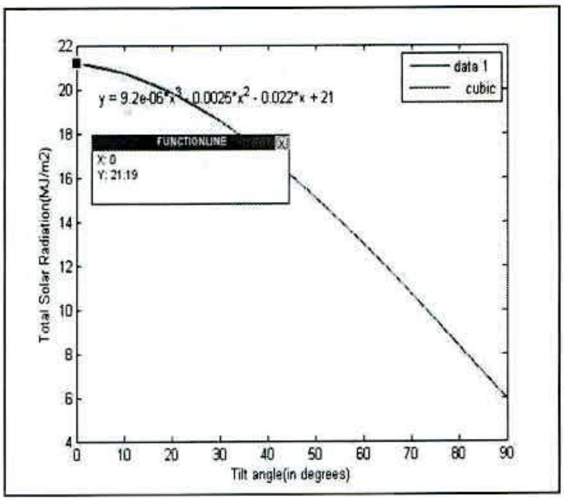


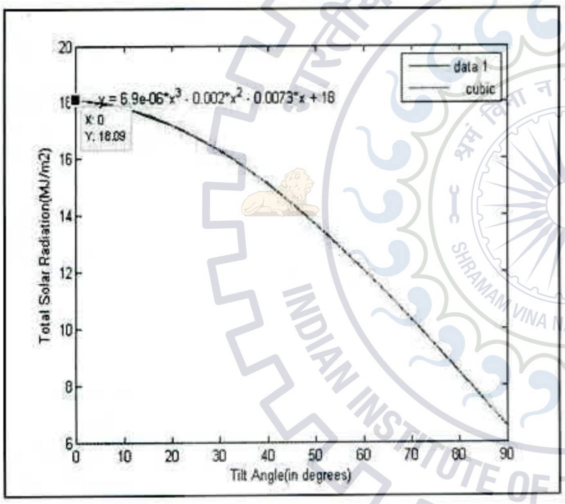
Fig. 6.17(a): Dehradun Monthly Tilt Angle (January to April)



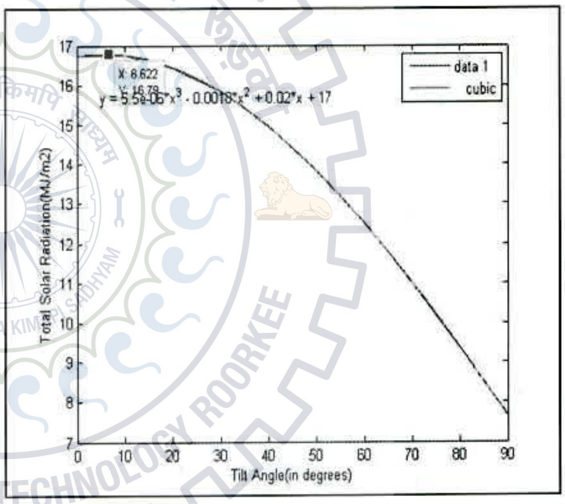
May



June



July



Aug

Fig. 6.17(b): Dehradun Monthly Tilt Angle (May to August)

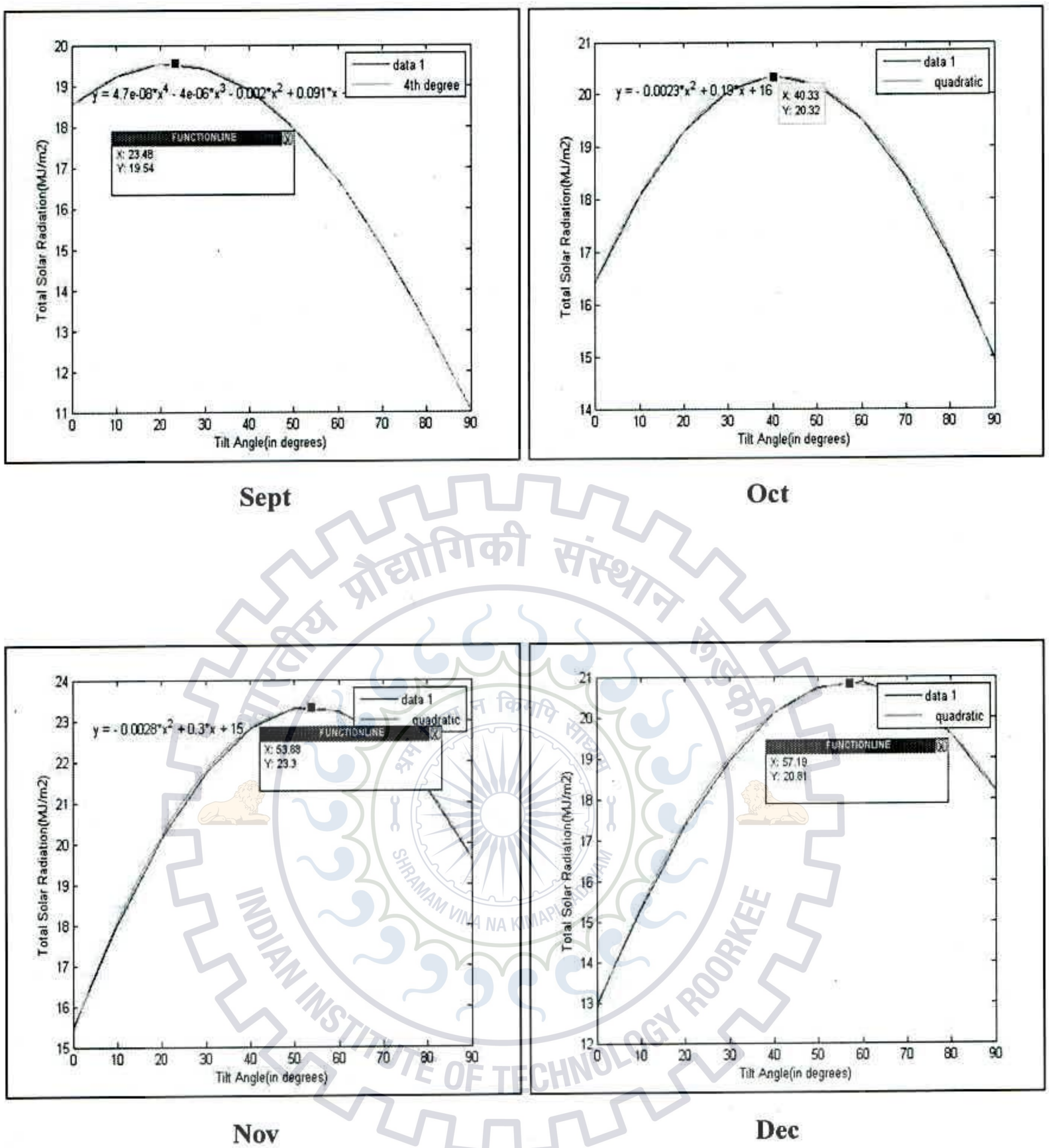


Fig. 6.17(c) : Dehradun Monthly Tilt Angle (September to December)

Graphs 6.17(a) to 6.17(c) show the optimum monthly tilt angle of Dehradun City. These monthly tilt angles are summarized in listed Figure 6.18.

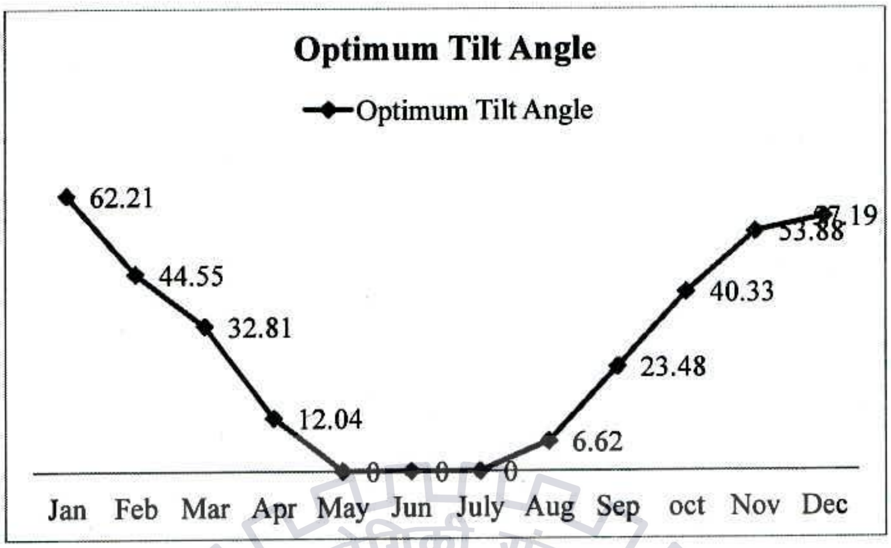


Figure 6.18: Monthly optimum tilt angle at Dehradun station

6.12 Results and Discussions for Optimum Tilt Angle

The result for the study of tilt angle is categorized into two sections. The first section contains the yearly and seasonal optimal tilt angle results calculated for each city, studied. The second section contains the energy received by the solar panel if the tilt angle is varied monthly, seasonally and yearly.

6.12.1 Optimum tilt Angle

The seasonal tilt angle is found by calculating the average of each season.In this study, April to September is taken as Summer Season and October to March is regarded as Winter Season, as the optimum tilt angle are comparable during these months .The yearly fixed tilt angle is found by calculating the average of tilt angles of each month of the year. Seasonally tilt angle is recommended for this wide variability in tilt angle. Yearly and seasonally tilt angles are found using figure 6.6 to figure 6.18. For example in Delhi, the optimum tilt angle in January is 53.28^0 and goes to minimum of zero degree in June. The optimum tilt angle increases to a maximum during the winter month and reaches upto 55.38^0 in December.The yearly fixed angle and seasonally adjusted tilt angle of different cities are listed in Table 6.5.

Table 6.6: Yearly fixed angle and seasonally adjusted tilt angle for each station

Place	Yearly Fixed Angle (in degrees)	Summer Optimum Angle (in degrees)	Winter Optimum Angle (in degrees)
Delhi	25.92	6.44	45.4
Hyderabad	20.3	2.36	38.22
Banglore	16.37	1.55	31.18
Kolkatta	21.37	3.26	39.5
Ahmedabad	22.7	3.71	41.69
Roorkee	26.3	6.11	46.48
Dehradun	27.76	7.02	48.5

6.12.2 Variation in collected energy based on tilt angle

From the tilt angle results mentioned in table 6.5 and based on these tilt angle, annual energy received by the solar panel is calculated when tilt angle is varied yearly, seasonally and monthly using graphs figures 6.5 to figure 6.17 for different cities.

Table 6.7: Energy collected energy when tilt angle is varied yearly, seasonally and monthly

Place	Annual Radiation for Yearly Fixed Angle	Annual Radiation for Seasonally Adjusted Angle	Annual Radiation for Monthly Adjusted Angle	Increment in Collected Energy Using Monthly Tilt Angle	Increment in Collected Energy Using Seasonaly Optimum Tilt Angle
Delhi	7190.82	7529.32	7598.78	5.67%	4.70%
Hyderabad	7800.21	8186.67	8269.93	6.02%	4.95%
Banglore	7328.80	7630.3	7730.81	5.48%	4.11%
Kolkatta	6182.48	6415.95	6471.77	4.68%	3.77%
Ahmedabad	7139.11	7433.51	7971.59	11.66%	4.12%
Roorkee	7208.65	7520.50	7604.07	5.48%	4.32%
Dehradun	7055.64	7415.31	7501.0	6.31%	5.09%

CHAPTER 7

CONCLUSIONS

Annual based fixed tilt is approximately same as lattitude of the location.The winter season optimum tilt for Delhi is 45.4^0 (lattitude+16.5^0) and for summer season is 6.44^0 (lattitude-22^0) which is in agreement with the results of many other researchers. From the table 6.7 it can be concluded that the gain of energy when using the monthly optimum tilt varies from 4.5% to 11.67% , compared to yearly average fixed angle. It is clear from table 6.7 that loss of collected energy is less than 1% if the tilt is adjusted sesonally compared to monthly optimum tilt.It can be concluded that, for higher efficiency solar panel should be designed such that tilt angle can be at least changed seasonally if monthly is not possible.

From Table 5.4, it can be concluded that EPBT and Lifetime Energy Efficiency for monocrystalline photovoltaic module, manufactured using present technology, varies from 7 to 9 years and 225 to 289 %, respectively. So the application of photovoltaic power module is energy efficient in India.

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