# Investigation of Variations in Collection Efficiency of Photovoltaic Panels

**M.Sc. Thesis**
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# ABSTRACT

# INVESTIGATION OF VARIATIONS IN COLLECTION EFFICIENCY OF PHOTOVOLTAIC PANELS

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This thesis reviews recent progress in solar cell research and development. Moreover it also explains the concepts and engineering related with solar electrical generators or the photovoltaics cells and panels. And also it is investigated that the performance of a photovoltaic (PV) panel is affected by its orientation and its tilt angle. This is because both of these parameters change the amount of solar energy received by the surface of the PV panel. A mathematical model was used to estimate the total solar radiation on the tilted PV surface, and to determine optimum tilt angles for PV panels installed in Gaziantep, Adiyaman, Diyarbakir, Mardin, Siirt and Sanliurfa. This study determined that the monthly optimum tilt angle for a PV panel changes throughout the year with its minimum value as $12^0$ in June and maximum value as $60^0$ in December.

# ÖZET

## FOTOVOLTAIK PANELLERIN VERIMLILIGINDEKI DEGISIMLERI ARASTIRMA

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EYLÜL 2005, 53 Sayfa

Bu tez günes pili arastirmalari ve gelisimi üzerine son yillardaki ilerlemeyi gözden geçirir. Ayrica, solar elektrik jeneratörleriyle veya fotovoltaik piller ve panellerle ilgili mühendislik çalismalarini ve görüsleri açiklar. Bir fotovoltaik (PV) panelin performansinin, panelin yönünden ve egim açisindan etkilendigi arastirilmistir. Bu yüzdendir ki bu parametrelerin her ikisi de PV panel yüzeyinden alinan günes enerjisinin miktarini degistirir. Egimli PV yüzeyi üzerindeki toplam günes radyasyonunu hesaplamak ve Gaziantep, Adiyaman, Diyarbakir, Mardin, Siirt ve Sanliurfa'da dösenen PV panelleri için en uygun egim açilarini saptamak amaciyla bir matematik modeli kullanildi. Bu çalisma, bir PV paneli için aylik en uygun egim açisinin, minimum degeri olan $12^0$ (Haziran ayinda) ve maksimum degeri olan $60^0$ (Aralik ayinda) ile yilin basindan sonuna kadar degistigini belirledi.

# ACKNOWLEDGMENTS

This work has been aided in no small measure by my advisor Mustafa Öztas, who has shown a great willingness to let his students present material and interact directly with other scientists in the field. This experience has been invaluable, as has the opportunity to work with him. Thanks for all the help along the way, and especially for your patient help with this thesis.

Thanks also to the other committee members for reviewing this work.

Several scientists have provided their time and expertise in preparing key samples specifically for this work. Thank you for taking the time to get me such great sets of cells, and for the many valuable discussions.

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# LIST OF SYMBOLS

| | |
|---|---|
| $H$ | direct-beam radiation normal to the horizontal surface (W/m$^2$) |
| $H_n$ | direct-beam radiation solar radiation (W/m$^2$) |
| $H_b$ | direct-beam radiation perpendicular to tilted surface (W/m$^2$) |
| $H_d$ | diffuse radiation on the horizontal surface (W/m$^2$) |
| $H_{d,p}$ | diffuse radiation on the tilted surface (W/m$^2$) |
| $H_{gr}$ | ground reflected radiation on the tilted surface (W/m$^2$) |
| $R_b$ | the ratio of beam radiation on tilted surface to that on horizontal (dimensionless) |
| $?_g$ | ground reflectance (dimensionless) |
| $H_T$ | total global solar radiation on the surface (W/m$^2$) |
| $S$ | tilt angle of PV panel ($^0$) |
| $n$ | day of year |
| $I$ | current (A) |
| $I_{mp}$ | maximum power current (A) |
| $I_{sc}$ | short circuit current (A) |
| $V$ | voltage (V) |
| $T_a$ | air température ($^0$C) |
| $T_p$ | panel température ($^0$C) |
| $V_a$ | air velocity (m/s) |
| $V_{oc}$ | open circuit voltage (V) |
| $V_{mp}$ | maximum power voltage (V) |
| $W_p$ | peak power (W) |

*Greek letters*

| | |
|---|---|
| ? | percentage efficiency |
| d | declination angle ($^0$) |
| ß | solar azimuth angle ($^0$) |
| ? | solar surface azimuth angle ($^0$) |
| ? | solar hour angle ($^0$) |
| a | solar altitude angle ($^0$) |
| $?_I$ | solar incidence angle ($^0$) |
| $?_Z$ | solar zenith angle ($^0$) |
| F | latitude of the location ($^0$) |

# CHAPTER 1

# INTRODUCTION

Solar cells hold the promise of clean renewable energy. The impact they will eventually hold on the global energy market is likely to be extremely significant, given recent advances in making the technology less expensive to produce and deploy. The supply of fossil fuels will inevitably dwindle, leading to a worldwide demand for a new source of power. Due to global warming, ozone depletion, and other environmental concerns, the replacement technology will likely be one such as solar photovoltaic power, which produces very little pollution during its fabrication, none while in use, and also very little at the end of its lifecycle if recycling programs are implemented [1].

Solar cells based on thin-film polycrystalline materials may provide much of the answer to inexpensive, widely available solar energy. With high speed, large area deposition of semiconductor materials on glass or other substrates, some sacrifice in efficiency compared to single-crystal technologies will likely be made. However, efficiencies up to 18.8% have been demonstrated, and the lower cost of materials promises lower end prices for the consumer. The ability to coat large areas is a very important point, since prices will go down as the scale of production goes up.

Several challenges present themselves when developing polycrystalline materials for large scale terrestrial applications. While research cells have achieved efficiencies comparable to single crystalline material [2], issues such as local defects and overall uniformity become increasingly important as the deposition area is increased. In addition, performing research on polycrystalline materials is not always straightforward because of the interactions between different layers of the solar cell. These interactions make it more difficult to determine the effects of a change in processing; for example, changing the temperature of CdTe deposition will not only affect the CdTe growth, but will also affect previously deposited layers.

Polycrystalline materials, however, can be remarkably forgiving, and do have several advantages over crystalline materials. Reasonable efficiencies can be produced by many different processing methods, with speeds of fabrication ranging from 10 µm/min to 1 µm/h. Modules may be fabricated monolithically, also decreasing processing costs. Finally, novel substrates such as polyamide may be used in the near future, which would reduce costs due to ease of processing and reductions in shipping costs.

# CHAPTER 2

# BACKGROUND TO PHOTOVOLTAICS

Faced with ever-increasing demand, the earth's sources of non-renewable energy are not expected to last long. Among the many contenders vying to replace fossil fuels, photovoltaic solar cells offer many advantages, including needing little maintenance and being relatively "environmentally-friendly"; the major drawback to date has been cost. In order for photovoltaics to be viable for large-scale energy conversion, their efficiency must be improved whilst making them cheaper.

## 2.1 Introduction to Photovoltaic (Solar Cell) Systems

Solar cells convert sunlight directly into electricity. Solar cells are often used to power calculators and watches. They are made of semiconducting materials similar to those used in computer chips. When sunlight is absorbed by these materials, the solar energy knocks electrons loose from their atoms, allowing the electrons to flow through the material to produce electricity. They are thus also known as ‘photovoltaic’ cells, a word that comes from the Greek word *photo*, meaning ‘derived from light’, combined with the name of the Italian physicist Alessandro Volta, who invented the first battery. This process of converting light (photons) to electricity (voltage) is called the *photovoltaic (PV) effect* [3].

Thin film solar cells use layers of semiconductor materials only a few micrometers thick. Thin film technology has made it possible for solar cells to now double as rooftop shingles, roof tiles, building facades, or the glazing for skylights or atria [4]. The solar cell version of items such as shingles offer the same protection and durability as ordinary asphalt shingles.

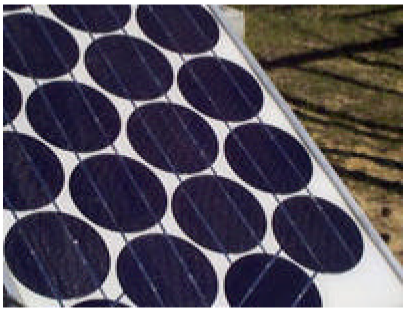
## 2.2 Solar Cells Efficiency and Technological Development

The performance of a solar cell is measured in terms of its efficiency at turning sunlight into electricity. Only sunlight of certain energies will work efficiently to create electricity, and much of it is reflected or absorbed by the material that makes up the cell. Because of this, a typical commercial solar cell has an efficiency of 15%—about one-sixth of the sunlight striking the cell generates electricity. Low efficiencies mean that larger arrays are needed, and that means higher cost. Improving solar cell efficiencies while holding down the cost per cell is an important goal of the PV industry, National Renewable Energy Laboratories (NREL) researchers, and other U.S. Department of Energy (DOE) laboratories, and they have made significant progress [5].

- The first solar cells, built in the 1950s, had efficiencies of less than 4%.
- A silicon solar cell which converted 6% of sunlight falling onto it into electricity was developed by Chapin, Pearson and Fuller in 1954.
- The efficiency of solar cells from single crystal silicon have been improved in the late 1970 and the early 1980 with an approximate efficiency of (10%-12%).
- 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.
- Solar cells using the passivated emitter and rear locally diffused cells (PERL) were developed by the University of New South Wales, in Australia with an efficiency of 23%.

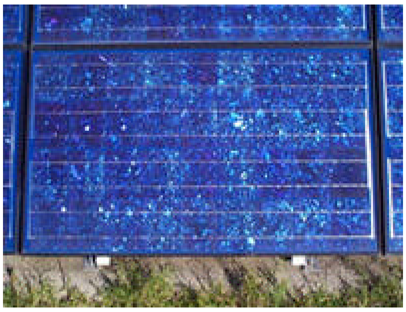
## 2.3 How Are Solar Cells Made?

Silicon solar cells are made using either single crystal wafers, polycrystalline wafers or thin films. 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)). 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 [6].



a) Single Crystal solar cells in panel

**(a)**



b) Polycrystalline solar panel

**(b)**

c) a-Si solar panel

**(c)**

Figure 2.1 Different types of Silion solar cells

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 diselenide/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 [7].

## 2.4 Principle of p-n Junction Solar Cell

In its simplest form, the solar cell consists of a junction formed between n-type and p-type semiconductors, either of the same material (homojunction) or different materials (heterojunction). The band structure of the two differently doped sides with respect to their Fermi levels can be seen in Figure 2.2. This type of interface is called a heterojunction ("hetero" because it is formed from two different materials, in comparison to the "homojunction" formed by two doped layers of the same material, such as the one in silicon solar cells).

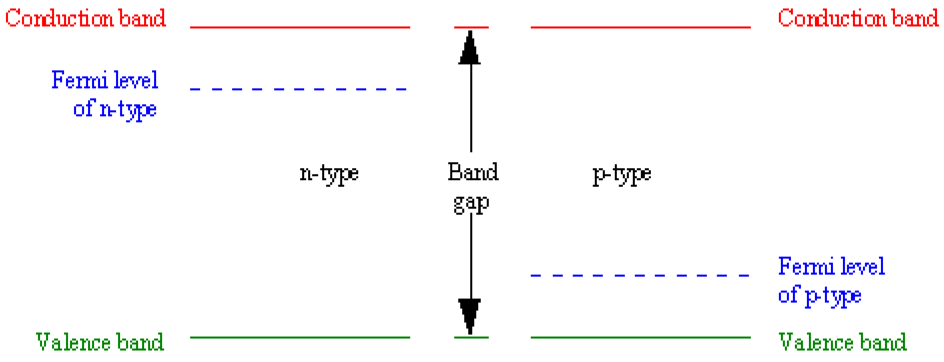


Figure 2.2 Band structure of differently-doped semiconductors

The bandgap of a semiconductor material is an amount of energy. Specifically, it's the minimum energy needed to move an electron from its bound state within an atom to a free state. This free state is where the electron can be involved in conduction. The lower energy level of a semiconductor is called the "valence band". And the higher energy level where an electron is free to roam is called the "conduction band". The bandgap (often symbolized by $E_g$) is the energy difference between the conduction band and valence band.

When the two halves are brought together, the Fermi levels on either side are forced in to coincidence, causing the valence and conduction bands to bend (Figure 2.3).

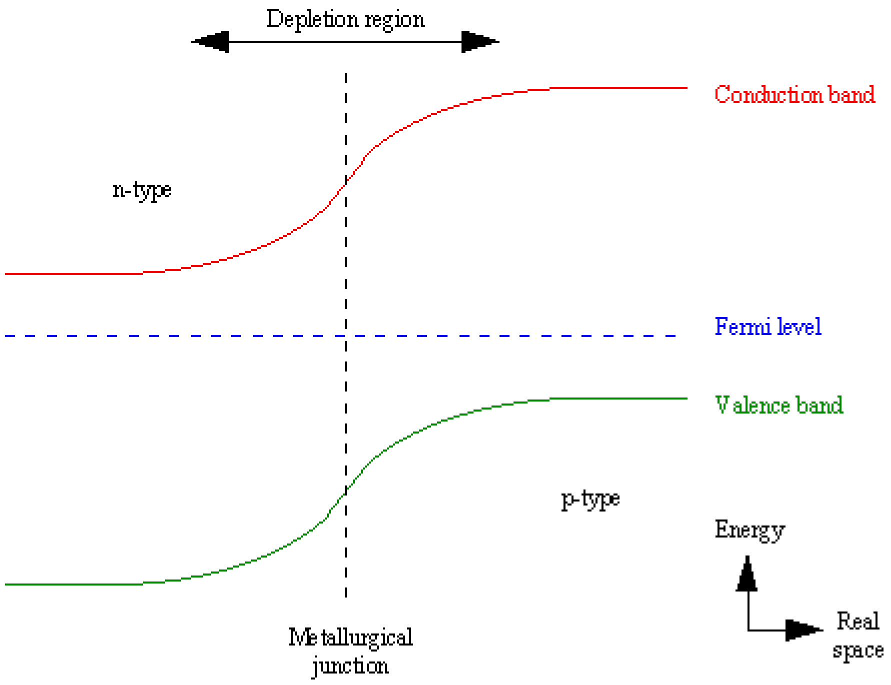


Figure 2.3 Heterojunction band-bending

These bent bands represent a built-in electric field over what is referred to as the depletion region. When a photon, with an energy greater than the bandgap of the semiconductor, passes through the solar cell, it may be absorbed by the material. This absorption takes the form of a band-to-band electronic transition, so an electron/hole pair is produced.

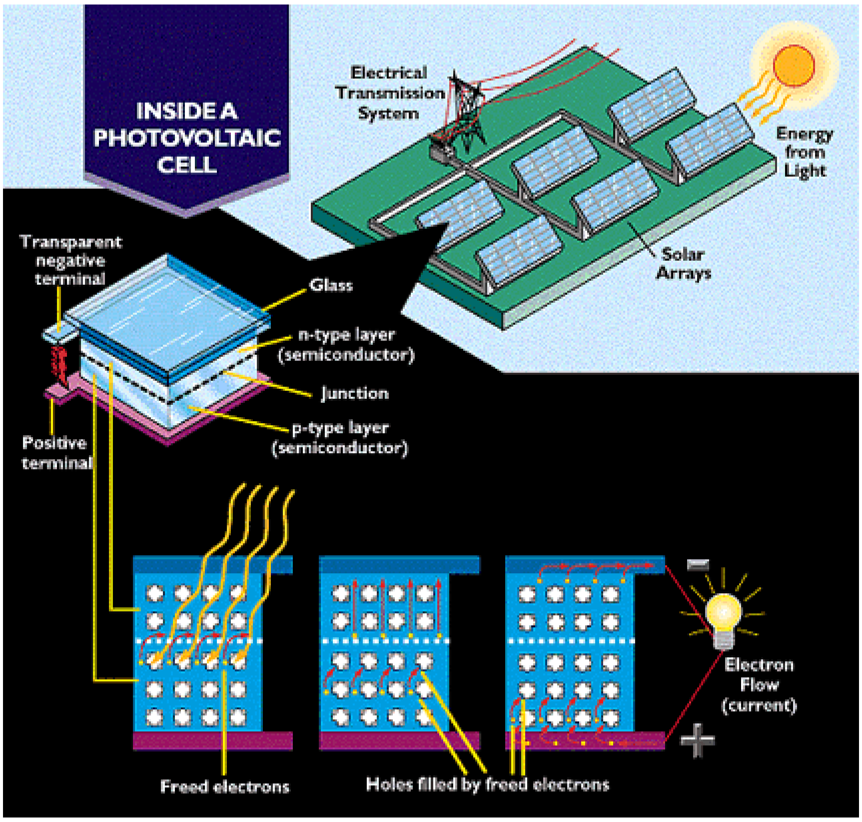


Figure 2.4 Inside a photovoltaic cell

As may be seen in the above diagram (Figure 2.4), there are two additional layers that must be present in a solar cell. These are the electrical contact layers. There must obviously be two such layers to allow electric current to flow out of and into the cell. The electrical contact layer on the face of the cell where light enters is generally present in some grid pattern and is composed of a good conductor such as a metal. The grid pattern does not cover the entire face of the cell since grid materials, though good electrical conductors, are generally not transparent to light. Hence, the grid pattern must be widely spaced to allow light to enter the solar cell but not to the extent that the electrical contact layer will have difficulty collecting the current produced by the cell. The back electrical contact layer has no such diametrically opposed restrictions. It need simply function as an electrical contact and thus covers the entire back surface of the cell structure. Because the back layer must be a very good electrical conductor, it is always made of metal [8].

## 2.5 How 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. 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 [9]. Therefore if a circuit is made (see Figure 2.5) 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.

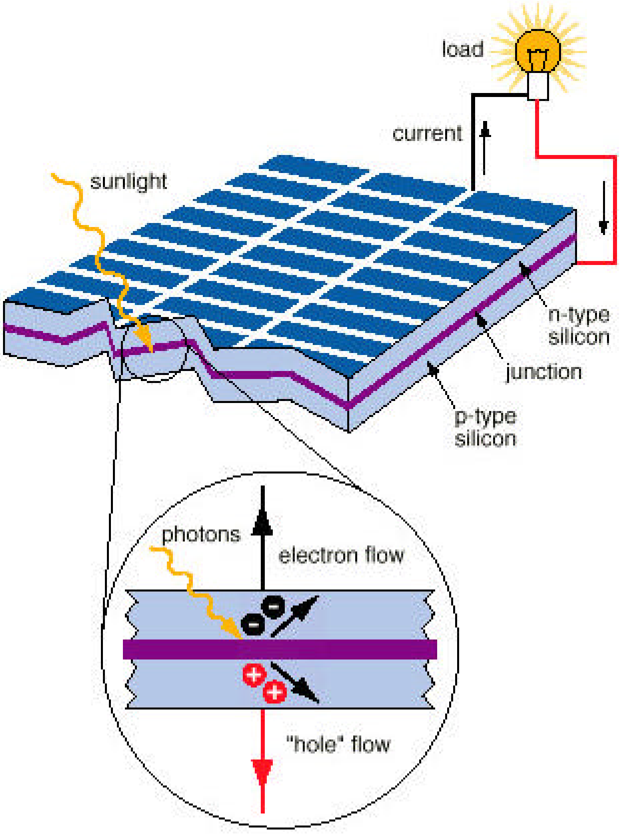


Figure 2.5 The Photovoltaic Effect in a Solar Cell

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 [10].

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 (1000 $Wm^{-2}$). The power output of the cell is almost directly proportional to the intensity of the sunlight (see Figure 2.6). (For example, if the intensity of the sunlight is halved the power will also be halved).

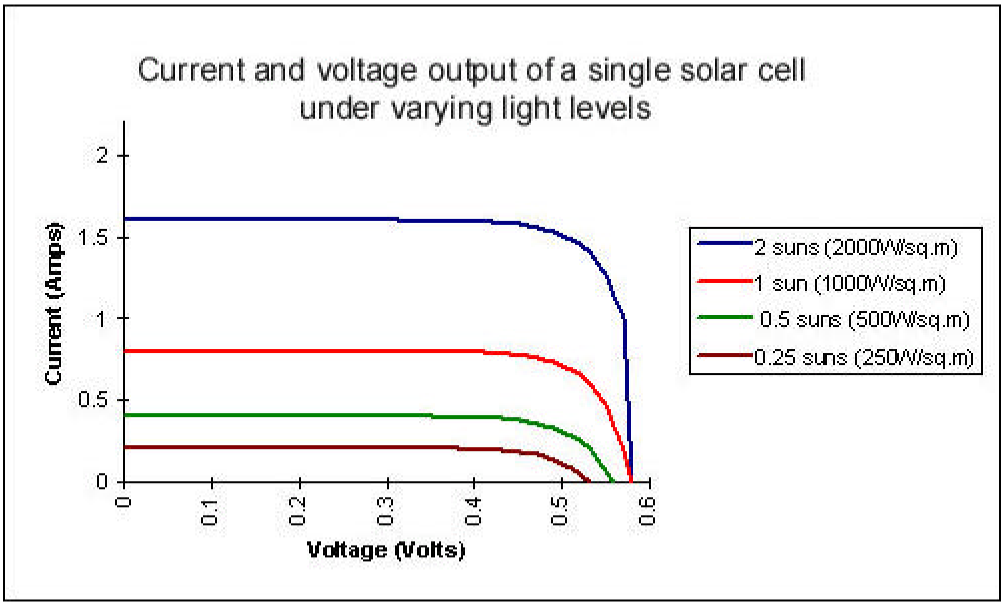


Figure 2.6 Graph showing current and voltage output of a solar cell at different light intensities.

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 [11].

## 2.6 Applications of the Solar Cells

Renewable and pollution free natural energy resources have been used in projects and programs throughout the developed, developing, and underdeveloped countries to provide clean power to people who have no grid power, whose grid power is unreliable, or who can not afford to purchase electric power. Projects and programs have been implemented as both government sponsored programs and as private programs with varying success and achievements. They are used for pumping drinking or irrigation water, for operation of metrology instruments, for telecommunications repeaters, for battery charging, and for stand-alone or hybrid photovoltaic/diesel generator electric power. These photovoltaic are used in public building (schools or hospitals), in the industry, and domestic every day home appliances. Domestic home appliances may include refrigerators, ranges, mixers, dishwashers, toasters, ironing, computers, radios and televisions and all possible electric powered instruments. Solar cells have also been used to power calculators, watches and clocks.

Successful experiments of remote area power system (RAPS) were accomplished in Australia as a stand alone hybrid system in Montague Island, in Kalbari Western Australia and rural locations. Grid connected photovoltaic were used in Germany rooftops, Japan rooftops, and the USA rooftops with a remarkable success of pay back policy. This policy allows power to be sold to the electric power company during the day and bought back during the night by the consumer. In the Olympic village for the 2000 games, 600 homes will use building integrated photovoltaic to accommodate all the athletes that will participate in the Olympic competition. This is the largest grid connected building integrated photovoltaic applications in the world [12].

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. More information on PV concentrators can be found later in this information file.

Solar cells are made using semiconductors such as silicon. Semiconductors have interesting electrical properties, making them useful for electronic devices such as the microprocessors used in computers. One of their properties is that they can be treated in different ways to become either 'positive' (*p*-type) or 'negative' (*n*-type).

## 2.7 Typical Solar Cell Schemes

**i)**

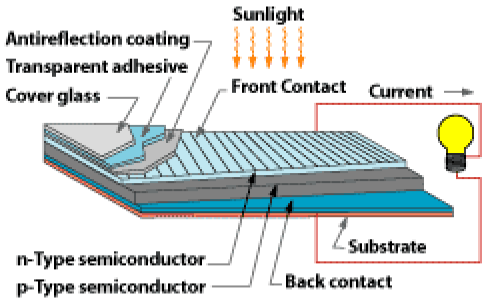


Figure 2.7 A typical solar cell scheme

As can be seen in the Figure 2.7, a typical solar cell consists of a glass or plastic cover or other encapsulant, an antireflective layer, a front contact to allow electrons to enter a circuit, a back contact to allow them to complete the circuit, and the semiconductor layers where the electrons begin and complete their journey.

**ii)**

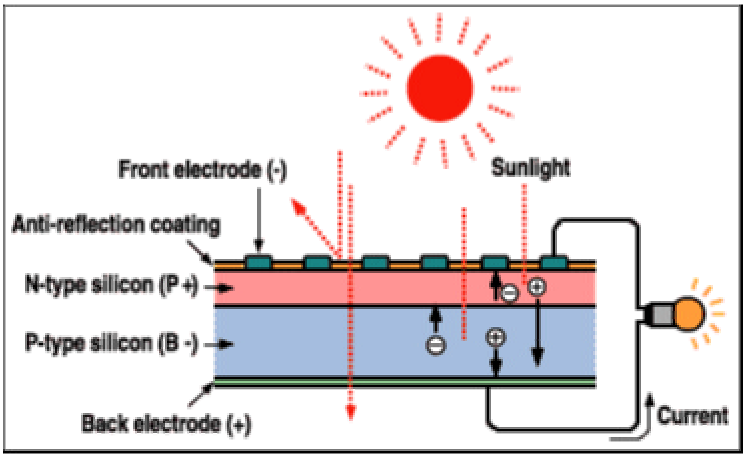


Figure 2.8 Solar cell scheme

A solar cell is a kind of semiconductor device that takes advantage of the photo-voltaic effect, in which electricity is produced when the semiconductor's PN junction is irradiated. As can be seen in the Figure 2.8, when light strikes a solar cell, part of it is reflected, part of it is absorbed, and part of it passes through the cell. The absorbed light excites the bound electrons into a higher energy state, making them free electrons. These free electrons move about in all directions within the crystal, leaving holes where the electrons used to be, and the holes also shift around the crystal. The electrons (-) collect in the N-layer, the holes (+) in the P-layer. When the outside circuit is closed, electricity flows.

**iii)**

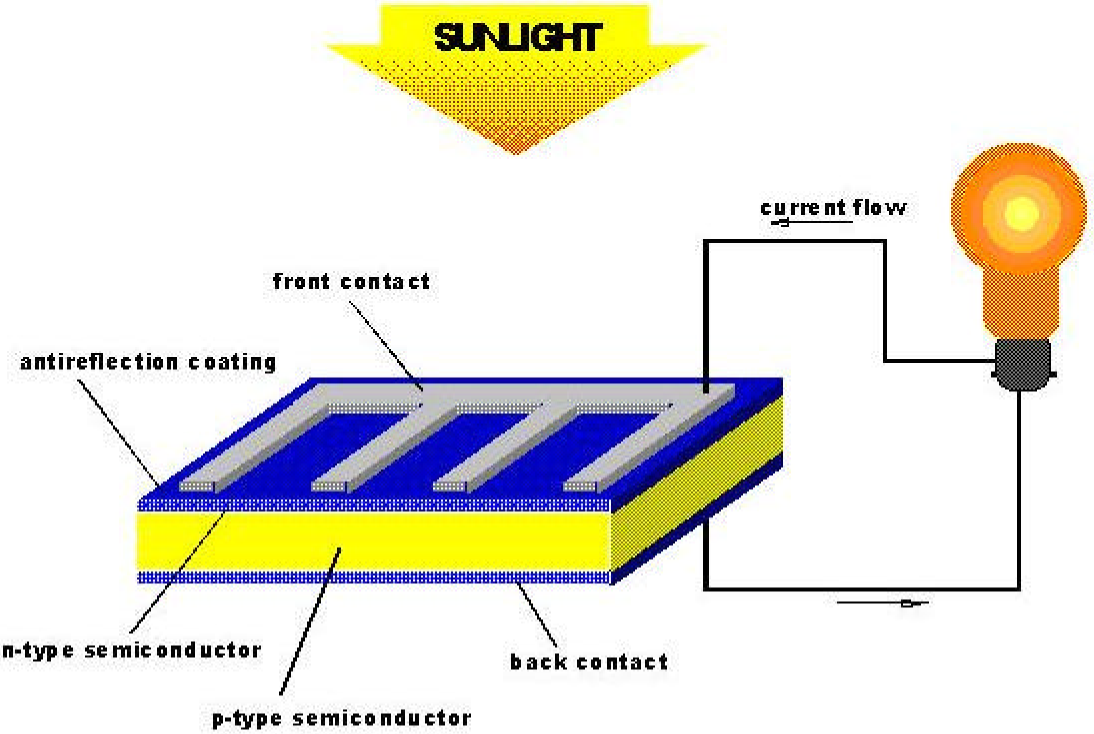


Figure 2.9 A solar cell scheme

A solar cell consists of two layers of semiconductor, one *p*-type and the other *n*-type, sandwiched together to form a '*pn* junction' as seen in the Figure 2.9. This *pn* junction induces an electric field across the device. When particles of light (photons) are absorbed by the semiconductor, they transfer their energy to some of the semiconductor's electrons, which are then able to move about through the material. For each such negatively charged electron, a corresponding positive charge is created called a 'hole'. In an ordinary semiconductor, these electrons and holes recombine after a short time and their energy is wasted as heat.

In a solar cell, however, the electrons and holes are swept across the *pn* junction in opposite directions by the action of the electric field. This separation of charge induces a voltage across the device [13]. By connecting the device to an external circuit, the electrons are able to flow-and this flow of electrons is what we call electricity.

# CHAPTER 3

# POLYCRYSTALLINE THIN FILM

## 3.1 Introduction

One scientific discovery of the computer semiconductor industry also has great potential in the photovoltaic (PV) industry: thin-film technology. The "thin film" term comes from the method used to deposit the film, not from the thinness of the film: thin-film cells are deposited in very thin, consecutive layers of atoms, molecules, or ions. Thin-film cells have many advantages over their "thick-film" counterparts [14]. The following figure shows a roll-base laminating system (Figure 3.1). It is part of a processing line used by Iowa Thin Films to produce polyimide based amorphous silicon solar cell.

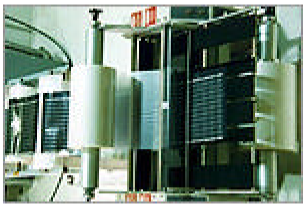


Figure 3.1 A roll-base laminating system

For example, they use much less material—the cell's active area is usually only 1 to 10 micrometers thick, whereas thick films typically are 100 to 300 micrometers thick. Also, thin-film cells can usually be manufactured in a large-area process, which can be an automated, continuous production process. Finally, they can be deposited on flexible substrate materials.

### 3.1.1 Thin-film deposition

Several different deposition techniques can be used, and all of them are potentially less expensive than the ingot-growth techniques required for crystalline silicon. We can broadly classify deposition techniques into physical vapor deposition, chemical vapor deposition, electrochemical deposition, or a combination. And like amorphous silicon, the layers can be deposited on various low-cost substrates (or "superstrates") such as glass, stainless steel, or plastic in virtually any shape. The thin film that can be seen in Figure 3.2 has been made by Iowa Thin Films. It is flexible and has the potential for many building applications.

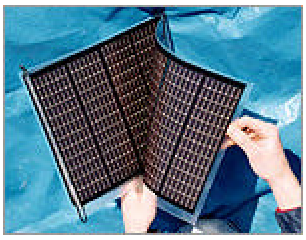


Figure 3.2 A thin film model

In addition, these deposition processes can be scaled up easily, which means that the same technique used to make a 2-inch x 2-inch laboratory cell can be used to make a 2-foot x 5-foot PV module—in a sense, it's just one huge PV cell. Thin films are unlike single-crystal silicon cells, which must be individually interconnected into a module. In contrast, thin-film devices can be made as a single unit—that is, monolithically—with layer upon layer being deposited sequentially on some substrate, including deposition of an antireflection coating and transparent conducting oxide [15].

### 3.1.2 Thin-film cell structure

The typical polycrystalline thin film has a very thin (less than 0.1 micron) layer on top called the "window" layer. The window layer's role is to absorb light energy from only the high-energy end of the spectrum. It must be thin enough and have a wide enough bandgap (2.8 eV or more) to let all available light through the interface (heterojunction) to the absorbing layer. The absorbing layer under the window, usually doped p-type, must have a high absorptivity (ability to absorb photons) for high current and a suitable band gap to provide a good voltage. Still, it is typically just 1 to 2 microns thick.

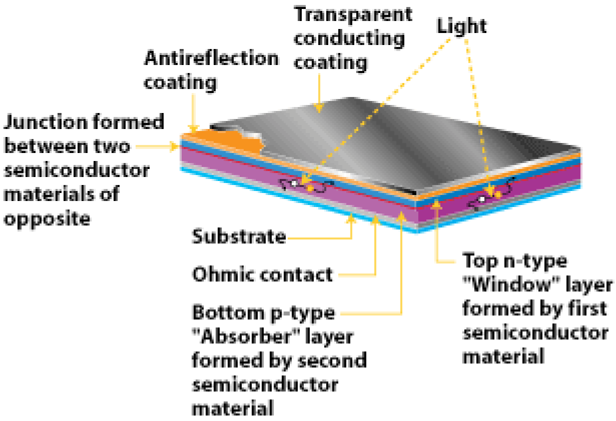


Figure 3.3 Polycrystalline thin-film cells

Polycrystalline thin-film cells have a heterojunction structure, in which the top layer is made of a different semiconductor material than the bottom semiconductor layer. The top layer, usually n-type, is a window that allows almost all the light through to the absorbing layer, usually p-type [16]. An "ohmic contact" is often used to provide a good electrical connection to the substrate (Figure 3.3).

### 3.1.3 Thin-film silicon

The term "thin-film silicon" typically refers to silicon-based PV devices other than amorphous silicon cells and single-crystalline silicon cells (where the silicon layer is thicker than 200 micrometers). These films have high absorptivity of light and may require cell thicknesses of only a few micrometers or less. Nanocrystalline silicon and small-grained polycrystalline silicon—considered thin-film silicon—may be able to replace amorphous silicon alloys as the bottom cell in multijunction devices [17]. As with other thin films, advantages include the savings of material, monolithic device design, use of inexpensive substrates, and manufacturing processes that are low temperature and possible over large areas.

### 3.2 Thin Film Polycrystalline Solar Cells

The types of devices in this study include CdTe- and $Cu(In_xGa_{1-x})Se_2$-based solar cells. The latter will be referred to as CIGS. These materials are p-type absorbers with bandgaps well matched to the solar spectrum (~1.5 and ~1.15eV respectively). In both cases, an n-type CdS layer is usually employed as the window layer, though other materials have been used with somewhat poorer best case results. The electronic behavior of these devices can be reasonably well described by standard diode equations with slight modifications. This assumption does break down under certain conditions (such as under high intensity illumination), which will be examined separately.

The figure 3.4 shows the device structures. Note that the CdTe-based cells use glass as a superstrate, so that light must first pass through the glass before it is absorbed by the semiconductor. Detailed information on state-of-the-art CdTe-based solar cells can be found in [18]. A similar reference for CIGS cells can be found in [12].

The materials which comprise the solar cell devices are polycrystalline thin films. CdTe grains are typically 1-5 µm in size, CIGS grains are slightly smaller: 1-2 µm in size.

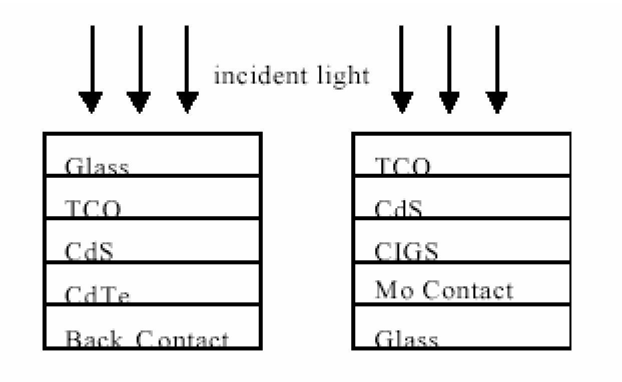


Figure 3.4 Cell device structures (not to scale). TCO stands for transparent conducting oxide.

For these materials to function in electronic devices, it is clear that significant grain boundary passivation must take place. Part of the goal of locally mapping the device response with high resolution is to assess how grain boundaries affect the overall device performance, and how different fabrication techniques and treatments affect the response near a grain boundary. Also, since each layer is polycrystalline, interface regions are expected to be complex in terms of carrier flow and junction formation. This *results in non-uniformity* considerations [5], where the interactions between the grains will lead to local variations in junction potential and resistivity, as well as increased recombination. Therefore a measured photoresponse at each spatial position will need to be subjected to various analytical tools to identify and separate the mechanisms responsible [19].

### 3.3 Polycrystalline Thin Film Growth

Polycrystalline thin-films are formed in a wide variety of thin-film deposition processes including chemical vapor deposition, physical vapor deposition, and sputter deposition.

A variety of models is being developed to study and simulate the evolution of the surface morphology and thin-film microstructure during growth. Both continuum and discrete models are being studied.

Topics of current interest include the effects of nucleation and substrate roughness on the average grain size and grain-size distribution, the effects of ion-erosion on facetting and on thin-film quality, and the development of improved mathematical methods for characterizing surface morphology [20].

# CHAPTER 4

# PHOTOVOLTAIC PANELS

## 4.1 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 [21]:

- 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 centimeters 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 100 $cm^2$ to 1000 $cm^2$ are made by either cutting 100 $cm^2$ 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.

One photovoltaic panel is basically a conjunct of photovoltaic cells assembled in aggregated form. Each cell assembled in panel helps to generation of total power amount of panel. The output voltage and current of one photovoltaic panel is related with the electrical connections between the solar cells in panel. If all photovoltaic cells of a panel are connected in series the output voltage is increased and the current will have the same of only one photovoltaic cell. But if all photovoltaic cells in a panel are connected in parallel, the output current is increased and the value of output voltage will be the same of one photovoltaic cell only. In both cases, the total power and energy generated are the same under the same solar irradiation level and temperature [22].

In all situations, the photovoltaic panels are assembled following the especific and severe engineering projects and the value of output voltage and current are fixed by assembler company of photovoltaic panel. All the technical attributes of photovoltaic panels are result of state of art of each assembler companies of photovotaic panels. However the cells and the panel assembly engineering are basically the same.

## 4.2 Arrays and Systems

If an application requires more power than can be provided by a single panel, larger systems can be made by linking a number of panels together. 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 [23]. In these cases, PV systems are used, comprised of the following parts (see figure 4.1):

(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 (e.g. 240 V AC)
(e) backup power supplies such as diesel startup generators (optional)
- framework and housing for the system
- trackers and sensors (optional);

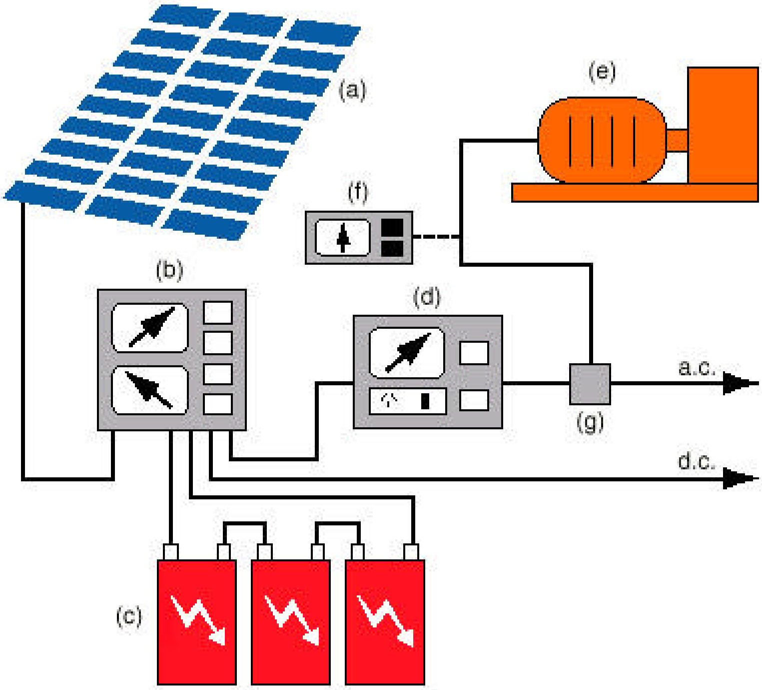


Figure 4.1 Elements of a PV System

Figure 4.2 Tracked PV Array

The Figure 4.2 shows a tracked PV array. It is containing 16 panels. 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 [24].

Arrays of panels 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 [25]. 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. For example, in summer a 50 watt panel will produce an average of 250 watt-hours of energy, and in winter about 100 watt-hours. These figures are indicative only, and professional assistance should be sought for more precise calculations [26].

Energy storage is often necessary when power is required when the sun is not shining - either at night or in cloudy periods - or in quantities greater than can be supplied directly from the array. Specially designed "deep-cycle" lead acid batteries are generally used. Unlike normal batteries, they can discharge about half of their stored energy several thousand times before they deteriorate. Each battery is usually 2 V, and the total battery bank usually has many batteries in series and parallel to give the required power rating. Battery banks need to be individually sized to suit the particular applications, depending on total daily solar radiation, total load, peak load and the number of days storage required. As a rule of thumb, battery storage costs about $250 per kWh of energy stored for domestic sized systems [27].

Inverters transform low voltage DC power (e.g. 12 V, 24 V, 32 or 48 V from batteries) into high voltage AC (generally 230 V in Australia) [28]. Inverters are necessary if mains-voltage appliances are to be used. In assessing the cost of the total system, it may be more economical to purchase an inverter and mass produced consumer appliances than to use low voltage DC appliances which may be more expensive.

Some appliances, such as high efficiency light globes are not presently available for low voltages. In this case, the cost of more panels must be balanced against the cost of an inverter. As a rule of thumb, inverters cost about $1 - $2 per watt of output, depending on size and features. For example a 1.2 kW sine wave inverter with energy management features costs approximately $2600. There is local research aimed at substantially reducing the cost of large inverters and several Australian companies manufacture inverters for the local and export market [29].

Sometimes wind generators are used in conjunction with PV systems, if the combination of sun and wind is viable. Small petrol or diesel generators are often used as the backup. These systems are relatively cheap to purchase (less than $1000 per kW) but expensive to run. Several Australian companies are developing total hybrid supply systems that optimize the use of each component.

### 4.3 Reliability of PVs

All PVs are now manufactured to exacting international standards that ensure a lifespan of at least 25 years [30].

PV panels are generally made by laminating the solar cells between specially toughened high transparency glass and an impervious backsheet of plastic so that no moisture can enter the panel to cause corrosion. This ‘sandwich’ construction is so durable that all manufacturers of PV panels now offer a 10 year performance warranty.

This guaranteed durability enhances the cost effectiveness of PVs particularly in applications where maintenance is a prime consideration.

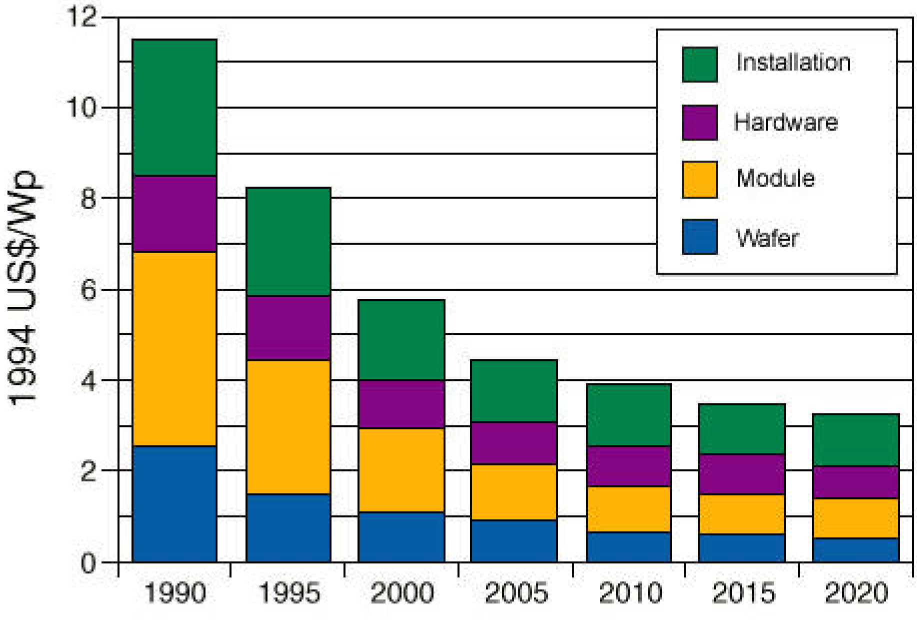


Figure 4.3 Graph showing component costs of PV system and price reduction over time

Figure 4.3 shows the relative proportion of cost of each element in a PV system, the cost of the cells makes up a very substantial proportion of the final cost, mainly due to the high purity

## 4.4 Photovoltaic Panel Performance

Performance of a photovoltaic panel or concentrating photovoltaic collector can be described in terms of its voltage and current output. The electrical power output from the panel is the product of these two variables. Voltage and current vary with the intensity of the solar irradiance and the temperature of the cell, all of which are described in the following figures. These figures were derived from real data taken on a commercial photovoltaic panel of approximately 0.65 $m^2$ [19, 31]. However, only the trends are important here and the solar designer should obtain similar information from the manufacturer of the specific panel or concentrator to be used in their design.

### 4.4.1 The I-V curve

The fundamental performance of a photovoltaic panel is represented by Figure 4.4, called an *I-V curve.* It is a plot of the voltage across the panel for different values of current. Since the voltage is a product of the current and the load resistance, lines of constant load resistance are shown to complete the description.

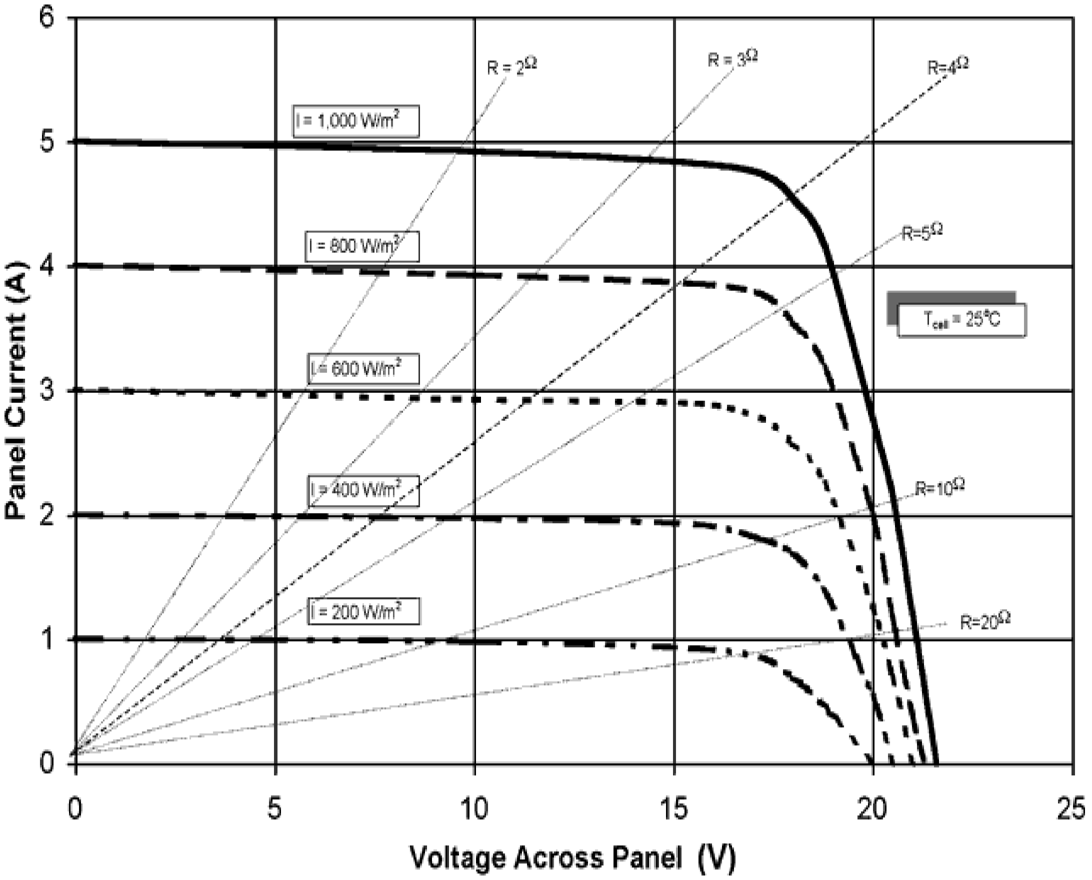


Figure 4.4 Photovoltaic panel output current as a function of the voltage across the panel. These I-V curves are shown for different levels of insolation. Also superimposed on graph are lines of constant load resistance. Data are for a cell temperature of 25°C and an air mass of 1.5

At low values of load resistance, the current is a maximum and the voltage across the cell approaches zero. This condition is equivalent to a short-circuit across the cell, and the current output at zero voltage is called the *short-circuit current* or $I_{sc}$. This current is a function of the size of the photovoltaic cell, and the number of cells connected in parallel [32].

As the load resistance increases, the current decreases slightly until a point is reached where the cell can no longer maintain a high current level, and it falls to zero. The point at which the panel current falls to zero represents an infinite resistance or an open circuit. The voltage across the panel at zero current is called the open-circuit voltage, $V_{oc}$, and represents the output of the unloaded panel. Note that the open-circuit voltage varies only a small amount as a function of solar irradiance (except at very low levels).

A single silicon photovoltaic cell produces an open-circuit voltage of slightly over 0.55 volts. The voltage produced by a photovoltaic panel is a function of how many cells are connected in series. In the case of the panel described below, there must be about 36 photovoltaic cells connected in series in order to produce over 20 volts.

### 4.4.2 Peak power point

The basic performance parameter required for a photovoltaic panel is neither voltage nor current but electrical power. Since electrical power is the product of current times voltage, one notes that there is no power produced at either extreme of the I-V curve [33]. However, as the load resistance increases from the short-circuit current condition, the voltage rises until the I-V curve starts falling to the open circuit point. There is a point along the curve where the maximum power is generated which occurs just as the I-V curve 'breaks'. This point is called the "peak power point" (PPP). Figure 4.5 shows the electrical power output of the photovoltaic panel in Figure 4.4.

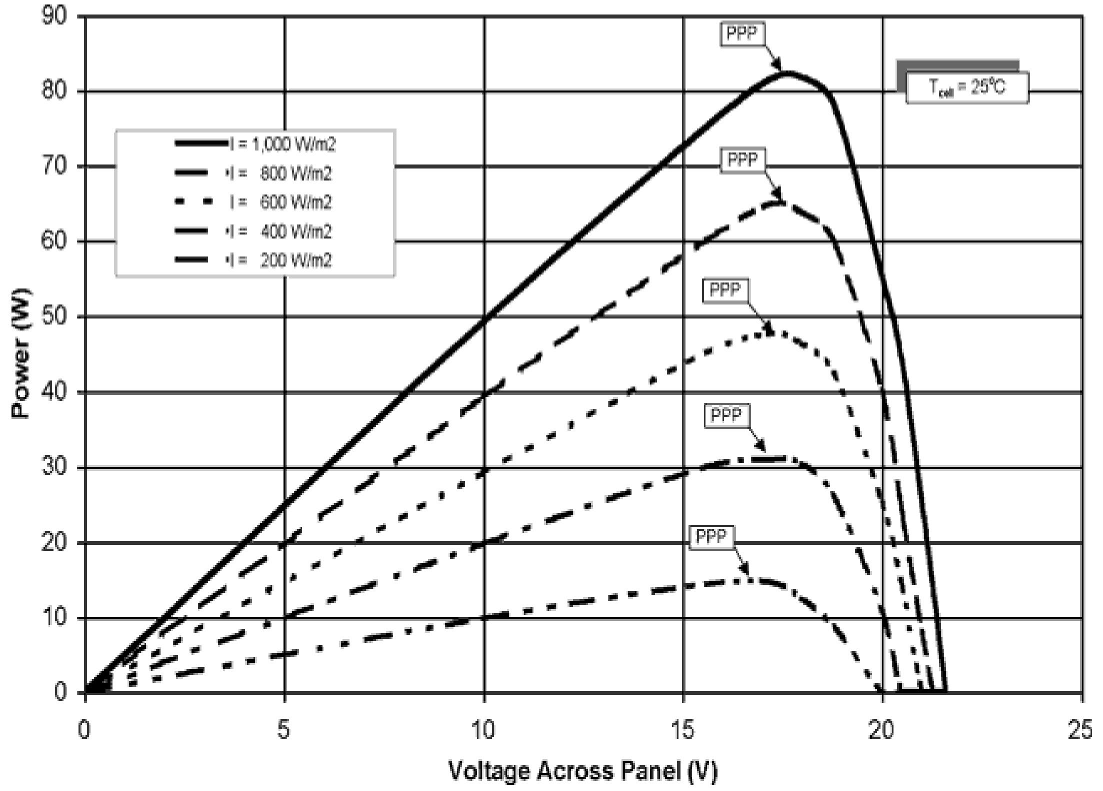


Figure 4.5 Power output of a photovoltaic panel at different levels of solar irradiance. The notation PPP defines the peak power point. Data is for a cell temperature of 25°C and an air mass of 1.5

Note that the peak power output occurs at a panel voltage of about 80% of the maximum open-circuit voltage, for a wide range of solar irradiance levels. In order to maintain maximum electrical power output from a photovoltaic panel, the load resistance should match this point. As can be seen on Figure 4.4, the load resistance must increase as solar irradiance decreases in order to maintain maximum power output from the panel [33]. Since the resistance of most electrical loads are fixed (except for electrical motors and batteries), special consideration must be taken in the system design to ensure that the maximum potential of the solar panel is utilized. There are electronic devices, called "peak power trackers" that ensure that the panels are operating close to their peak power point [34].

### 4.4.3 Cell temperature loss

An important characteristic of the photovoltaic cell is the reduction of output voltage as cell temperature increases [35]. Figure 4.6 shows this characteristic for the photovoltaic panel described in Figures 4.4 and 4.5. Although not obvious on this curve, the short circuit current increases slightly with temperature.

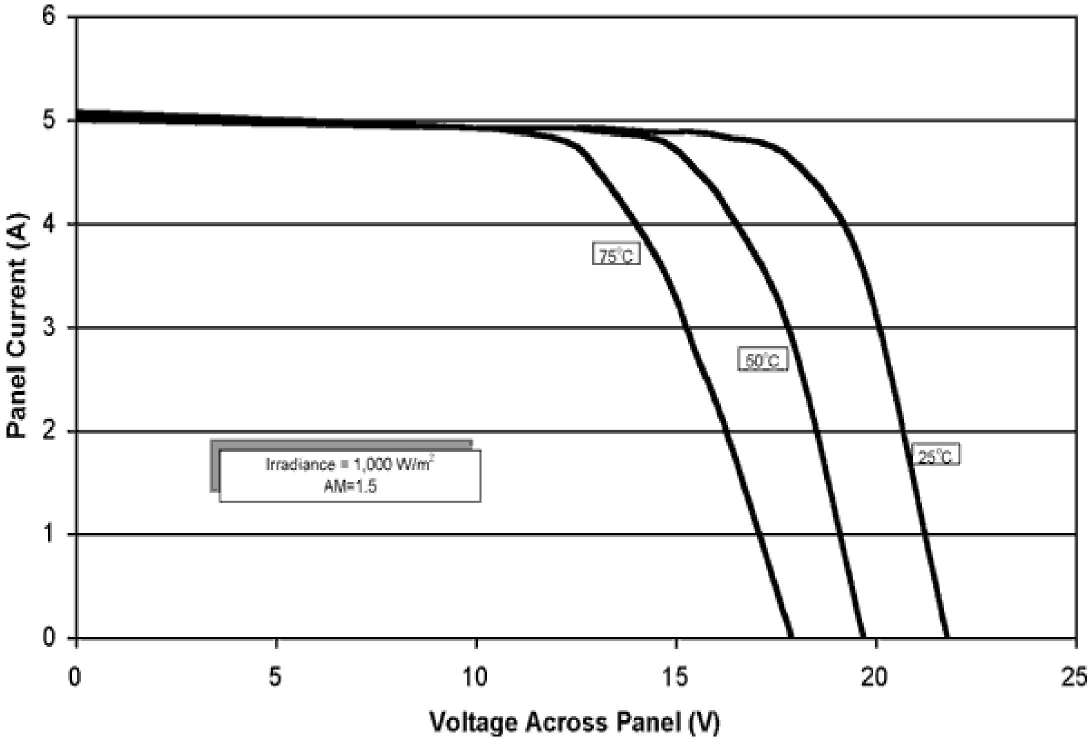


Figure 4.6 Effect of cell temperature on photovoltaic panel output. Data shown are for an irradiance of 1,000 W/m$^2$ and an air mass of 1.5

All of the data presented so far have been for photovoltaic cells at a temperature of 25°C. In a real system design, this is seldom the case. Photovoltaic cells are usually encapsulated in a panel to provide rigidity and physical protection of the front surface. Since panels must reject 80% to 90% of the solar energy incident upon them, and usually this transfer is to the ambient air, both the air temperature and the wind speed and direction have great effects on this [36].

The concept of a "normal operating cell temperature" (NOCT) has been defined in order to provide some sense of the ability of a specific panel to reject heat and provides a design guideline for system performance analysis. Normal operating cell temperature is the cell temperature under 'standard operating conditions', ambient air temperature of 20°C, solar irradiance of 800 W/m$^2$ and wind speed of 1 m/s. NOCT values are specific to a particular panel or collector, but generally are about 50°C for flat-plate panels [37].

All data presented above are for an air mass of 1.5 (AM=1.5). The *air mass* is an indication of the path length that solar irradiance travels through the atmosphere. An air mass of 1.0 means the sun is directly overhead and the radiation travels through one atmosphere (thickness). The air mass is approximately equal to the reciprocal of the cosine of the zenith angle and an air mass of 1.5 would represent a zenith angle of 48.2 degrees or an altitude angle of 41.8 degrees.

# CHAPTER 5

# CHARACTERISTICS OF PV PANELS

## 5.1 Starting the Engineering

### 5.1.1 Answers in photovoltaics – mathematics (basic)

### 5.1.1.1 Introduction

In order to complete the following exercises, it is necessary to understand the following concepts:

- The power delivered by any electrical supply is equal to the voltage multiplied by the current, i.e. power in watts = voltage in volts * current in amps.

$$P = V * I \qquad \textbf{(5.1)}$$

- Percentage efficiency=(power output / power input)*100%

$$? = (P_{el} / P_{sun}) * 100\% \qquad \textbf{(5.2)}$$

Power output is the electrical power delivered by the module ? $P_{el}$

Power input is the power provided by the sun ? $P_{sun}$

Once these concepts are accepted then the exercises use only basic mathematics, i.e. multiplication and division.

### 5.1.1.2 PV cells for room lighting

(a) In order to find the power output of this PV cell, the equation 5.1 should be used:

$I = 2$ A, $V = 0.5$ V,

$P = I * V = 2\ A * 0.5\ V = 1\ W$

(b) How many PV cells are needed to produce 10 Watts?

This question repeats the comparison but in this time with Watts.

$n = 10\ W / 1\ W = 10$

(c) Answer (b): 10 cells are necessary to produce 10 Watts. If one cell has an area of 0.01 $m^2$, then the total area of the cells to produce 10 Watts must be:

$$A = 10 * 0.01\ m^2 = 0.1\ m^2$$

(d) This question includes two separate parts:

i) How much power does a PV cell with an area of 1 $m^2$ produce?

$$x = ((10\ W * 1\ m^2) / 0.1\ m^2) = (10 / 0.1)\ W = (1 / 0.01)\ W = 100\ W$$

ii) How many energy-efficient light bulbs would be lit?

$$n = 100\ W / 10\ W = 10$$

### 5.1.2 Exercises in photovoltaics – connecting PV cells (basic)

**Introductory note:**

These exercises deal with basic electrical knowledge relating to series and parallel connections. Connecting PV cells is similar to connecting batteries.

#### 5.1.2.1 PV cells connected in series

- Connecting in series, implying an increase in voltage but constant current;

$A_{all} = A_{cell}$ and $V_{all} = n * V_{cell}$, where n is the number of cells.

(a) If each PV cell produces 0.5 V then the four PV cells must produce four times this voltage:

$V_{all} = 4 * V_{cell} = 4 * 0.5\ V = 2\ V$

(b) There are two methods to reach the same result:

Given; $A_{cell} = 1\ A$, $V_{cell} = 0.5\ V$, $n = 4$

i) First calculate the power of each PV cell and then multiply by the number of PV cells:

$P_{cell} = A_{cell} * V_{cell} = 1\ A * 0.5\ V = 0.5\ W$ and

$P_{all} = 4 * P_{cell} = 4 * 0.5\ W = 2\ W$

ii) Alternatively calculate the total power across the load in one step using the result of 1.(a):

$P_{all} = A_{all} * V_{all} = 1\ A * 2\ V = 2\ W$

### 5.1.2.2 PV cells connected in parallel

- Connecting in parallel, implying an increase in current but constant voltage;

$V_{all} = V_{cell}$ and $A_{all} = n * A_{cell}$, where n is the number of cells.

(a) If each PV cell delivers a current of 0.6 A and there are three PV cells in parallel then the total current flowing through the load must be:

$A_{all} = 3 * A_{cell} = 3 * 0.6\ A = 1.8\ A$

(b) This question is similar to 1. (b) but again there are these two approaches:

Given; $A_{cell} = 0.6\ A$, $V_{cell} = 0.5\ V$, $n = 3$

i) First calculate the power of each PV cell and then multiply by the number of PV cells:

$P_{cell} = A_{cell} * V_{cell} = 0.6\ A * 0.5\ V = 0.3\ W$ and

$P_{all} = 3 * P_{cell} = 3 * 0.3\ W = 0.9\ W$

ii) Alternatively calculate the total power across the load in one step using the result of 2.(a):

$P_{all} = A_{all} * V_{all} = 1.8\ A * 0.5\ V = 0.9\ W$

### 5.1.3 Electrical power generated (EPG) and electrical energy generated (EEG)

#### 5.1.3.1 Electrical power generated (EPG)

Now is necessary to fix the electrical power available by the photovoltaic panel under especific sun irradiation level. The electrical useful power, in direct current circuits, is the result of the voltage * current.

Electrical Power (Watt) = Voltage (Volt) * Current (Ampere)

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.

- The rate of electrical power that one photovoltaic panel may generate is fixed below:

<u>Given:</u> V = 12 V and I = 3.9 A

EPG (W) = Voltage (V) x Current (A)

EPG (W) = 12 V x 3.9 A

EPG (W) = 46.8 Watts (by only one panel)

Electrical power generated (EPG) here is the amount power generated by only one photovoltaic panel, and this value may change along the days because any causes, like air configurations, temperature and strong changes in solar irradiation level that may be increased at the noon [38].

### 5.1.3.2 Electrical energy generated (EEG)

Above was fixed the total power that one photovoltaic panel may generate. To know the values of the energy is necessary to know the time. The energy value may be calculated by:

Energy (Watt-hour) = Power (Watt) x Time (hour)

We will also specify energy in units of kilowatt-hours:

$$\text{Energy} = \text{Power (in kilowatts)} * \text{Time (in hours)} = \#\text{ of kilowatt-hours} \qquad \textbf{(5.3)}$$

A good target for $\mathbf{E_{used}}$ for an energy efficient home is 10 kilowatt-hours. Electrical energy from the grid in the United States typically costs between 6 to 12 cents per kilowatt-hour [38]. So, for example, if you use 10 kilowatt-hours a day, and the cost of power is about 10 cents per kilowatt-hour, then your electrical costs would be about \$1 per day (ten times 10 cents), or \$30 per month.

Also, we need to know how long the sun shines each day on average. Let this be denoted by $\mathbf{T_{sun}}$ ,

$$\mathbf{T_{sun}} = \textbf{Hours of Sunshine on average.}$$

Using the formula for power and energy (Power = Energy / Time), we have

$$\mathbf{P_{peak\ panels} = E_{used} / T_{sun}}$$

We can understand by this equation that the fewer hours of sunshine available, the more peak power from the panels will be needed.

Then, by the equations shown is possible to know the total energy that will be generated by only one photovoltaic panel. Now it is necessary to know the time of each day which the sunlight is on photovoltaic panels and the level of the sunlight.

These levels must be nearly 800 Watts/m$^2$. The sunlight level of irradiation presents variations along the seasons of year and the latitude. These regions of the earth which the solar irradiation is strong present in long times of a day. Here will be fixed that the periods of ideal irradiation level is between 10:00 am and 3:00 pm. Now is possible to fix the energy amount that will be generated:

- From 10:00 am until 3:00 pm we have 5 hours by day, so:

EEG (Wh) = EPG (W) x Time (hour)

EEG (Wh) = 46.8 (W) x 5 hours

EEG (Wh) = 234.0 Wh (by only one panel)

- From 11:00 am until 6:00 pm we have 7 hours by day, so:

EEG (Wh) = EPG (W) x Time (hour)

EEG (Wh) = 46.8 (W) x 7 hours

EEG (Wh) = 327.6 Wh (by only one panel)

- From 8:00 am until 7:00 pm we have 11 hours by day, so:

EEG (Wh) = EPG (W) x Time (hour)

EEG (Wh) = 46.8 (W) x 11 hours

EEG (Wh) = 514.8 Wh (by only one panel)

Until now are available the total power and energy generated by photovoltaic panel in study when it is exposed under specific solar irradiation level. In engineering works, you may to use a energy value of one panel and multiply by panels number used in the array. Do not forget those values of voltage and current available are dependent of the electrical kind connection used. But the energy amount generated will be the same for any kind of electrical connection.

## 5.2. Determining Optimum Tilt Angels and Orientations of Photovoltaic Panels in Gaziantep, Turkey

The performance of a photovoltaic (PV) panel is affected by its orientation and its tilt angle with the horizontal plane. This is because both of these parameters change the amount of solar energy received by the surface of the PV panel. A mathematical model was used to estimate the total solar radiation on the tilted PV surface, and to determine optimum tilt angles for a PV panel installed in Gaziantep, Turkey. The optimum tilt angles were determined by searching for the values of angles for which the total radiation on the PV surface was maximum for the period studied. This study determined that the monthly optimum tilt angle for a PV panel changes throughout the year with its minimum value as $12^0$ in June and maximum value as $60^0$ in December.

### 5.2.1 Introduction

Solar cells change the received solar energy into electricity, thus they have received attention as clean energy devices which do not release hazardous pollutants into the environment. The efficiency of the photovoltaic (PV) systems has been increased, while their production cost reduced which contributed to the expansion of PV systems globally [39]. Energy production using PV power system and utilization of the energy produced by this system in agricultural applications, especially in places which receive abundant amounts of solar radiation, are one of the best alternative and clean energy production techniques.

For the optimum design of PV systems for any application, it is important to determine their performance at the site of installation. The amount of power produced by a PV panel depends upon the amount of sunlight it is exposed to. More light means more power. To intercept the most sunlight, a PV panel must be positioned so that the sun’s rays arrive at the panel directly; perpendicular to its surface. When a PV panel is not aimed directly at the sun, it does not intercept as much light as it can. The best way to collect maximum daily energy is to use tracking systems. How much a tracker will enhance a particular PV system’s performance depends upon the application and local conditions. The trackers are often expensive and are not always applicable. Thus, the optimum slopes of PV panels at any latitude, for any surface azimuth angles and on a day or in a month of a year, have to be determined for design purposes. Definite value is rarely given by researchers for optimum tilt angles. Lunde [40] suggested $S_{opt} = F \pm 15^0$, Duffie and Beckman [41] $S_{opt} = (F + 15^0 \pm 15^0$ and Lewis [42] reported $S_{opt} = F \pm 8^0$.

$S_{opt}$ ? optimum tilt angle of PV panel ($^0$)

F ? latitude of the location ($^0$)

Gaziantep city, located in Southeast Anatolia Region in Turkey, has a great solar radiation potential, as the number of sun hours (Figure 5.1) is large. Furthermore, the amount of solar intensity in Gaziantep is about 4.9 kW/m$^2$ based on averages of long years (1990-2004).

These data show that solar energy could be used for certain applications, especially in agriculture. One of the problems faced in this region is that electricity cut-off is large especially in rural areas. In addition, there has been increasing interest from growers in the region about the utilization of PV systems to irrigate small areas with drip irrigation systems and using solar energy for drying purposes. Therefore, the goal of this study was to determine optimum panel tilt angles and to investigate the effects of panel tilt angles, fixed and two-axis tracking of sun rays on the amount of solar radiation received by a PV panel and the power generation with theoretical calculations and experiments.

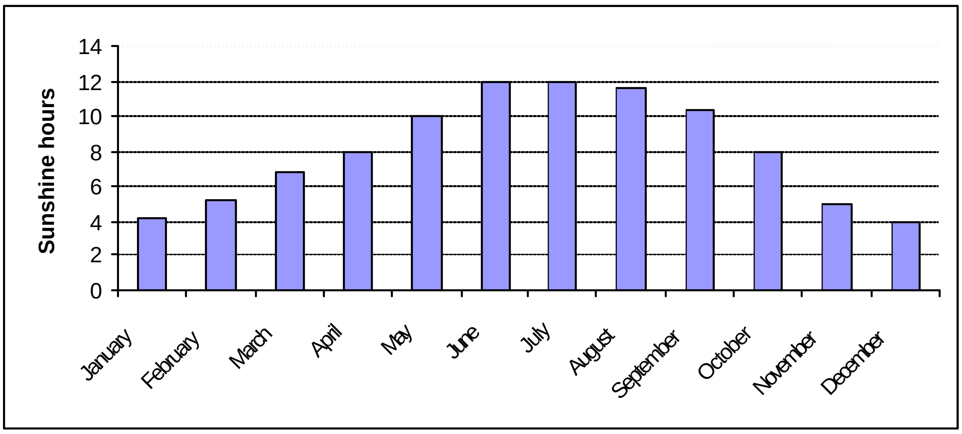


Figure 5.1 Annual variation of daily sunshine hours in Gaziantep, Turkey (average 1990-2004) (Gaziantep Meteorological Station, 2005)

### 5.2.1.1 Solar radiation on a tilted south facing and two-axis tracking surface

The declination angle (d) is the angular position of the sun at solar noon with respect to the plane of the equator. Its value is given by

$d = 23.45*\sin[360*(284+n)/365]$ **(5.4)**

The solar hour angle (? ) is the angular displacement of the sun east or west of the local meridian; morning positive, afternoon negative and zero at solar noon. The hour angle is determined as

? = minutes before noon / 4 **(5.5)**

Solar altitude angle (a) is the angle between the sun’s rays and the horizontal plane and its value is determined by

a = sin$^{-1}$([cos(F)cos(d)cos(?)]) + [sin(F)sin(d)] **(5.6)**

The azimuth angle (ß) is the angle between true north and the projection of the sun’s rays onto the horizontal. The azimuth angle can be calculated by

ß = cos$^{-1}$(([sin(a)sin(F)] - sin(d)) / cos(a)cos(F)) **(5.7)**

The zenith angle ($?_Z$) is the angular distance of the sun from the local vertical. The zenith angle is directly related to the solar elevation angle by

$?_Z$ = 90 – a **(5.8)**

Surface azimuth angle (?) is the angle between the normal of the panel and the sun’s rays. The general formula for this angle is

? = 0 for south facing surface **(5.9)**

? = 180 – ß for two-axis tracking surface **(5.10)**

Solar incidence angle ($?_I$) is the angle between the normal of the panel and the sun’s rays. The general formula for this angle is

$$\begin{aligned} ?_I = \cos^{-1}([\sin(d)\sin(F)\cos(S)]) &- [\sin(d)\cos(F)\sin(S)\cos(?)] \\ &+ [\cos(d)\cos(F)\cos(S)\cos(?)] + [\cos(d)\sin(F)\sin(S)\cos(?)\cos(?)] \\ &+ [\cos(d)\sin(S)\sin(?)\sin(?)] \end{aligned} \qquad \textbf{(5.11)}$$

For a surface facing true south, $? = 0$ is used. For two-axis tracking system, $?_I = 0$. The tilt angle of the two-axis tracking panel was determined by

$$S = 90 - a = ?_Z \qquad \textbf{(5.12)}$$

The relationship between the intensity of the direct-beam radiation normal to the horizontal surface (H) and the maximum direct beam-solar radiation ($H_n$) is

$$H_n = H / \cos(?_Z) \qquad \textbf{(5.13)}$$

The amount of direct-beam solar radiation perpendicular to the tilted surface ($H_b$) is determined by

$$H_b = H_n\cos(?_I) \qquad \textbf{(5.14)}$$

$R_b$ is the ratio of beam radiation on the PV panel to that on the horizontal, which can be expressed as

$$R_b = H_b / H = \cos(?_I) / \cos(?_Z) \qquad \textbf{(5.15)}$$

Thus, the direct-beam radiation perpendicular to the tilted panel can also take the form as

$$H_b = HR_b \qquad \textbf{(5.16)}$$

Tilted surfaces can only see some part of the sky. The amount of the sky seen by the tilted surface is expressed as (1+cos(S))/2. Hence, the diffuse radiation on the plane of the tilted surface ($H_{d,p}$) is determined as

$$H_{d,p} = H_d\,[(1+\cos(S))/2] \qquad \textbf{(5.17)}$$

where $H_d$ is the diffuse radiation on the horizontal surface. The portion of the ground seen by the tilted surface is defined by (1-cos(S)) * $?_g$ /2. Thus, ground reflected radiation on the tilted surface ($H_{gr}$) is determined by

$$(H_{gr}) = (H + H_d)[(1+\cos(S))/2] ?_g \tag{5.18}$$

Total radiation received on the plane of the tilted PV panel is the summation of direct-beam, diffuse and ground reflected radiations on the tilted panel as

$$H_T = H_b + H_{b,p} + H_{gr} \tag{5.19}$$

### 5.2.2 Simulation of PV panel performance

PV modules typically have a manufacturer's rated power output value in Watts (at 25 $^0$C) for specific size panel. This value can vary significantly, depending on the performance of the panel. Since the panels are located on a building in a congested urban environment an allowance factor of 0.94 is needed to account for the decreased efficiency of the panels due to dirt accumulation on the panel surfaces. The panels are all wired into a DC to AC power inverter, which has a manufacturer rated efficiency. PV cell performance varies with the spectral distribution of solar radiation. This spectral distribution varies in turn with the solar location, season, local weather conditions, altitude and time of day.

Simulation of PV panel performance was investigated utilizing Visual Basic to calculate to power generated by the PV panel for each hour of the year. The Visual Basic programming prompts the user to enter: the number of PV modules; the size of each PV module (in square meters); and the manufacturer's rated power per PV module (in Watts). These inputs are utilized by the software programming to calculate the PV panel efficiency. The user also inputs the city and the inverter efficiency. The programming accesses the solar location as well as the dry bulb temperature, the horizontal solar radiation, and direct radiation figures directly from the specified city's weather database. This data is utilized, along with the PV panel efficiency and tilt angle (0-60$^0$) to produce 8,760 hourly total radiation calculations spanning from January 1 through December 31. All data had been found according to two single crystalline PV modules (Model AP-120, Astro Power, INC., Deleware, USA). Inputs for the baseline building included 162 PV modules, 2 square meters per module, a manufacturer's power rating of 240 Watts per module (120 Watts per square meter of module), and a 93% inverter efficiency.

### 5.2.3 Results and discussions

### 5.2.3.1 Monthly and seasonal optimum tilt angles

The effect of tilt angle on maximum total radiation received by a surface facing true south at solar noon was investigated for the course of a full calendar year. The effect of tilt angle from $0^0$ to $60^0$ from the horizontal plane is shown in Figure 5.2 from this comparison, it was determined that maximum radiation on the south facing surface at solar noon was obtained with $30^0$, $40^0$ and $50^0$ tilt angles from January to March; with $0–10–20^0$ from April to August and $40–50–60^0$ from September to December. In other words, higher tilt angles during fall and winter and lower tilt angles during the summer allow maximum radiation to be received by the surface.

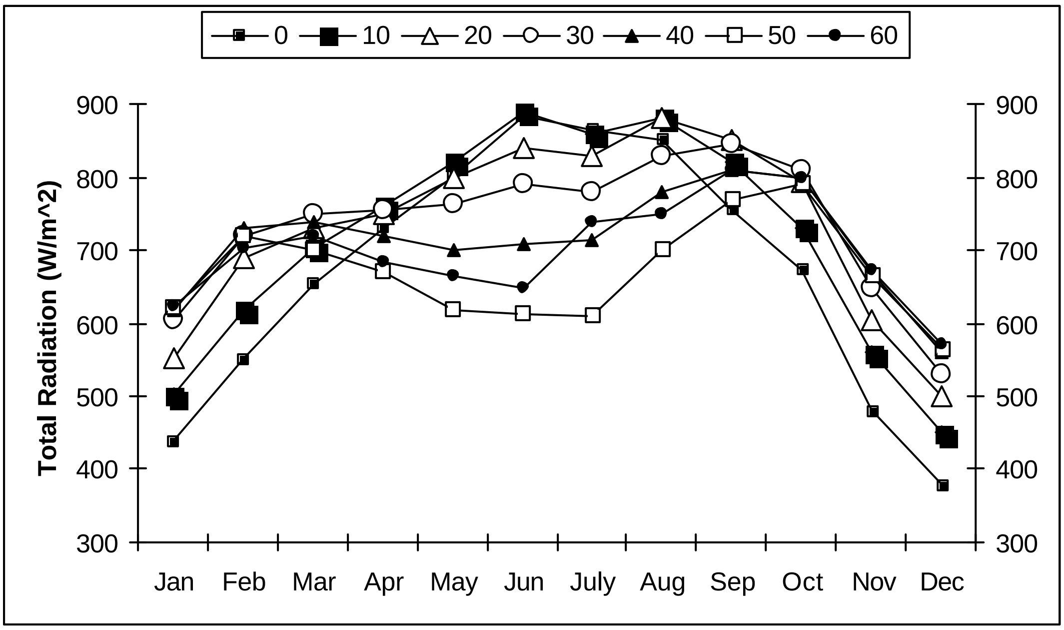


Figure 5.2 The effect of tilt angle on maximum radiation for a south facing surface

In a different analysis, the optimum monthly tilt angle was found by searching for the values for which $H_T$ is a maximum (Figure 5.3). Monthly adjustments of approximately $10^0$ from January to May, $4\text{-}8^0$ from May to July and

$9^0$ from July to November were found to be necessary to obtain maximum radiation on the surface of the panel.

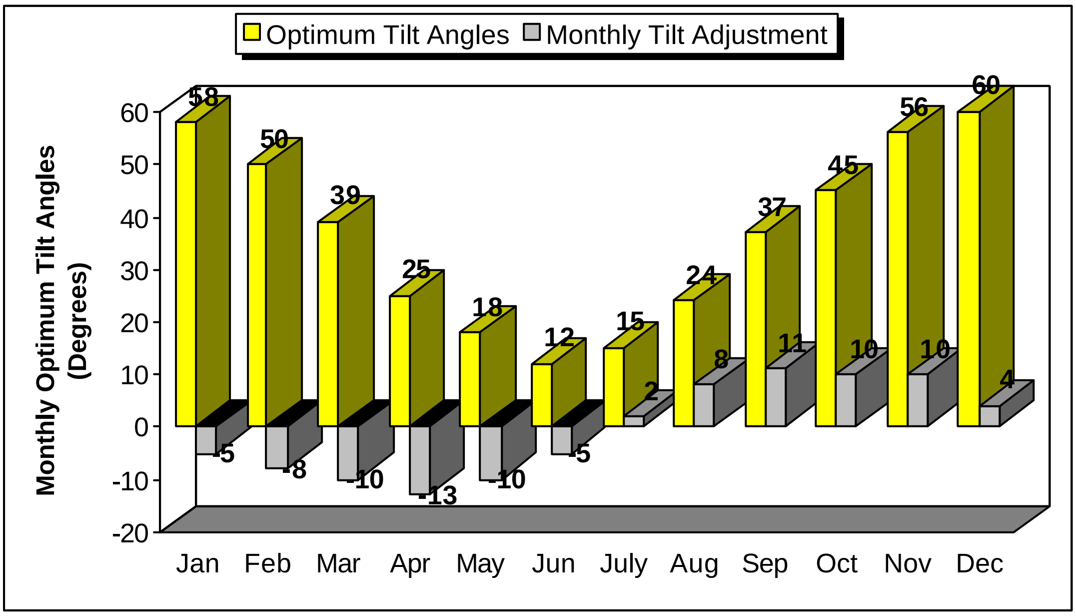


Figure 5.3 Optimum monthly tilt angles and monthly tilt adjustments for the course of a full year

### 5.2.3.2 Fixed vs. two -axis solar tracking

In order to see the effect of solar tracking on the energy generated by the PV panel, an experiment was conducted on a clear day on 12.06.2005 from 7 a.m. to 7 p.m. with one panel fixed tilt angle of $14^0$ facing true south while two-axis solar tracking was applied to the second panel ($PV_T$) following azimuth and altitude angles of the sun throughout the day.

Figure 5.4 illustrates the amount of total solar radiation measured in perpendicular direction to the plane of fixed and two-axis tracking panel on 12.06.2005. It is clear that there is a substantial amount of solar radiation which could be utilized to generate electricity during the early morning and late afternoon hours.

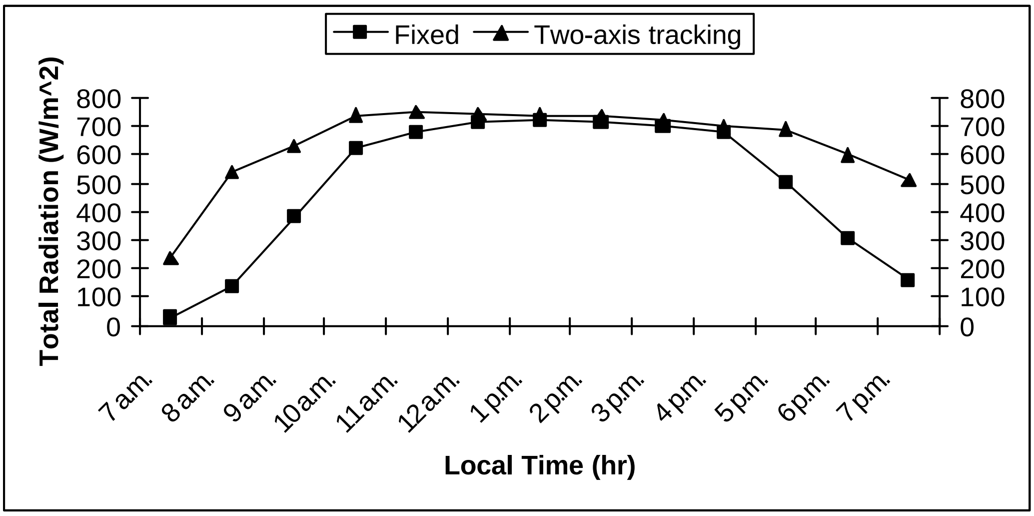
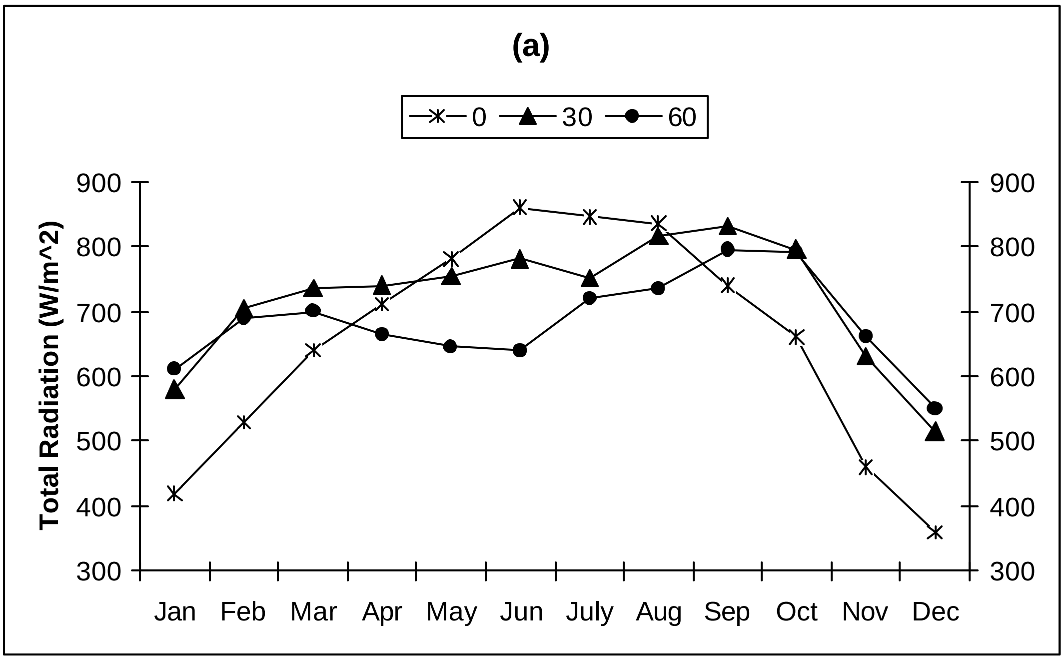


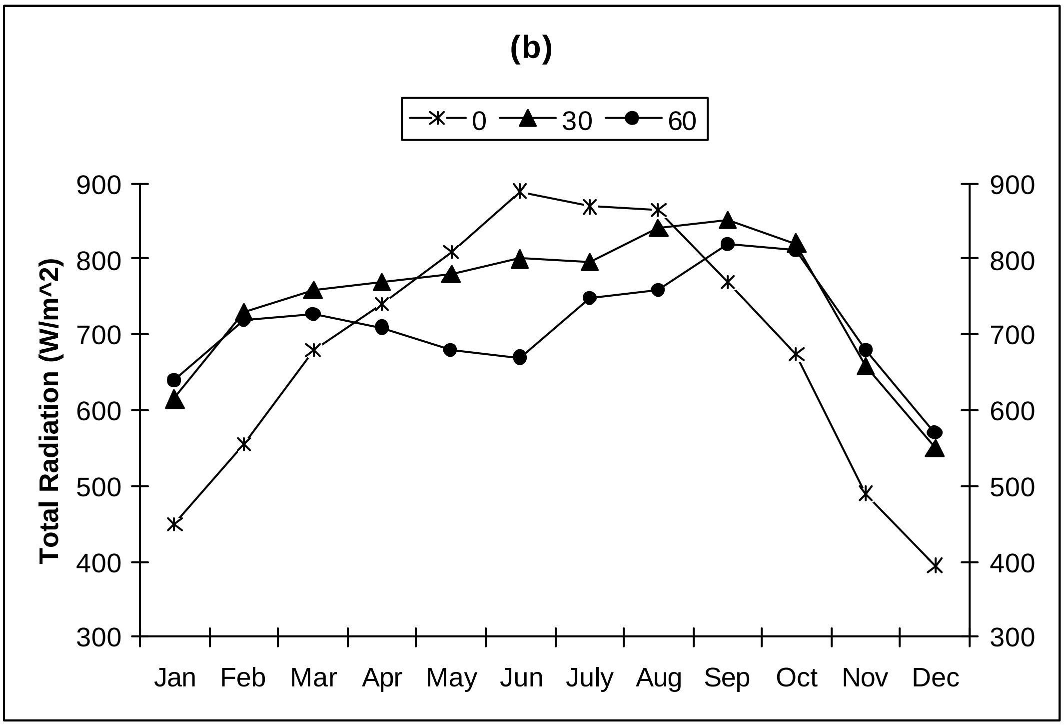
Figure 5.4 Hourly total radiation received by fixed and two-axis tracking panel on 12.06.2005 in Gaziantep

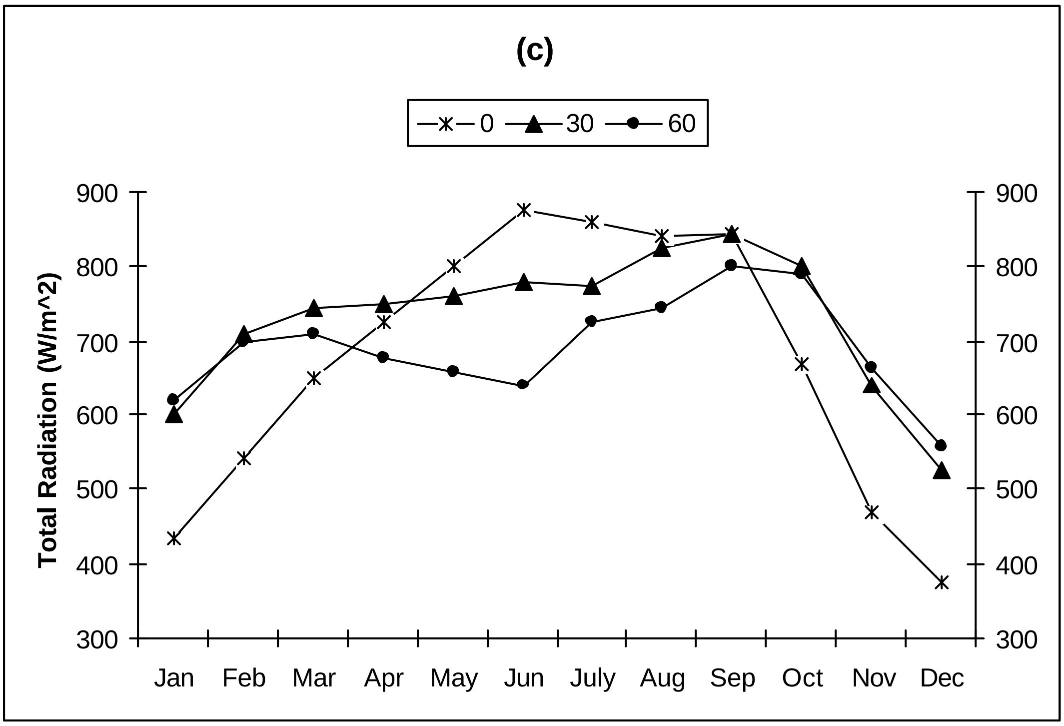
### 5.3 The Effect of Tilt Angles for PV Panels

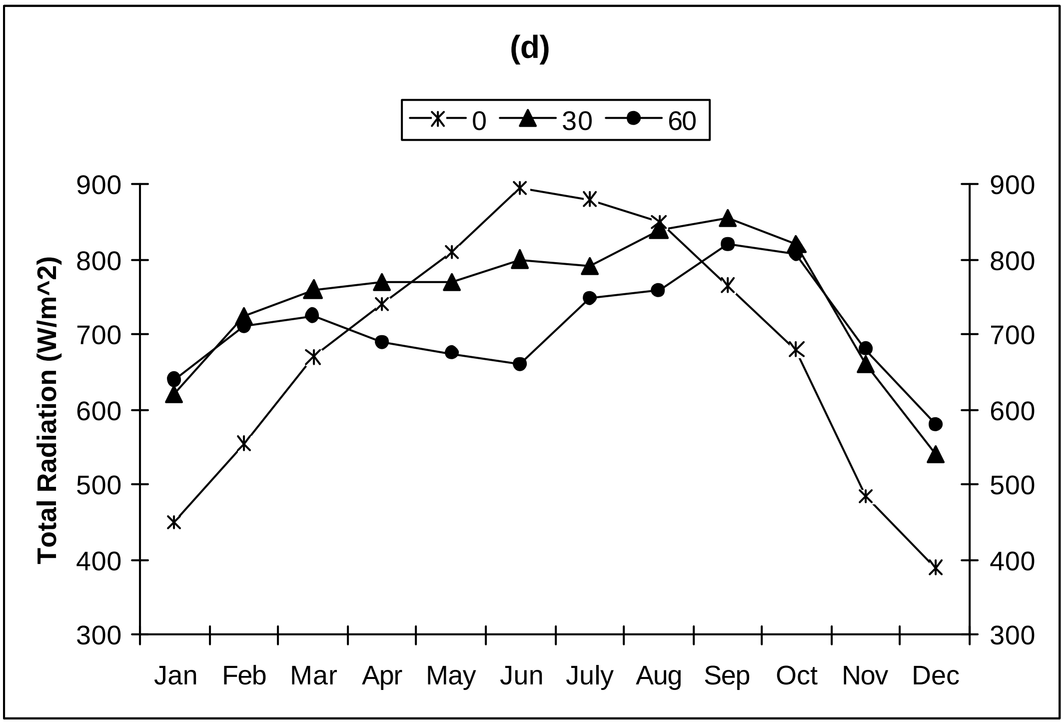
The Southeast Anatolia Region in Turkey has the greatest solar radiation potential, as the number of sun hours is large. Furthermore, the performance of a photovoltaic (PV) panel is affected by its tilt angle.

The effect of tilt angle on maximum radiation for a south facing surface at the cities of the Southeast Anatolia Region in Turkey has been seen in Figure 5.5 ((a), (b), (c), (d) and (e)).




(b)
0
30
60
Total Radiation (W/m^2)
900
800
700
600
500
400
300
Jan
Feb
Mar
Apr
May
Jun
July
Aug
Sep
Oct
Nov
Dec


(c)
0
30
60
Total Radiation (W/m^2)
900
800
700
600
500
400
300
Jan
Feb
Mar
Apr
May
Jun
July
Aug
Sep
Oct
Nov
Dec



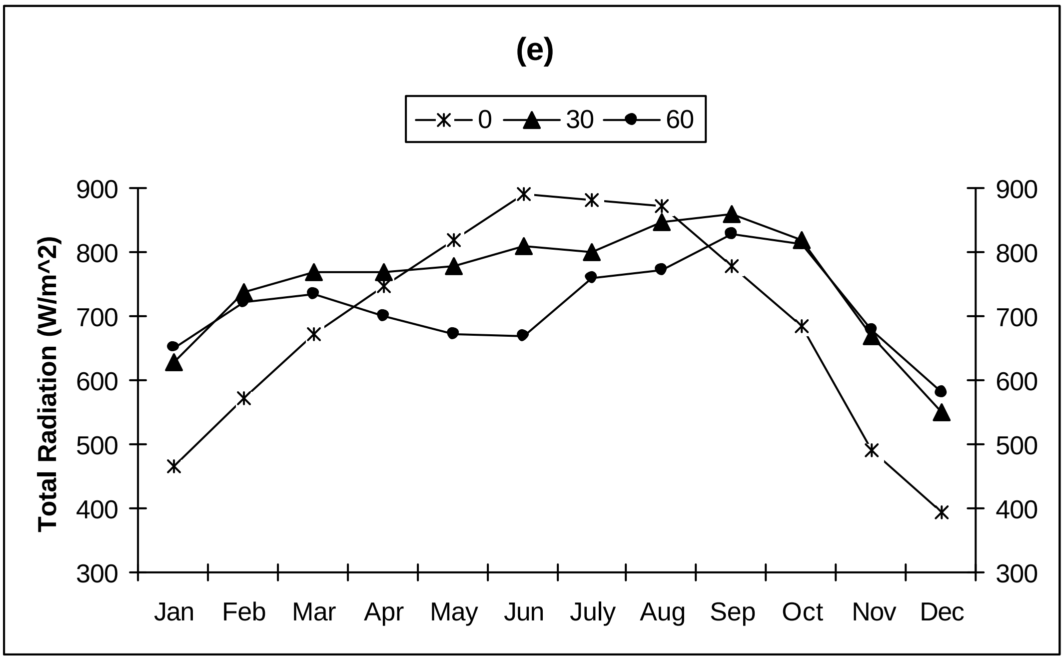


Figure 5.5 The effect of tilt angle on maximum radiation for a south facing surface in (a) Adiyaman, (b) Diyarbakir, (c) Mardin, (d) Siirt and (e) Sanliurfa

The performance of a photovoltaic (PV) panel is affected by its orientation and its tilt angle with the horizontal plane. Total radiation at the cities in the Southeast Anatolia Region depending upon these parameters has been seen in the above figure (Figure 5.5) as (a), (b), (c), (d) and (e).Tilt angle effect on the amount of radiation and power generation of the PV panels was investigated by changing the tilt angle of the fixed panel (facing true south) from $0^0$ to $60^0$ from the horizontal plane at solar noon at the cities in the Southeast Anatolia Region. From this comparison, it was determined that maximum radiation on the south facing surface at solar noon was obtained with $0^0$ tilt angle from May to September; with 30 - $60^0$ tilt angles from January to May and from September to December.

Also the amount of power produced by a PV panel depends upon the amount of sunlight it is exposed to. For example, Adiyaman (Figure 5.5 (a)) has less total radiation than the other cities in the Southeast Anatolia Region because it has less sunlight than the other cities in this region and Sanliurfa (Figure 5.5 (e)) has more total radiation than the others because it has more sunlight than the other cities in this region.

# CONCLUSIONS

Photovoltaics are a very promising technology for generating electricity in the future. Current PV cells are reliable and are already cost effective in certain applications such as remote power. The cost of photovoltaics has come down more than twenty-fold since the early 1970's, and research continues on several different technologies in an effort to reduce costs to levels acceptable for wide scale use. The use of photovoltaics will not be constrained by material or land shortages and the sun is a virtually endless energy source. The future extent of the use of photovoltaics will depend upon research to bring the costs down, and upon the value societies place on the negative environmental impacts associated with other forms of electrical generation.

The market for photovoltaic cells is presently growing at about 30% per year, and the cost of panels is declining continuously in real terms, due to both new technologies and mass production. There are confident predictions from leading PV manufacturers in USA, Japan and Europe that the price of PV power will be competitive with mains electricity within 10 years.

These predictions generally refer to power at the panel, and do not take into account the various other system costs mentioned above. The price of the balance of systems components are not declining as rapidly as the cost of panels, so the total system costs will decline more slowly. This factor is encouraging research into appliances that can be used directly from the panels, and do not need to rely on inverters and battery storage. Integrating panels into buildings also reduces the balance of systems costs.

The optimum values of tilt angles and orientation of a PV panel in Gaziantep, Turkey, were determined using a mathematical model and by a computer package. This study determined that the monthly optimum tilt angle for an PV panel changes throughout the year, with its minimum value as $12^0$ in June and maximum value as $60^0$ in December.

The mathematical model utilized in this study can be used to compute the optimum tilt angle and maximum amount of solar radiation on a PV panel installed in other locations.

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