PHOTOVOLTAIC POWER GENERATION FOR POLYCRYSTALLINE SOLAR CELLS AND TURNING SUNLIGHT INTO ELECTRICITY

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ABSTRACT

PHOTOVOLTAIC POWER GENERATION FOR POLYCRYSTALLINE SOLAR CELLS AND TURNING SUNLIGHT INTO ELECTRICITY

ÇAPAR Şule
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This thesis is an overview of photovoltaic (PV) power generation in order to provide the reader with a general understanding of photovoltaic power generation and how PV technology can be practically applied. We provide a review of the history, the present status and possible future developments of photovoltaic materials for terrestrial applications. We were investigated the analysis of the system performance, evaluation of the system efficiency and power output, taking into account the weather conditions. From our work , we can conclude that a photovoltaic system should be applied, not just for generating electricity, but also for improving general aspects including the use of thermal energy behind the panel during the summer, daylight provision inside the room, shade provision for the interior of the building during the winter, and aesthetical contribution to the interior view and exterior of the building.

Keywords: solar cell, photovoltaic, solar panel

ÖZET

GÜNEŞ PİLLERİ İÇİN FOTOVOLTAİK GÜÇ ÜRETİMİ VE GÜNEŞ IŞIĞININ ELEKTRİK ENERJİSİNE ÇEVRİMİ

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Bu tez okuyucuya fotovoltaik güç üretimi ve fotovoltaik teknolojisinin pratikteki uygulaması hakkında genel bilgi verecek şekilde hazırlanmıştır. Aynı zamanda dünyadaki uygulamalar için fotovoltaik materyallerin geçmişi, günümüzdeki durumu ve gelecekteki olası durumları özetle sunulmuştur. Sistem performansı, sistem veriminin geliştirilmesi ve güç çıkışının hava şartlarına bağlı olarak inceledik. Fotovoltaik sistem sadece elektrik üretimi değil bunun yanı sıra yaz ayları boyunca panel arkasındaki ısı enerjisini, kış ayları boyunca binanın dış görünüşünü ve ara bölgelerdeki estetiğini, gün ışığından verimli olarak kullanımını sağlamaktadır.

Anahtar Kelimeler: Güneş pili, Fotovoltaik, Güneş paneli

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CHAPTER 1

INTRODUCTION

Thin-film photovoltaic technologies are being developed as a means of substantially reducing the cost of photovoltaic (PV) systems. The thin-film modules are expected to be cheaper to manufacture owing to their reduced material costs, energy costs, handling costs and capital costs. However, thin films have had to be developed using new semiconductor materials, including amorphous silicon, copper indium diselenide, cadmium telluride and film crystalline silicon [1].

One important way to convert solar radiation into electricity occurs by the photovoltaic effect which was first observed by Becquerel [2]. It is quite generally defined as the emergence of an electric voltage between two electrodes attached to a solid or liquid system upon shining light onto this system. Practically all photovoltaic devices incorporate a pn-junction in a semiconductor across which the photovoltage is developed. These devices are also known as solar cells. The semiconductor material has to be able to absorb a large part of the solar spectrum. Dependent on the absorption properties of the material the light is absorbed in a region more or less close to the surface. When light quanta are absorbed, electron hole pairs are generated and if their recombination is prevented they can reach the junction where they are separated by an electric field. Even for weakly absorbing semiconductors like silicon most carriers are generated near the surface [3,4]. For practical use solar cells are packaged into modules containing either a number of crystalline Si cells connected in series or a layer of thin-film material which is also internally series connected. The module serves two purposes, it protects the solar cells from the ambient and it delivers a higher voltage than a single cell which develops only a voltage of less than 1 V [5].

Thin-film solar cells are manufactured by applying thin layers of semiconductor materials to a solid backing material. Sunlight entering the intrinsic layer generates free electrons. The p-type and n-type layers create an electric field across the intrinsic layer. The electric field drives the free electrons into the n type layer while positive charges collect in the p-type layer. The total thickness of the p-type, intrinsic, and n-type layers is about one micron. Although less efficient than single- and polycrystal silicon, thin-film solar cells offer greater promise for large-scale power generation because of ease of mass-production and lower materials cost. Thin-film is also suitable for building-integrated systems because the semiconductor films may be applied to building materials such as glass, roofing, and siding [6]. Using thin films instead of silicon wafers greatly reduces the amount of semiconductor material required for each cell and therefore lowers the cost of producing photovoltaic cells. Gallium arsenide (GaAs), copper indium diselenide (CuInSe2) [7], cadmium telluride (CdTe) [8] and titanium dioxide (TiO2) are materials that have been used for thin film PV cells. Titanium dioxide thin films have been recently developed and are interesting because the material is transparent and can be used for windows [9]. Tin oxide is used in place of a metallic grid for the top layer of thin film photovoltaic sheets. Amorphous (uncrystallized) silicon is the most popular thin-film technology. It is prone to degradation and produces cell efficiencies of 5-7%. Double- and triple-junction designs raise efficiency to 8-10%. The extra layers capture different wavelengths of light. The top cell captures blue light, the middle cell captures green light, and the bottom cell captures red light. The most efficient PV modules usually employ single-crystal silicon cells, with efficiencies up to 15%. Poly-crystalline cells are less expensive to manufacture but yield module efficiencies of about 11%. Thin-film cells are less expensive still, but give efficiencies to about 8% and suffer greater losses from deterioration [10].

Photovoltaics (PV) or solar cells as they are often referred to, are semiconductor devices that convert sunlight into direct current (DC) electricity. The usage of solar energy for heat has a long history but the origin of devices which produce electricity is much more recent: it is closely linked to modern solid-state electronics. Solar cells operate according to what is called the photovoltaic effect, ("photo"–light, "voltaic"–electricity). In the photovoltaic effect, "bullets" of sunlight–photons–striking the surface of semi-conductor material such as silicon, liberate electrons from the material’s atoms. Certain chemicals added to the material’s atoms. Certain chemicals added to the material’s composition help establish a path for the freed electrons. This creates an electrical current. Through the photovoltaic effect, a typical four-inch silicon solar cell produces about one watt of direct current electricity. Groups of PV cells are electrically configured into modules and arrays, which can be used to charge batteries, operate motors, and to power any number of electrical loads. With the appropriate power conversion equipment, PV systems can produce alternating current (AC) compatible with any conventional appliances, and operate in parallel with and interconnected to the utility grid. The solar cells found a ready application in supplying electrical power to satellites [11]. Terrestrial systems soon followed; these were what we would now call remote industrialor professional applications, providing small amounts of power in inaccessible and remote locations, needing little or no maintenance or attention. Examples of such applications include signal or monitoring equipment, or telecommunication and corrosion protection systems. Since then, numerous photovoltaic systems have been installed to provide electricity to the large number of people on our planet that do not have (nor, in the foreseeable future, are likely to have) access to mains electricity. Power supply to remoter houses or villages, lighting, electrification of the healthcare facilities, irrigation and water supply and treatment will form an important application of photovoltaics for many years to come. The first conventional photovoltaic cells were produced in the late 1950s, and throughout the 1960s were principally used to provide electrical power for earth-orbiting satellites. In the 1970s, improvements in manufacturing, performance and quality of PV modules helped to reduce costs and opened up a number of opportunities for powering remote terrestrial applications, including battery charging for navigational aids, signals, telecommunications equipment and other critical, low power needs. In the 1980s, photovoltaics became a popular power source for consumer electronic devices, including calculators, watches, radios, lanterns and other small battery charging applications. Following the energy crises of the 1970s, significant efforts also began to develop PV power systems for residential and commercial uses both for stand-alone, remote power as well as for utility-connected applications. During the same period, international applications for PV systems to power rural health clinics, refrigeration, water pumping, telecommunications, and off-grid households increased dramatically, and remain a major portion of the present world market for PV products. In the recent years, production of solar cells has been growing by 30% a year, reaching almost 400MW in 2001. Perhaps the most exciting new application has been the integration of solar cells into the roofs and facades of buildings during the last decade of the 20th century providing a new, distributed, form of power generation. Today, the industry's production of PV modules is growing at approximately 25 percent annually, and rapidly accelerating the implementation of PV systems on buildings and interconnection to utility Networks [12].

Solar systems begin with the solar module. Modules gather solar energy in the form of sunlight and convert it into direct current (DC) electricity. The more sunlight they receive, the more electricity they produce. Solar modules are the heart of the system. They are the power generators. Thin-film photovoltaic modules are manufactured by depositing ultra-thin layers of semiconductor material on a glass or thin stainless-steel substrate in a vacuum chamber. A laser scribing process is used to separate and weld the electrical connections between individual cells in a module. Thin-film photovoltaic materials offer great promise for reducing the materials requirements and manufacturing costs for PV modules and systems. Photovoltaic systems have a number of merits and unique advantages over conventional power-generating technologies. PV systems can be designed for a variety of applications and operational requirements, and can be used for either centralized or distributed power generation. PV systems have no moving parts, are modular, easily expandable and even transportable in some cases. Energy independence and environmental compatibility are two attractive features of PV systems. The fuel (sunlight) is free, and no noise or pollution is created from operating PV systems. In general, PV systems that are well designed and properly installed require minimal maintenance and have long service lifetimes. At present, the high cost of PV modules and equipment (as compared to conventional energy sources) is the primary limiting factor for the technology. Consequently, the economic value of PV systems is realized over many years. In some cases, the surface area requirements for PV arrays may be a limiting factor. Due to the diffuse nature of sunlight and the existing sunlight to electrical energy conversion efficiencies of photovoltaic devices, surface area requirements for PV array installations are on the order of installed peak array capacity [13].

The aim of this thesis is to assembled information from numerous sources to provide an objective overview of photovoltaics for power generation. I present the reader with a summary of the basics of photovoltaic power conversion, list the primary technologies, describe the most popular applications, and list manufacturers and organizations involved in photovoltaic power generation. This study also investigates the efficiency of the BIPV and the variation of electrical power generation from the PV system during 1 year. It is concluded that the yearly average efficiency of the sunshade solar panel is 12.7% (average over 27.6 ^{o}C surface temperature), with a minimum of 4.2% (average over 12.6 ^{o}C surface temperature) in January and a maximum of 20.4% (average over 45.2 ^{o}C surface temperature) in July.

CHAPTER 2

PHOTOVOLTAICS

2.1 Introduction

Photovoltaics is a high-technology approach to converting sunlight directly into electrical energy. The electricity is direct current and can be used that way, converted to alternating current or stored for later use. Conceptually, in its simplest form a photovoltaic device is a solar-powered battery whose only consumable is the light that fuels it. There are no moving parts; operation is environmentally benign; and if the device is correctly encapsulated against the environment, there is nothing to wear out. Because sunlight is universally available, photovoltaic devices have many additional benefits that make them usable and acceptable to all inhabitants of our planet. Photovoltaic systems are modular, and so their electrical power output can be engineered for virtually any application, from low-powered consumer uses-wristwatches, calculators and small battery chargers-to energy-significant requirements such as generating power at electric utility central stations (see figure 2. 1).

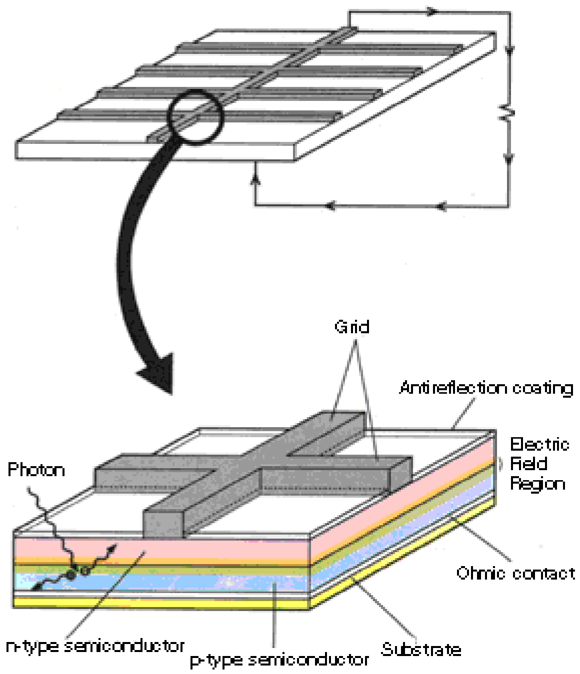

Figure 2.1 Grid contact structure.

Moreover, incremental power additions are easily accommodated in photovoltaic systems, unlike more conventional approaches such as fossil or nuclear fuel, which require multimegawatt plants to be economically feasible. To understand the many facets of photovoltaic power, one must understand the fundamentals of how the devices work. Although photovoltaic cells come in a variety of forms, the most common structure is a semiconductor material into which a large-area diode, or p-n junction, has been formed. The fabrication processes tend to be traditional semiconductor approaches-diffusion, ion implantation and so on. Electrical current is taken from the device through a grid contact structure on the front that allows the sunlight to enter the solar cell, a contact on the back that completes the circuit, and an antireflection coating that minimizes the amount of sunlight reflecting from the device. See Figure 2. 2

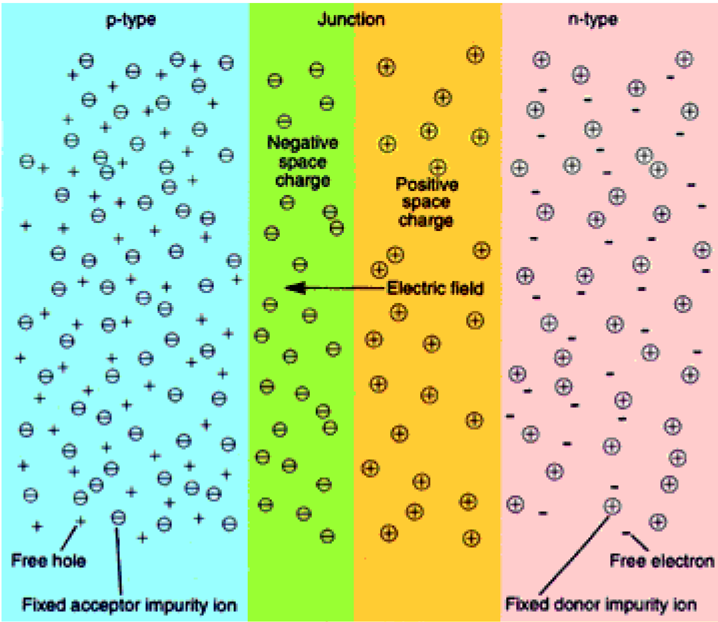

Figure 2.2 A schematic depiction of a rudimentary solar cell that shows the important features.

The fabrication of the p-n junction is key to successful operation of the photovoltaic device (as well as other important semiconductor devices). It will be assumed that the semiconductor material is single-crystal silicon. Although photovoltaic technologists today use many other varieties of semiconductors, crystalline-silicon concepts represent a reasonable compromise for this discussion because they are well known and understood by physics students [14].

Silicon is representative of the diamond crystal structure. Each atom is covalently bonded to each of its four nearest neighbors; that is, each silicon atom shares its four valence electronic with the four neighboring atoms, forming four covalent bonds. The valence band has 4N availability energy states and 4N valence electrons and is therefore filled. Conversely, the conduction band is completely empty at absolute zero. Thus the semiconductor is a perfect insulator at absolute zero. As the temperature of the solid is raised above absolute zero, energy is transferred to the valence electrons, making it statistically probable that a certain number of the electrons will be raised in energy to such an extent that they are free to conduct electrical charge in the conduction band. These electrons are called intrinsic carriers. The amount of energy necessary to bridge the valence and conduction bands is referred to as the forbidden gap or energy gap E_g, which is 1.12 eV at room temperature for silicon. Even at room temperature, however, the amount of conductivity is still quite small. At 300 K there are 1.6 x 10^{10} intrinsic carriers per cubic centimeter; thus the material is still a very good insulator compared with a metal, which has approximately 10^{22} carriers per cubic centimeter. To modify the conductivity to more useful values, one must introduce small controlled amounts of impurities into the host materials. By substituting, or "dopping," the silicon, which is in column IV of the periodic table, with either column-III materials (boron, aluminum, gallium or indium) or column-V materials (phosphorous, arsenic or antimony), one can increase and control precisely the number of conduction band electrons or valence band holes (deficiencies of electrons). A column-V dopant completes the covalent bond and leaves an additional, loosely bound electron that can be transferred to the conduction band by an energy of about 40-50 meV, termed the ionization energy. Column-III impurities leave the covalent bond deficient of one electron (that is, with a hole). An electron from the valence band can transfer to the empty site and satisfy the bond requirement. In effect the hole moves, because the transferred electron leaves behind a hole. The amount of energy required to thus place the hole in the valence band ranges from 45 to 160 meV. By varying the density of the doping impurities, one can design the silicon to range from a poor conductor of electricity to a near-metallic conductor. Silicon that has been doped with column-III elements is called a p-type semiconductor; that doped with column-V elements is called an n-type semiconductor [15].

2.2 The p-n junction diode

When a uniform p-type sample is metallurgically joined to a uniform n-type sample, the configuration produces the all-important p-n junction. Instantaneously the positive and negative electrical charges redistribute, establishing internal electric fields that determine, in part, the properties of the semiconductor diode. At the instant of formation, there exist on the n side, extending to the junction, uniform concentrations n_{n0} of mobile free electrons and p_{n0} of mobile free holes. On the p side there exist uniform concentrations of p_{p0} of mobile holes and n_{p0} of free electrons, also extending to the junction. The concentrations satisfy the relation

$$n_{n0}\,p_{n0} = n_{p0}\,p_{p0} = n_i^2 \qquad (2.1)$$

Here n_i is the intrinsic-carrier concentration at the given temperature of the material.

At the instant of junction formation, the concentration of electrons is much larger on the n side than on the p side. An analogous condition applies to the hole concentrations, which are larger on the p side than the n. The large difference in carrier concentrations sets up an initial diffusion current: Electrons flow from the n region into the p region, and holes flow from the p region into the n region. This flow of charge results in a region near the junction that is depleted of majority carriers-that is, of electrons on the n side and of holes on the p side. The fixed donor and acceptor impurity ions in this depletion region are no longer balanced by the free charges that were there. As a result, an internal electric field builds up with a direction that opposes further flow of electrons from the n region and holes from the p region. The magnitude of the field is such that it exactly balances the further flow of majority carriers by diffusion. The region around the junction is depleted of majority carriers, and a space-charge layer forms in the region of high electric fields, as shown in figure 2.2. Thus in the absence of externally applied potentials, no current will flow.

Contact can be made with the two ends of the p-n junction to form a two-terminal device. A positive voltage applied to the p side relative to the n side encourages current flow across the junction. Conversely, a negative voltage applied to the p side relative to the n side further discourages current flow relative to the zero-voltage case. The former condition is referred to as forward bias and the latter as reverse bias. These two conditions can best be described in terms of the ideal-diode equation:

$$I = I_0\,[\exp(qV / kT) - 1.0] \qquad (2.2)$$

Here I is the external current flow, I_0 is the reverse saturation current, q is the fundamental electronic charge of 1.602×10^{-19} coulombs, V is the applied voltage, k is the

Boltzmann constant, and T is the absolute temperature. Under large negative applied voltage (reverse bias), the exponential term becomes negligible compared to 1.0, and I is approximately $-I_0$. I_0 is strongly dependent on the temperature of the junction and hence on the intrinsic-carrier concentration. I_0 is larger for materials with smaller bandgaps than for those with larger bandgaps. The rectifier action of the diode-that is, its restriction of current flow to only one direction-is key to the operation of the photovoltaic device.

If light is allowed to impinge on a p-n junction device, the equilibrium conditions of the device are disturbed. Minority carriers-that is, electrons in the p material and holes in the n material-are created in sufficient quantities to lower the potential energy barrier at the junction, allowing current to flow and establish a voltage at the external terminals. The availability of current and voltage produces usable power.

As shown in figure 2.3 , the photovoltaic device can be modeled as an ideal diode in parallel with a light-induced current generator I_L, whose magnitude is a function of the generation of electron-hole pairs by the absorption of incoming light and the collection efficiency for these charge carriers. The current and voltage characteristics are modified by light to

$$I = I_0 [\exp (qV / kT) - 1.0] - I_L \tag{2.3}$$

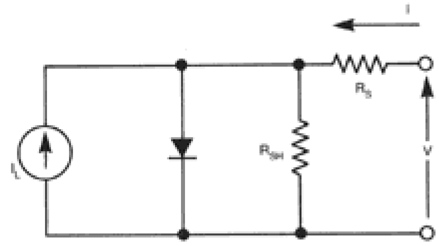

Figure 2.3 Circuit of the solar cell.

There will be resistive losses due to series and shunt resistance. A current-voltage diagram, like that in figure 2.3 characterizes the important operational parameters of the cell, among which are the short-circuit current Isc, the open-circuit voltage Voc, and the current and voltage at the maximum power point [16].

2.3 Performance Efficiency

Because of its importance for describing and comparing the performances of photovoltaic devices, efficiency must be measured carefully. In the past, and to a certain extent even today, efficiency results have been controversial. The most important factor affecting the accuracy of the efficiency measurements is the light source used to illuminate the cell. One typically uses a light source that has a carefully controlled spectrum. This so-called solar simulator must be accurately duplicated by each group hoping to make the measurement, or critical correction factors must be applied that take into account a number of factors characterizing the differences in spectral quality among the various solar simulators.

For each photovoltaic material the simulator must duplicate what the cell experiences in the real world under natural sunlight. Control solar cells, or standards, can be very helpful in correcting for the material differences. Additionally, one must accurately know and be able to duplicate from measurement to measurement the intensity of the light and the junction temperature. Another critical factor in determining the accuracy of an efficiency measurement is the definition of the area of the cell, as the short-circuit current measurement is strongly dependent on the cell area. Much discussion has gone into determining whether the total area, the active area or the aperture area should be used. The active area is used only with small, laboratory-scale devices. Aperture and total--area standards are used with commercial-sized cells and modules.

2.4 Photovoltaic cell materials

Single-crystal silicon has been the material of choice for high-performance, highly reliable solar cells since the successful deployment of silicon photovoltaic systems for space power. Most of the terrestrial photovoltaic power systems sold today are also crystalline silicon. The need to lower the cost of terrestrial photovoltaic power has focused research efforts on alternative materials as well as on less expensive means of producing solar-grade silicon.

Crystalline silicon is made by growing large cylindrical single crystals, called boules. The boules are sliced into thin wafers, from which photovoltaic devices are made. Slicing is an expensive and material-wasteful process. Several approaches have been investigated to minimize the cost of the original silicon material and to eliminate the slicing step.

A less expensive material, polycrystalline silicon, by passes the expensive and energy-intensive crystal growth process. The molten silicon is instead cast directly into either cylindrical or rectangular ingots. The polycrystalline material has a large number of crystallites separated by grain boundaries. The material has poorer crystalline quality, and light-induced electron-hole pairs can recombine at the grain boundaries without producing current in the external circuit. Although polycrystalline materials result in less efficient solar cells than crystalline silicon, they are sufficiently cheaper that they are commercially viable. The cast material must still be sliced, however, leading to a loss of about half of the material. Improvements in sawing techniques such as multiple-wire saws continue to reduce the loss in producing thinner wafers.

Another approach to producing less costly materials is to avoid most of the sawing altogether. Several techniques that produce silicon in sheet form have been developed. The first commercial success was the edge-defined film-fed growth (EFG) ribbon process, in which polycrystalline silicon is grown by extracting the crystallizing silicon melt through a graphite die. By this technique, thin ribbons of polycrystalline silicon can be grown either as multiple separate ribbons or as polygons of material that can be separated into silicon blanks for fabrication into finished solar cells with minimal loss of material. An alternative approach has been to grow the ribbon from parallel supporting dendrites (like a soapy water film grown between two wires). By carefully controlling the thermal profiles, one can grow a film of nearly single-crystal material. Other techniques, such as horizontal ribbon growth and spin casting, have also been demonstrated. Regardless of the approach, ultimately the cost of silicon solar cells will depend on the starting material.

The lowest-cost approach would be to minimize the required amount of semiconductor material. Thin films have been developed that are only a few micrometers thick. Such films are produced by a number of vapor-deposition approaches carried out with in-line, highly automated systems. The techniques are adaptable to a number of semiconductor materials that are optimized for solar cell operation. It has been shown that silicon, with its bandgap of 1.12 eV, is not optimal. Materials with bandgaps nearer to 1.5 eV, such as GaAs and CdTe, have higher theoretical efficiencies. Thin films are cheaper than crystalline structures but typically have lower efficiencies. Ultimately, however, thin films will be necessary for producing low-cost electricity, because the bottom line-the cost per watt-is more important than efficiency.

2.5 Economics of photovoltaics

For photovoltaics to be widely used, the costs must be competitive with those of conventional forms of electricity. In the US, the average price for electricity if 6-7 cents per kilowatt-hour. Today photovoltaics generate electricity at 20-30 cents per kilowatt hour; therefore the costs must come down by about a factor of 5 to compete in the bulk electricity market.

A number of factors influence photovoltaic energy costs. Foremost are the module efficiency, lifetime and cost per unit area. The US Department of Energy chose a target of 6 cents per kilowatt-hour for its terrestrial photovoltaic program. the interrelationships of cost and module efficiency that lead to specific electricity costs, given a 30-year lifetime for the module and making a number of economic assumptions. From these curves it is clear that lower-efficiency modules have to cost less than higher-efficiency modules to produce the same cost of electricity. Hence there is a premium on higher efficiency. Similar curves exist for concentrator systems, but higher efficiencies are required to offset the higher balance-of-system costs associated with the necessary lenses or mirrors and Sun trackers. In both cases, efficiency can be traded off against area-related costs (such as land, wire and support structure) to achieve the same cost of electricity.

The annual worldwide commercial production of photovoltaics amounts to about 60 MW, divided approximately equally amount the US, Japan and the European Community. Most of the markets are of the high-value variety-that is, markets where today's photovoltaic systems are competitive with traditional ways of providing electrical power. These applications are largely remote from the electrical grid, serving such needs as water pumping, remote communication, refrigeration, signal lights, emergency lighting, pipeline corrosion protection and village power. The competition typically is with diesel generators and with extension of electrical transmission lines. The cost of grid extension is such that if a power requirement lies more than about half a kilometer from the electrical line, photovoltaics will be cost-effective compared with the line extension.

As the cost of photovoltaic systems declines, the number of cost-effective applications increases. The ultimate application, bulk electrical power generation, is expected to occur within the next 10 to 20 years, when photovoltaics decline the price below about 10 cents per kilowatt hour. Various utility niche markets are expected to grow before these large-power markets do.

Market growth will be tied to the continuing decline in photovoltaic costs relative to conventional supplies. The industry will need to build larger, more cost-effective production plants that take advantage of available economies of scale. Investment in these new, large plants will require identification of sustainable markets. Many high-value applications taken together, including international rural electrification projects, could provide the necessary market pull [17].

CHAPTER 3

SEMICONDUCTOR SOLAR CELLS

3.1 Solar cell operation

The operation of a semiconductor solar cell will be illustrated on the example of a p-n junction under illumination. The p-n junction is effectively an interface between n and p type semiconductors: in other words, semiconductor where excess electrons and holes have been introduced by the addition of impurities. The fundamental characteristic of the junction is the presence of a strong electric field, indicated by the slope of the edges of the conduction and valence band in the junction region Fig.3.1.

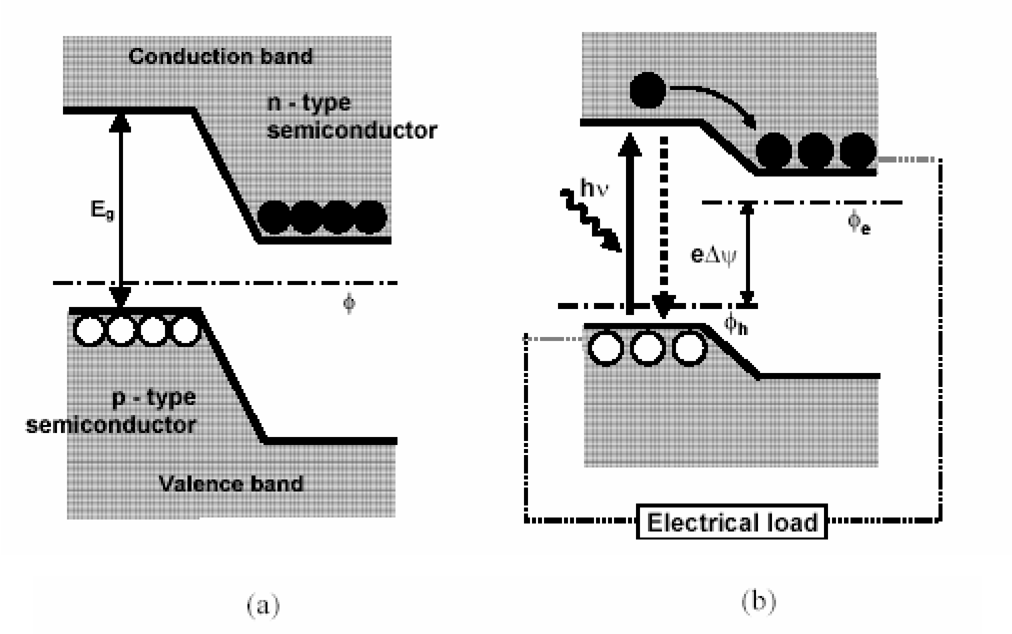

Figure 3.1 Semiconductor p-n junction in equilibrium (a) and under illumination (b).

In equilibrium, the electrochemical potentials on the two sides of the junction are equal, and there is no net electric current. Under illumination, electron-hole pairs are generated in the semiconductor, and are subsequently separated by the electric field of the junction (see Fig.3.1) with the bandgap of the semiconductor E_g playing the role of the excitation energy.

$$I = I_l - I_0 \left[e^{qV/kT} - 1\right] \qquad (3.1)$$

The resulting I-V characteristic is shown in figure 3.2. The photogenerated current I_l is equal to the current produced by the cell at short circuit (V=0). The open circuit voltage V_{oc} (when I=0) can easily be obtained as

$$V_{oc} = \frac{kT}{q} \ln[1 + I_1 / I_0] \tag{3.2}$$

No power is generated under short or open circuit. The maximum power P produced by the conversion device is reached at a point on the characteristic where the product IV is maximum. This is shown graphically in Fig. 3.2 where the position of the maximum power point represents the largest area of the rectangle shown. One usually defines the fill-factor ff by

$$ff = \frac{P_{max}}{V_{oc}} = \frac{V_m I_m}{V_{oc} I_l} \tag{3.3}$$

where V_m and I_m are the voltage and current at the maximum power point.

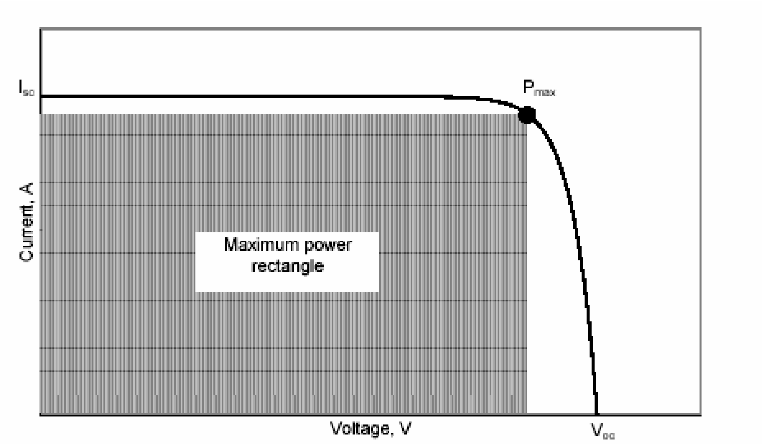

Figure 3.2 The I-V characteristic of an ideal solar cell.

The principal difference between a semiconductor solar cell in the nature of optical absorption of the semiconductor which occurs in a broad spectral range rather than in a narrow spectral line. Indeed, a sufficiently thick slab may absorb all photons with energy in excess of the semiconductor bandgap E_g [18].

3.2 Structure of solar cells

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 millimetre 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.

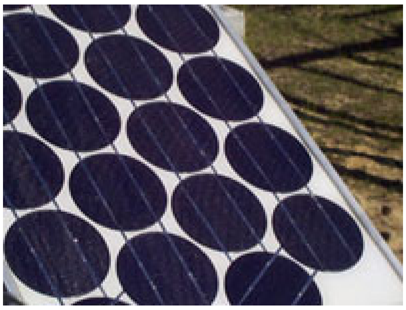

Figure 3.3 Single Crystal solar cells in panel.

Figure 3.4 Amorphous-Si solar panel.

Crystalline silicon cells dominate the photovoltaic market. To reduce the cost, these cells are now often made from multicrystalline material, rather than from the more expensive single crystals. Crystalline silicon cell technology is well established. The modules have long lifetime (20 years or more) and their best production efficiency is approaching 18%. See figure 3.3. Amorphous silicon solar cells are cheaper (but also less efficient) type of silicon cells, made in the form of amorphous thin films which are used to power a variety of consumer products but larger amorphous silicon solar modules are also becoming available. See figure 3.4. Cadmium telluride and copper indium diselenide thin-film modules are now beginning to appear on the market and hold the promise of combining low cost with acceptable conversion efficiencies. High-efficiency solar cells from gallium arsenide, indium phosphide or their derivatives are used in specialised applications, for example, to power satellites or in systems which operate under high-intensity concentrated sunlight.

The structure of a typical silicon solar cell is illustrated in Fig.3.5. The electrical current generated in the semiconductor is extracted by contacts to the front and rear of the cell. The top contact structure which must allow light to pass through is made in the form of widelyspaced thin metal strips (usually called fingers) that supply current to a larger bus bar (Transparent conducting oxide is also used on a number of thin film devices). The cell is covered with a thin layer of dielectric material - the antireflection coating, ARC – to minimise light reflection from the top surface.

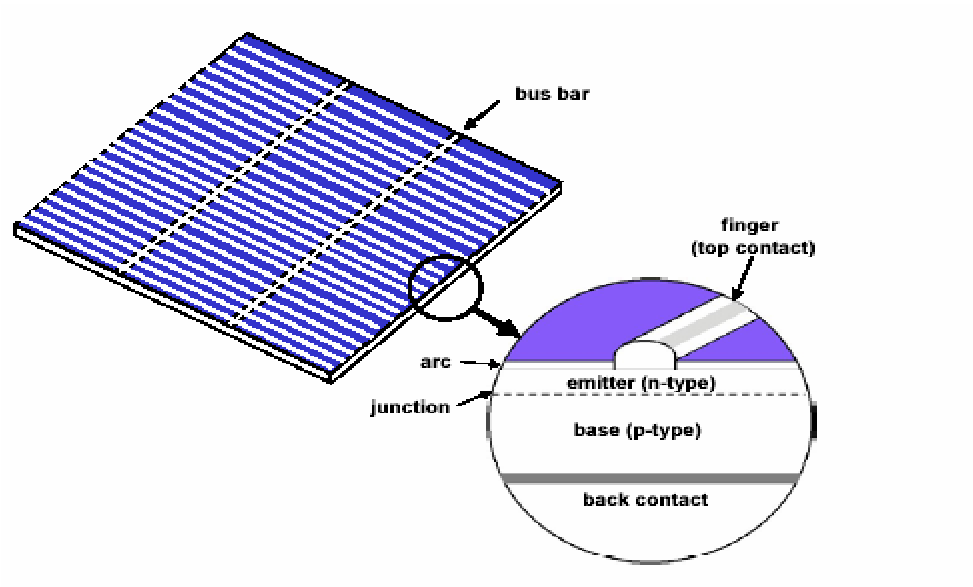

Figure 3.5 The structure of a typical crystalline silicon solar cell.

The energy conversion process in solar cells is very different from the operation of the classical heat engine, and it is instructive to consider the limitations and losses that occur in more detail. The fundamental mechanisms responsible for losses in solar cells are apparent from the discussion of solar cell operation earlier in this section: heat is produced on carrier generation in the semiconductor by photons with energy in excess of the bandgap, and a considerable part of the solar spectrum is not utilised because of the inability of a semiconductor to absorb the below-bandgap light. These losses can be reduced, but only going over to more complex structures based on several semiconductors with different bandgaps. A device called tandem cell, for example, represents effectively a stack of several cells each operating according to the principles that we have just described. The top cell is made of a high-bandgap semiconductor, and converts the short-wavelength radiation. The transmitted light is then converted by the bottom cell. This arrangement increases considerably the achievable efficiency: high efficiency space cells operating at close to 30% are now commercially available. There are also amorphous silicon cells where a double or triple stack is used to boost the low efficiencies of single-junction devices and reduce the degradation which is observed in these materials.

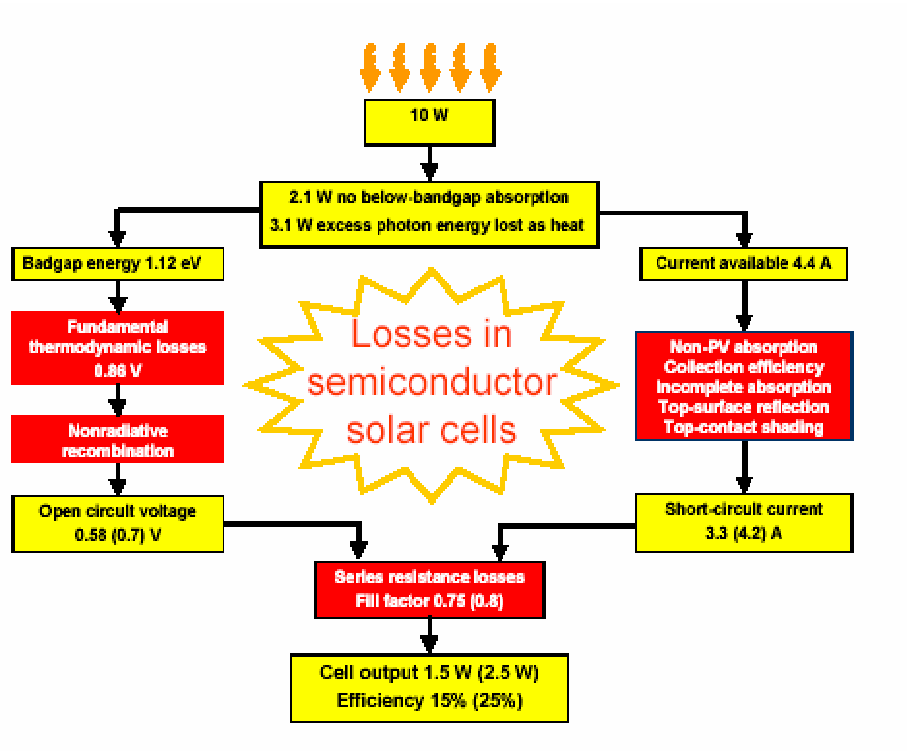

Figure 3.6 The various losses in a semiconductor solar cell, shown here on the example of 100x100mm monocrystalline silicon cell. Figures are for production cells; best experimental values in are in brackets.

Other losses reduce the typical efficiency of commercial devices to roughly 50% of the achievable maximum (Fig. 3.6), somewhat less in thin-film devices. A ubiquitous loss mechanisms present in all practical devices is non-radiative recombination of the photogenerated electron-hole pairs. Such recombination is most common at impurities and defects of the crystal structure, or at the surface of the semiconductor where energy levels may be introduced inside the energy gap. These levels act as stepping stones for the electrons to fall back into the valence band and recombine with holes. An important site of recombination are also the ohmic metal contacts to the semiconductor. Measures taken to minimise the recombination losses include careful processing to maintain long minority-carrier lifetime, and protecting the external surfaces of the semiconductor by a layer of passivating oxide to reduce surface recombination. The contacts can be surrounded by heavily-doped regions acting as "minority-carrier mirrors" which impede the minority carriers from reaching the contacts and recombining. The losses to current by recombination are usually grouped under the term of collection efficiency: the ratio between the number of carrier generated by light and the number that reaches the junction. Considerations of the collection efficiency affect the design of the solar cell. In crystalline materials, the transport properties are usually good, and carrier transport by simple diffusion is sufficiently effective. In amorphous and polycrystalline thin films, however, electric fields are needed to pull the carriers. The junction region is then made wider to absorb the main part of the photon flux. Other losses to the current produced by the cell arise from light reflection from the top surface, shading of the cell by the top contacts, and incomplete absorption of light. The last feature can be particularly significant for crystalline silicon cells since silicon – being an indirect-gap semiconductor - has poor light absorption properties. Measures which can be taken to reduce these losses include the use of multi-layer antireflection coatings, surface texturing to form small pyramids, and making the back contact optically reflecting. When combined with a textured top surface, this geometry results in effective light trapping which provides an good countermeasure for the low absorptivity of silicon. Top-contact shading is reduced in some cells by forming these contacts in narrow laser grooves, or all the contacts can be moved to the rear of the cell. Another common loss in commercial cells involves ohmic losses in the transmission of electric current produced by the solar cell, usually grouped together as a series resistance, which reduce the fill factor of the cell. The principal characteristics of different types of cell in or near commercial production are summarised in table 3.1.

Material	Commerical products	Best R&D	Technology
Mono-or multi-cryst. silicon	10-18	25	İngot/wafer
Amorphous silicon	5-8	13	Thin film
Copper indium diselenide	8	16	Thin film
Cadmimium telleride	7	16	Thin film

Table 3.1. Solar cell efficiencies achieved by the principal semiconductor technologies.

In addition to crystalline silicon, much effort is focused on the manufacture of thin-film devices which have lower material requirements. On the example of dye sensitised solar cell, that photovoltaic materials are no longer restricted to semiconductors. Furthermore, there is considerable research activity into purely molecular materials. A number of research groups have demonstrated solar cells based on conducting polymers, often in combination with fulerene derivatives as electron acceptors to create the p-n junction. There is much to look forward to if their success matches the achievements of the LED technology.

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. As polycrystalline wafers are made by casting they are significantly cheaper to produce, but not as efficient as monocrystalline cells. The lower efficiency is due to imperfections in the crystal structure resulting from the casting process.

Almost half the silicon is lost as saw dust in the two processes mentioned above. Amorphous silicon, one of the thin film technologies, is made by depositing silicon onto a glass substrate from a reactive gas such as silane (SiH_4). 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 [19].

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

3.3 Work principle of solar cells

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 ionise 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. Therefore if a circuit is made, 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.

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

* the type and area of the material;
* the intensity of the sunlight; and
* the wavelength of the sunlight.

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

Polycrystalline silicon solar cells have an efficiency of less than 20% at this time and amorphous silicon cells, are presently about 10% efficient, due to higher internal energy losses than single crystal silicon. A typical single crystal silicon PV cell of 100 cm^2 will produce about 1.5 watts of power at 0.5 volts DC and 3 amps under full summer sunlight ($1000Wm^{-2}$). The power output of the cell is almost directly proportional to the intensity of the sunlight. (For example, if the intensity of the sunlight is halved the power will also be halved).

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

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

Other types of PV materials which show commercial potential include copper indium diselenide ($CuInSe_2$) and cadmium telluride (CdTe) and amorphous silicon as the basic material [18].

CHAPTER 4

PHOTOVOLTAIC PANEL

4.1 Categories of 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:

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

2. 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.

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

4.2 System design

For practical use, solar cells are laminated and encapsulated to form photovoltaic modules. These are then combined into arrays, and interconnected with other electrical and electronic components – for example, batteries, charge regulators and inverters – to create a photovoltaic system. A number of issues need to be resolved before an optimum system design is achieved. These issues include the choice between a flat plate or concentrating system, and whether fixed tilt will be used or the modules will 'track' the sun. Answers to these questions will vary depending on the solar radiation at the site of the installation and its variation during the year. Specific issues also relate to whether the system is to be connected to the utility supply (the 'grid') or is intended for stand-alone operation.

Most photovoltaic arrays are installed at fixes tilt and, wherever possible, oriented towards the equator. The optimum tilt angle is usually determined by the nature of the application. Arrays which are to provide maximum generation over the year (for example, some grid-connected systems) should be inclined at an angle equal to the latitude of the site. Stand-alone systems which are to operate during the winter months have arrays inclined at a steeper angle of latitude + 15^0 If power is required mainly in summer (for example, for water pumping and irrigation), the guide inclination is latitude – 15^o.

The amount of solar energy captured can be increased if the modules track the sun. Full two-axis tracking, for example, will increase the energy available by almost 40% over a non-tracking array fixed at the angle of latitude - at the expense, however, of increased complexity. Single axis tracking is simpler but yields a smaller gain. Tracking is particularly important in systems which use concentrated sunlight. These systems can partially offset the (high) cost of solar cells by the use of inexpensive optical elements (mirrors or lenses). The cells, however, then usually need to be cooled and it should also be borne in mind that only the direct (beam) solar radiation can be concentrated to a significant degree, thus reducing the available energy input. This effectively restricts the application of concentrator systems to regions with high amounts of solar radiation and clear skies.

There is a considerable difference between the design of stand alone and grid connected systems. Much of the difference stems from the fact that the design of stand-alone systems endeavours to make the most of the available solar radiation. This consideration is less important when utility supply is available, but the grid connection imposes its own particular issues which must be allowed for in the system design [20].

4.2.1 Stand-alone systems

PV systems are ideally suited for applications in isolated locations. An important parameter in these application is the required security of supply. Telecommunication and systems used for marine signals, for example, need to operate at a very high level of reliability. In other applications, the user may be able to tolerate lower reliability in return for a lower system cost. These considerations have an important bearing on how large PV array and how large energy storage (battery) should be installed, in other words, on system sizing. Among the variety of sizing techniques, sizing based on energy balance provides a simple and popular technique which is often used in practice. It gives a simple estimate of the PV array necessary to supply a required load, based on an average daily solar irradiation at the site of the installation, available now for many locations in the world. Choosing the month with the lowest irradiation (usually December in northerly latitudes), one can determine the solar radiation incident on the inclined panel, and the array size can be found from the energy balance equation:

Array size (in Wp) = Daily energy consumption \ Daily solar radiation (4.1) where the Daily solar radiation should be equated to the Peak Solar Hours in specifies how many PV modules need to be installed to supply the load under average conditions of solar irradiation. The battery size is then estimated ‘from experience’ – a ‘rule of thumb’ recommends, for example, installing 3 days of storage in tropical locations, 5 days in southern Europe and 10 days or more in the UK. Other sizing methods include the elegant random walk method (Bucciarelli,1984) which treats the possible states of charge of the battery as discrete numbers which are then identified as sites for a random walk. Each day, the system makes a step in the ransom walk depending on solar radiation: one step up if it is ‘sunny’ and one step down if it is ‘cloudy’. Bucciarelli (1986) subsequently extended this method to allow for correlation between solar radiation on different days. These and other more complex sizing techniques have been summarised by Gordon (Gordon, 1987).

PV installations not connected to a utility power line are referred to as ‘’stand-alone systems’’ The two basic types of stand-alone systems are : (1) direct systems, which utilize the PV electricity as it is produced, and (2) battery storage systems, which have the capability of storing PV generated electrical energy for use when the sun is not shining. Some stand – alone systems with battery storage include a DC to AC inverter to allow alternating current (AC) appliances to be used. AC appliances are generally cheaper and more readily available.

An example of a direct system is a water pumping facility which pumps water during the (suny) day to a storage tank for later use. A battery storage system. On the other hand, stores PV electricity in a battery to power an electricial device (e.g. a light, a pump) even when the sun is not shining.

The range of applications for stand-alone systems is a tremendous. Whenewer the economics of providing electricitiy from the utility grid are in question, photovoltaics should be considered. Examples of situatiıons where the economics of grid power are question are (1) when the utility monthly facilities charge (meter charge) is a majority of a monthly electric Bill, (2) when electricity is a needed far away from a utility distrubution line or (3) where hard surfaces such as parking lots or sidewalks are between a proposed electrical load and a utility connection

For remote or portable large power needs (greater than 500 wats), it has been common to use gasoline, propane, or diesel powered generetors. Associated with this option is the high cost of maintenance, as well as the purchase and transportation of fuel.

With low maintanence costs and no fuell requirements, PV is an ideal source of power for remote or portable applications.

It is also possible to couple a PV system with a fosil-fuel generatör. İn this type of system, the generator is used to recharge the PV battery system during long periods of cloudy weather. This ''hybrid'' system requires much less fuel and maintenance for the generator, while extending battery life [21].

4.2.2 Utility-interactive Systems

Unlike stand-alone systems, utility-interactive systems are connected to the electrical utility grid. These systems are typically located on residential or commercial buildings. The house pictured in Figure 4.1. has a utility-interactive PV system. These systems have a PV array that supplies power to the building throught a high quality inverter. This inverter converts PV-generated DC electricity compatible with the utility grid. This AC electricity is supplied to the main electrical service of the building. Offsetting the purchase of power from the utility grid. When the PV system is not generating as much power as the building is using, the utility grid provides the additional needed power. When the PV systems are generating more power than the building is using, excess power is sold into the utility grid.

Figure 4.1 Home Solar Cell.

Selling power back to an electric utility may not be as attractive as it sounds. Some utilities meter electrical energy purchased and sold seperately. Customers pay a retail rate for electricity purchased from the utility but are paid a lower avoided cost (wholesale) rate for electricity sold to a utility. There is usualy a significant difference between these two rates. Under current conditions it is much more cost effective to use a PV system to displace the need for utility power than to generate revenue with it. Until photovoltaic power becomes cheaper relative to utility power, utility-interactive systems should be sized so that very little power has to be sold back to utility.

A major benefit of utility-interactive PV is that it can be widely distributed. This asset will lead to the installation of many small scale "distributed generation" power plants located on buildings. Over time, this could reduce the need for additional large centralized power plant construction and costly utility grid distribution network expansion. The nature of distributed generation can increase national energy security by increasing the number of power plants that would have to be targeted in order to shut down the national utility grid. Other examples of distributed generation technologies are wind turbines, fuel cells and micro turbines.

Another benefit of utility-interactive PV systems is that they produce electrical power when the sun is shining strongest and the electrical utility grid needs it the most. They produce the most electrical power when the demand on the electrical utility grid is highest due to building air conditioning. This benefit is currently not well rewarded but may be in the future through the use of solar load control devices, demand management systems and real time pricing scenarios.

4.2.3 Grid-connected systems

Grid connected systems (see figure 4.2) have grown considerably in number since the early 1990s spurred by Government support programmes for 'photovoltaics in buildings' in a number of countries, led initially by Switzerland and followed by more substantial programmes in Germany and Japan. One feature that affects the system design is the need for compliance with the relevant technical guidelines to ensure that the grid connection is safe; the exported power must also be of sufficient quality and without adverse effects on other users of the network. Many of the grid connection issues are not unique to photovoltaics. They arise from the difficulties trying to accommodate 'embedded' or distributed generators in an electricity supply system designed around large central power stations. It is likely that many of these features of grid connection will undergo a review as electricity distribution networks evolve to absorb a higher proportion of distributed generators: wind farms, co-generation units, or other local energy sources.

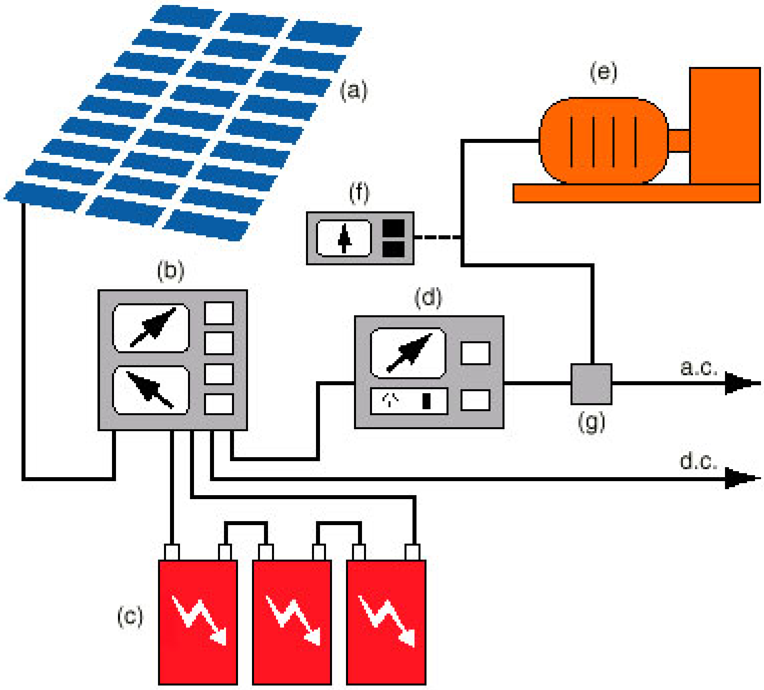

Figure 4.2 Grid connected systems.

The electricity supply system in twenty or thirty years time might be quite different from now, and new and innovative integration schemes will be needed to ensure optimum integration. Photovoltaic generators are likely to benefit from these changes, particularly from the recent advances in the technology of small domestic size co-generation units which have a good seasonal synergy with the energy supply from solar sources, and can share the cost of the grid interface [22].

4.3 Elements of a PV System

Building Integrated PV (BIPV) is the application of this technology into buildings by replacing conventional building materials. For example, in a BIPV project spandrel glass (in arch spaces), skylights, or roofing materials might be replaced with architecturally equivalent PV modules that serve the dual function of building skin and power generator As the builders are saving the costs of conventional materials it becomes more economical to buy and use photovoltaics. BIPV systems can either be tied to the available utility grid or they may be designed as stand-alone, off-grid systems. One of the benefits of grid-connected BIPV systems, is that on-site production of power is typically greatest at or near the time of a building's peak loads. This provides energy cost savings through peak shaving and demand-side-management (DSM) capabilities. For optimum BIPV integration, it is desirable to involve the architects, engineers, builders, utility and code officials, and users from the very earliest stages of the project. Because photovoltaic collection areas can be extensive, they can have a significant impact on building design.

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 Trackers are used to keep PV panels directly facing the sun, thereby increasing the output from the panels. Trackers can nearly double the output of an array. Careful analysis is required to determine whether the increased cost and mechanical complexity of using a tracker is cost effective in particular circumstances.

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. Backup or auxiliary power supplies are required when complete reliability of electricity supply must be guaranteed, when it is uneconomical to provide battery storage for infrequent extended cloudy periods, or when some appliances have large and intermittent power requirements that are uneconomical to meet from the PV system. 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 optimise the use of each component [23].

4.4 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. In these cases, PV systems are used, comprised of the following parts

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

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

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

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

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

- framework and housing for the system
- trackers and sensors (optional);

CHAPTER 5

THE SIMULATION AND MEASURED PERFORMANCE OF BUILDING INTEGRATED PHOTOVOLTAIC PANELS

5.1 Introduction

The incorporation of photovoltaics into buildings, referred to as building integrated photovoltaics (BIPV) offers an aesthetically pleasing means of displacing centrally located utility generated power with distributed renewable energy. Building integrated photovoltaics replace conventional building elements such as roof tiles, asphalt shingles, facade elements, and shading devices with photovoltaic modules that perform the same functions but also provide electrical power.

Building integrated photovoltaics, the integration of photovoltaic cells into one of more of the exterior surfaces of the building envelope, represents a small but growing photovoltaic application. In order for building owners, designers, and architects to make informed economic decisions regarding the use of building integrated photovoltaics, accurate predictive tools and performance data are needed. A building integrated photovoltaic test bed has been constructed at the National Institute of Standards and Technology to provide the performance data needed for model validation. The facility incorporates four identical pairs of building integrated photovoltaic panels constructed using single-crystalline, polycrystalline silicon film, and amorphous silicon photovoltaic cells.

5.2 Efficiency of Photovoltaic Cell Panels

The efficiency of the building integrated photovoltaic panels in converting the incident solar radiation into electrical energy is referred to as the conversion efficiency,

$$\eta_c = \frac{\int_0^{\tau} P_o d\tau}{A\int_0^{\tau} H_T d\tau} \qquad (5.1)$$

where A is a representative area, m^2, H_T is the incident solar radiation, W/m^2, P_o is the panels electrical power output, W and τ is the time interval selected for monitoring, h.

Unlike other variables in Eq. 5.1, the selection of an appropriate area is somewhat subjective for the building integrated photovoltaic panels. For example, the area of each cell within a panel times the number of cells yields an area referred to as the cell area. The aperture area is defined as the sunlit opening in the building wall prior to adding the sashing used for mounting the BIPV panels. A third area, as the coverage area, is defined as the portion of the panel covered by the cells including the areas associated with the spaces between cells.

Figure 5.1 gives the overall efficiency of the building integrated photovoltaic panel. There are two efficiencies plotted for each building integrated photovoltaic panel in figure 5.1. The bars in the foreground are computed using sunrise to sunset of the incident irradiance and power output. The background bars are the efficiencies of the

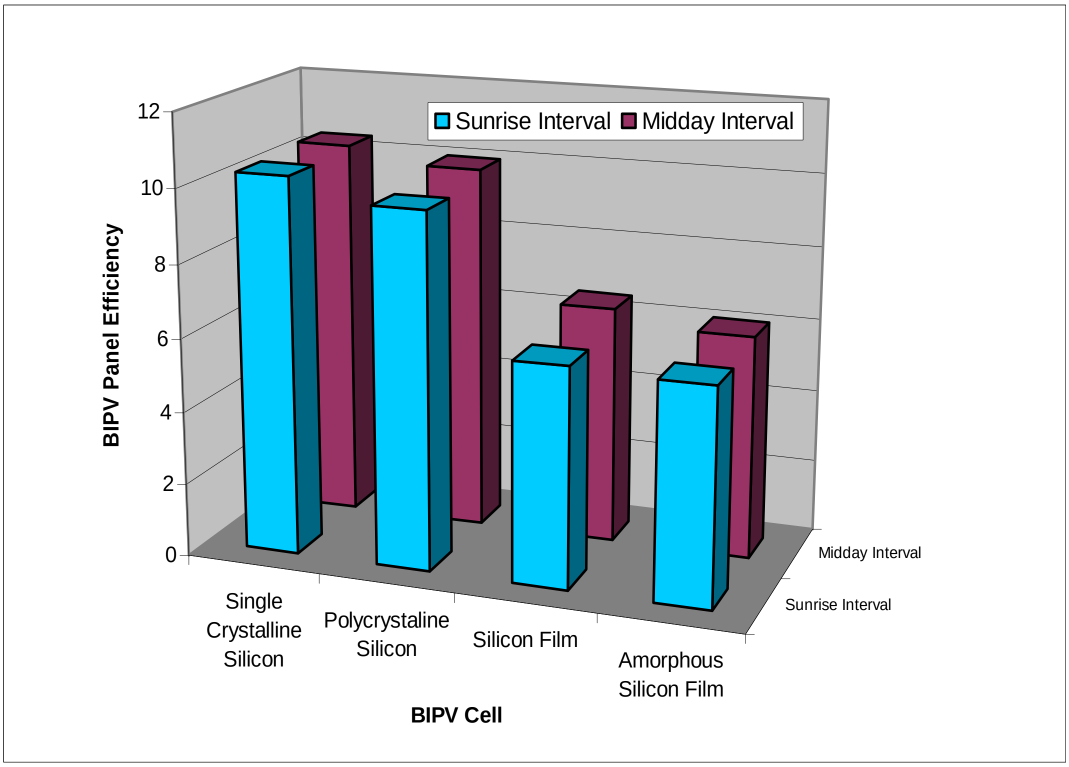

Figure 5.1 Overall BIPV Conversion Efficiency.

various panels computed only during the middle of each day when shading along the vertical sides of the panels.

The monthly building integrated photovoltaic conversion for the non-insulated panels is shown in figure 5.2. With the exception of the amorphous silicon panels, the highest conversion efficiency was obtained during the month of January. The monthly variation in efficiency is primarily attributed to variations in the incident angle, which varies from 27.4^{o} at solar noon on December 21 to a value of 74.3^{o} at solar noon on June 21. Variations in cell temperatures and shading on the cells due to the surrounding mullions are also responsible, to a lesser extent, for the monthly variations. It is interesting to note that the monthly conversion efficiencies of the amorphous silicon panels are relatively constant from month to month compared to the remaining panels. This behavior is attributed to the fact that amorphous silicon panels are less affected by the angle of incidence relative to the other cell technologies.

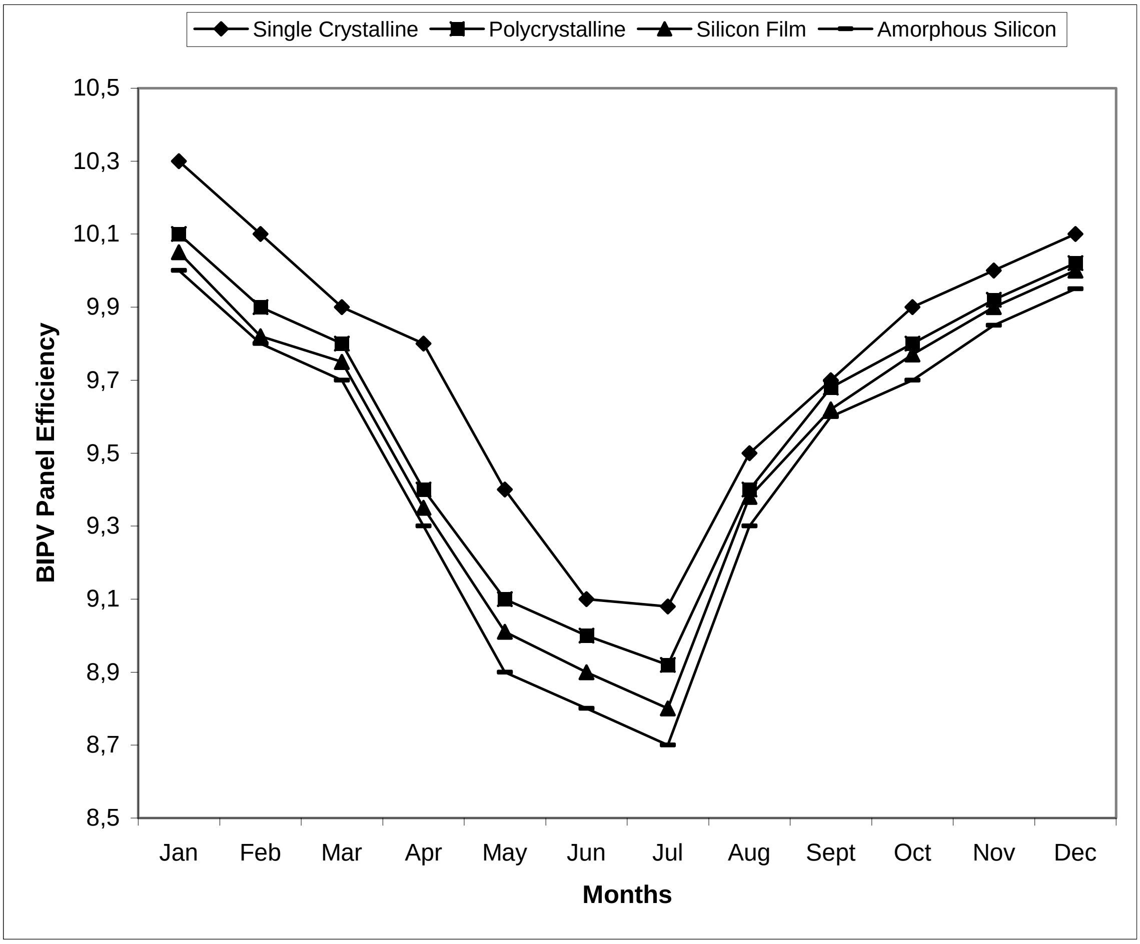

Figure 5.2 Monthly BIPV Conversion Efficiency - Sunrise/Sunset.

Figure 5.3 shows the monthly conversion efficiencies computed using only the data captured during the mid-day intervals. The monthly efficiency of the single-crystalline, polycrystalline, and silicon film panels decreases from January through March in a near linear manner. The amorphous silicon BIPV panel conversion efficiencies slightly increase during this time interval. After April, the efficiencies decline until June. The BIPV panel efficiencies for June and July are almost equivalent. During August all of the efficiencies improved relative to July. The efficiencies decrease slightly in September and, with the exception of the amorphous silicon panels, improve each month through December.

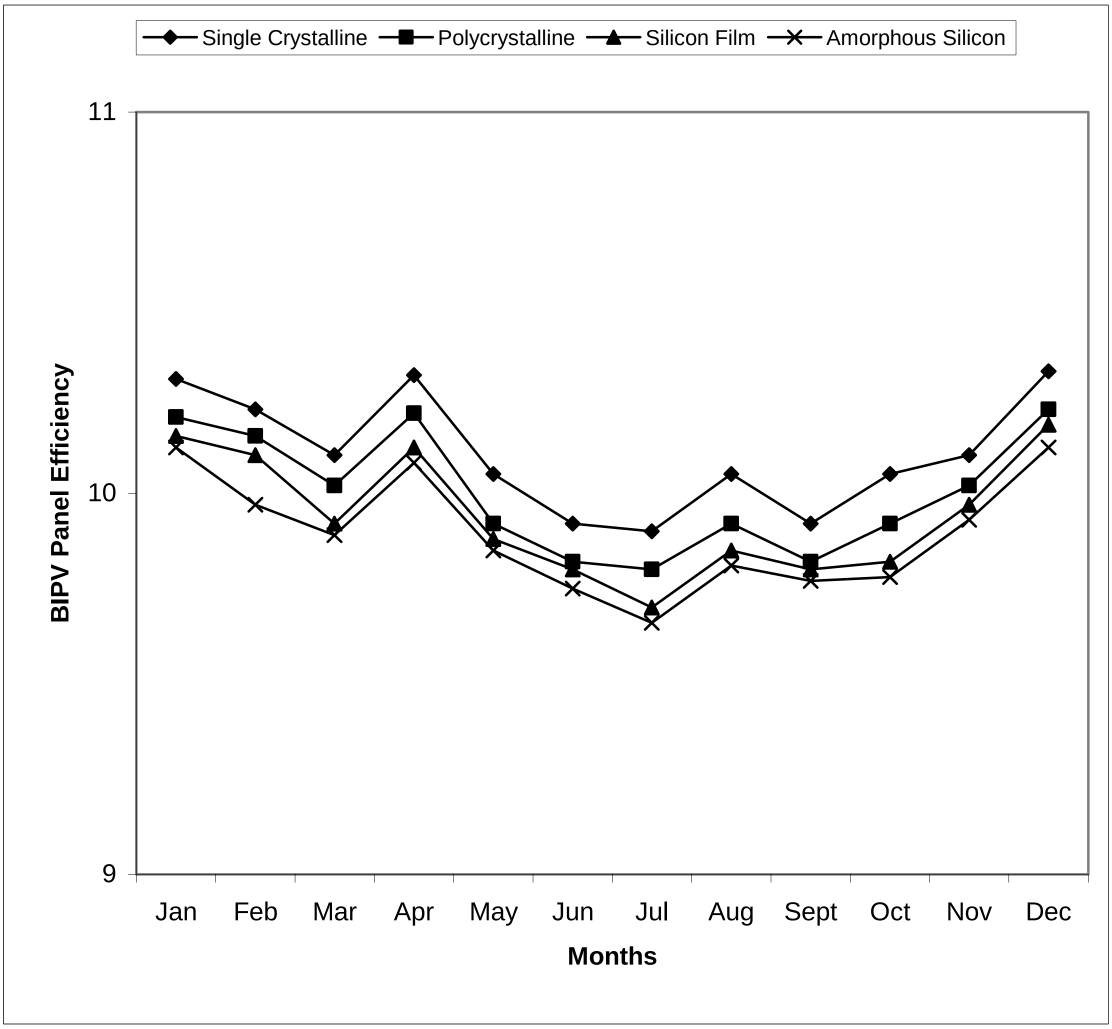

Figure 5.3 Monthly BIPV Conversion Efficiency - Midday Interval.

Comparing Figures 5.2 and 5.3, the conversion efficiencies are comparable for the months of January through April, September through December. The greatest differences are observed for the months of May through August. It is believed that these larger differences are due to the greater angles of incident between the BIPV panels and the sun that occurs during the central hours of the days during these months. The difference in conversion efficiency between the sunrise to sunset results, Figure 5.2, and the results for the mid-day intervals, Figure 5.3, is much less significant for the amorphous silicon panels than is exhibited by the other cell technologies. The single-crystalline, polycrystalline, and silicon film panels were most efficient during January and least efficient during the months of June and July. The month-to-month variation in efficiency is attributed primarily to the large variations in incident angle. The incident angle between the sun and BIPV panels varied from a low of 27.4° on December to 74.3° on June for these vertical south-facing panels.

5.3 Measurement and Analysis Performance

5.3.1 Introduction

There has been growing international interest in the implementation of photovoltaic (PV) power systems in commercial buildings, which generally involve either building integrated PV (incorporated into the building roof and facades) or stand-alone PV panels. In dense urban environments, where security and expensive real estate mmare often major concerns, building integrated PV (BIPV) systems have the distinct advantage of being an intrinsic component of a building's overall structure and electrical system. In addition, BIPV systems are being utilized more and more by major architectural firms for their aesthetic and conceptual qualities.

5.3.2 Simulation of BIPV performance

PV modules typically have a manufacturer's rated power output value in Watts (at 25 °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 thr 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 BIPV performance was investigated utilizing Visual Basic to calculate to power generated by the BIPV system 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 collector efficiency. The user also inputs the city and the inverter eficiency. The programming accesses the solar location as well as the drybulb 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 collector efficiency and tilt angle (90°

being vertical) to produce 8,760 hourly PV power output calculations spanning from January 1 through December 31. The programming proceeds to adjust these PV output figures further to account for inverter losses and panel dirt accumulation. These hourly results are summed to achieve monthly power output figures (in kWh per square meter of PV modules). All datas had been found according to the Polycrystalline PV module (Model Arcosolar M73, Siemens). 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. The results, described as annual power output per square meter of PV module, is displayed in Figure 5.4. for the baseline building in the city of Gaziantep. Another set of simulations was executed with the assumption that

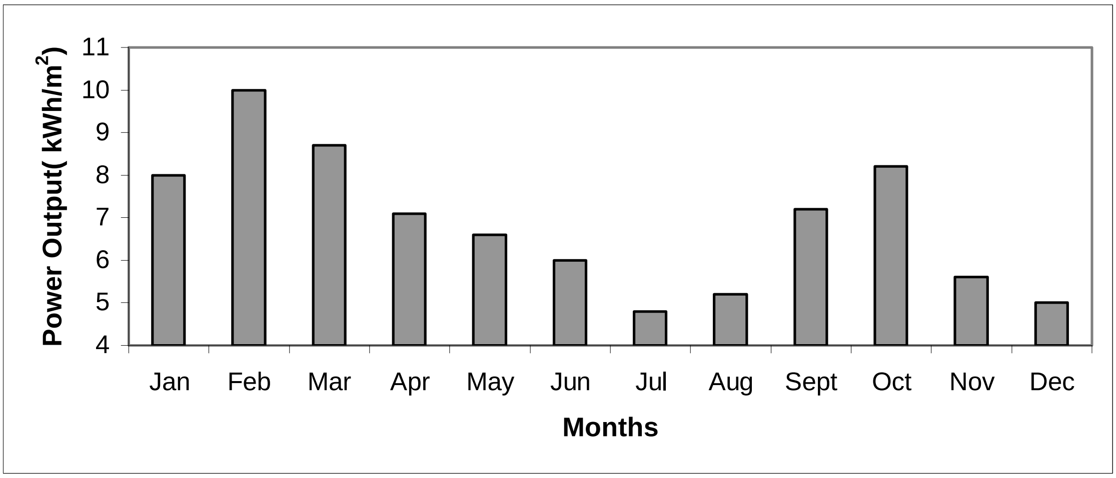

Figure 5.4 Vertical BIPV power output.

the BIPV collectors were set at a tilt angle of 35 degrees from vertical. The Visual Basic code automatically adjusts for this new PV angle and the result is increased direct solar radiation striking the PV collectors. To achieve this angle for the collectors an architect might either design the entire Southern curtain wall at the desired angle or separate and hang the PV collectors at an angle from the vertical facade. Due to the PV collector angle being closer to true perpendicular to the direct solar radiation, the PV output results shown in Fig. 5.5 improved significantly over the vertical PV orientation (Fig. 5.4). Fig. 5.4 illustrates the effect of a very small angle between a vertical PV surface and the sun during the summer months. There is a dramatic decrease in PV power from May through

September. Fig. 5.5 reveals a 104% improvement over the vertical PV results by utilizing a 35° tilt for the PV collectors. It has been seen that the PV panel's output current is proportional to the solar radiation that strikes it. It is important to understand that this radiation level is reduced if the panel is not pointing directly at the sun. Like other parts of this problem, the amount that it is reduced can be calculated. The cell’s output must be multiplied by the cosine of the angle of incidence of the incoming light.

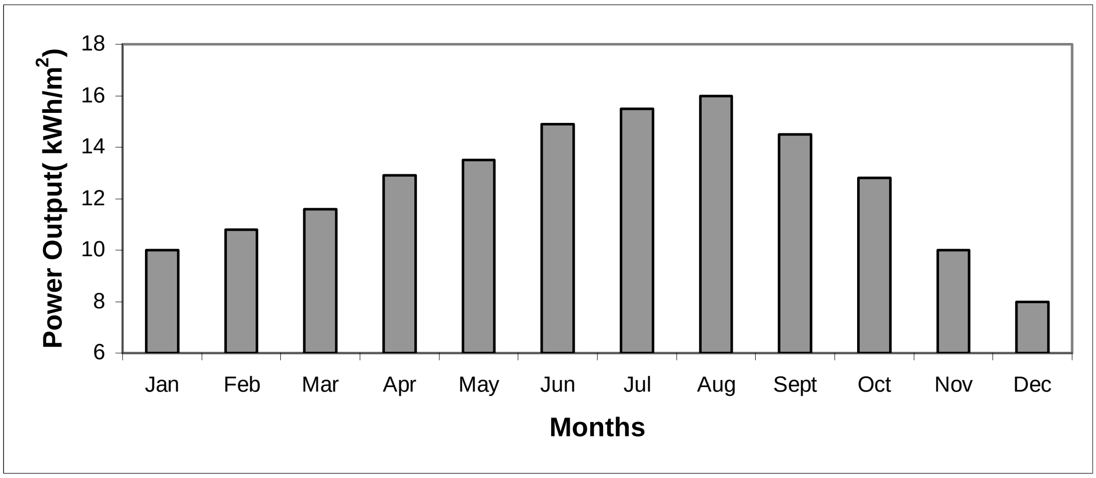

Figure 5.5 Tilt BIPV power output.

5.3.3 Photovoltaic system sizing and applications

A typical PV cell made of crystalline silicon is 12 centimeters in diameter and 0.25 millimeters thick. In full sunlight, it generaters 4 amperes of direct current at 0.5 volts or 2 watts of electrical power. PV modules consist of PV cells connected in series (to increase the voltage) and in parallel (to increase the current) so that the output of a PV system can match the requirements of the load to be powered. If more power is required, modules can be appropriately connected in series or parallel to form what is called a PV array.

The energy output of a PV system can be increased by having the PV modulles track the sun as it moves across the sky on a daily basis instead of being fixed in one orientation. Tracking arrays work well with certain applications such as direct PV water pumping. Most tracking systems require climates with a high fraction of direct beam versus diffuse sunlight to work well. Climates with high humidity have lower fractions of directs beam sunlight. The added complexity, maintenance and costs of tracking arrays needs to be compared with the incrased energy benefit of the tracking arrays in order to make an informed decision of which type of array, fixed or tracking, is the best option for each PV application.

PV modules power is rated by peak approximate DC power output at standard testing conditions (STC), STC are laboratory test conditions and are very different from the conditions that the modules will see when operating in the sun. These conditions are solar intensity of 1,000 watts per square meter (317 BTU/hr-ft^2) and a module temperature of 25^{o}C (77^{o}F). Actual operating conditions on a sunny day may be solar intensity of 800 Watts per square meter (254 BTU/hr-ft^2) and module temperature 50^{o}C (122^{o}F). PV module power is proportional to solar intensity so it will be less than rated at lower solar intensity levels. Also, PV module power is reduced as the operating temperature increases. Typically, PV module power is reduced by about 5 % for every 10^o (18^{o}F) increase in operating temperature above STC temperature. Failure to consider this reduction could cause major design errors.

To size a PV system, first energy needs must be known, all daily loads. A load includes anything that uses electricity from power source, such as lights, televisions, radios, or batteries. Some loads need electricity all the time, such as refrigerators, whereas others use electricity less often, such as power saws. To determine total energy consumption, multiply the wattage of the appliance by the number of hours so it is used in a day. Some appliances do not give the wattage, one has to calculate the wattage by multiplying the amperes times the volts. After adding the totals for each appliance, then it can be decided what power output need for the PV system[24].

Below is given one example of how the calculating for the solar module and battery might be. The calculation depends on four factors of power consumption, the energy supply, the solar module and battery capacity.

5.3.3.1 Calculating the power consumption per day

To calculate the power consumption here is a list of some users (only example):

* Lamp	40 W
* Fluorescent lamp	16 W
* TV (color)	60 W
* TV (black and white)	20 W
* Radio	5 W

* Tape recorder 20 W

To calculate the total power consumption per day you have to consider the effect, time of use and power consumption of each user.

Amount	User	User effect (W)	Time (h)	Power consumption (Wh) per day
3	Lamp	10	5	150
1	Fluorescent Lamp	16	1	16
1	TV (color)	45	5	225
	Daily Power consumption			391 Wh

5.3.3.2 To determine the energy supply e.g. north Sweden

May/June/July ~ 4,41 $kWh/m^2/day$

March/April ~ 2,10 $kWh/m^2/day$

Aug/Sep ~ 2,14 $kWh/m^2/day$

Oct – Feb ~ 0,22 $kWh/m^2/day$

5.3.3.3 Determine the size of the module

In consideration of the loss factor (transfer, transmutation and adaptation) of around 25 % (0,75 factor).

Module power (P)= energy supply per day (Wh)/[solar radiation ($kWh/m^2/day$) **x** loss factor 0,75]; P = Wh / [($kWh/m^2/day$) x 0,75]; In our example: P = 391 /[4,41 kWh x 0,75] ~ **118W.**

If one occupies the house only during weekends, the module should have lower power than that of the whole week, since the power is consumed for only two days; i.e. $P_{weekend}$= 2/5 x P_{daily} (calculated module); in this case one needs a **51W** module.

5.3.3.4 Determine the necessary capacity of battery

The right calculated capacity of the battery makes sure to bridgeover adverse weather days and nights [24], i.e. daily energy supply : systemvoltage = electric power consumption ; 391 Wh : 12V = 32,58 Ah. In consideration of an energy buffer about 2 days, i.e. 32,58 Ah x 2 = 65,16 Ah. In consideration of the safety factor (prevent an overcharging of the battery which decreases the life span of the battery and increases the risk for the battery to freeze); 65,16 Ah x 2 = 130,32 Ah ~ **130 Ah**

Load	Daily Use (hrs)		Wattage		Total Energy Consumption (watt-hrs)
Radio	2	x	25	=	50
Lamps (fluorescent)	3	x	27	=	81
VCR	0.5	x	30	=	15
Television	6	x	60	=	360
Total Daily Energy Consumption					**506 watt-hrs**

For the items listed above, a system that produces an average daily energy output of 506 watt-hours would be needed. Obviously, different parts of the country receive varying amounts of sunlight. Because sunlight is the source of power for PV. Remember that PV systems are rated by peak watt, which is the amount of power produced when the module receives 1,000 watts per square meter of exposure to the sun (insulation) [25].

Let's examine Gaziantep. In Gaziantep for each peak watt that a PV module is rated, it will produce a yearly average of 3,95 watt-hrs of electricity daily. If a PV system in Gaziantep wanted be to used for the appliances listed in the table, 506 watt-hrs would be divided by 3,94, divided that by 0.8 to account for inefficiency of the batteries and, finally, multiplied by 1.2 to cover anything that may have been overlooked. A PV system rated at 124 peak watts be found that needed. If 50-watt modules were bought, three modules would be needed, because the next highest number is round up to.

506	/	3,94	=	128,426
128	/	0,8	=	160
160	x	1,2	=	133
133	/	50	=	3 modules

5.4 Efficiency Characteristics of Photovoltaic Panel in Gaziantep

5.4.1 Introduction

In the new century, PV applications would appears a great potentially in energy and building services engineering due to its direct electricity generation, further, this technology is helpful to the environmental protection of modern life. During the process of energy conversion, apart from electricity generation, when optical energy is imposing on a PV panel, it changes into heat in a great portion which is then dissipated away. So far, many models have been developed for the purpose of photovoltaic simulation. For example, Brinkwotth et al. [26] proposed a model to study the effect of thermal regulation; Yoo et al. [27] reported their study in Korea for building integrated photovoltaics; Hirata et al. [28] reported a model to consider the output variation of photo volltaic panels including seasonal variation; Yang et al [29] built a model to investigate the performance of crystalline silicon photovoltaics; Recently, Zhu et al. [30] has dveloped a heat transfer model to simulate a building integrated photovoltaic system. Gaziantep city, located in Southestern Anatolia Region in Turkey,has a great solar radiation potential, as the number of sun hours (Fig.5.6.) is large. 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.

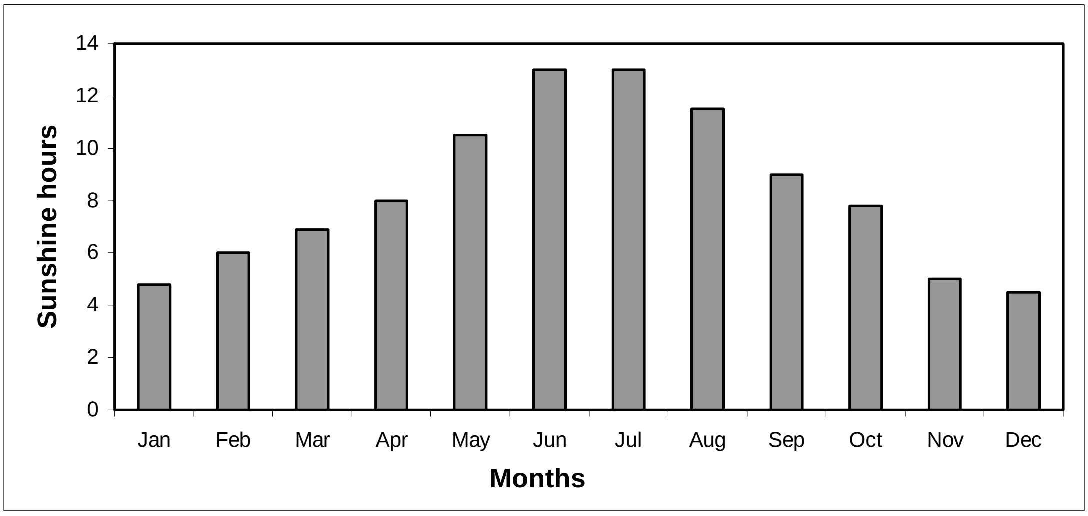

Figure 5.6 Annual variation of daily sunshine hours in Gaziantep, Turkey (Gaziantep Meterological Station).

5.4.2 Operation results for 1 year

To simplify the analysis of the results of the 1 year operation, we first analyze only the results for the sunshade module for every month (12 months): From January 2003 to December 2003.

5.4.2.1 Summer season results (June, July, August and September)

Among the summer months, selected as June, July, August and September, Figs 5.7, 5.8 and 5.9 show plots of the PV power generation results, respectively, for June 2003, July 2003, August 2003 and September 2003, along with the solar irradiance, as a function of day. Table 5.1 shows the total power generation, total solar radiation and the efficiency for summer months.

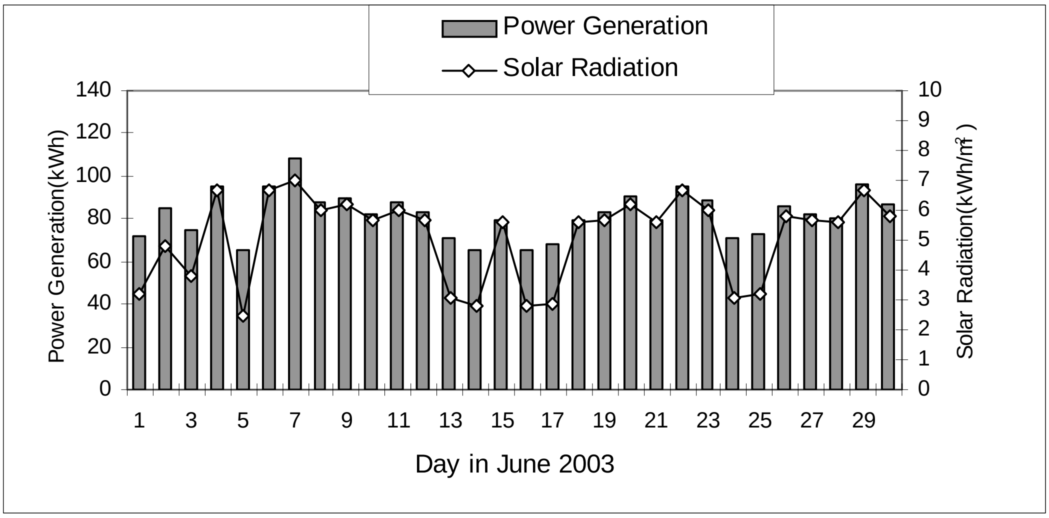

Figure 5.7 PV power generation results for the summer month (June 2003).

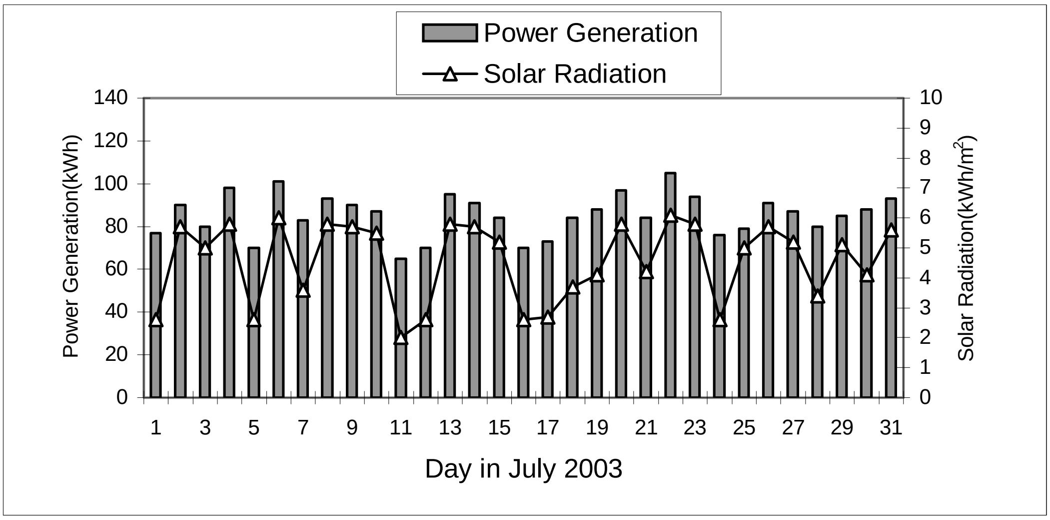

Figure5.8 PV power generation results for the summer month (July 2003).

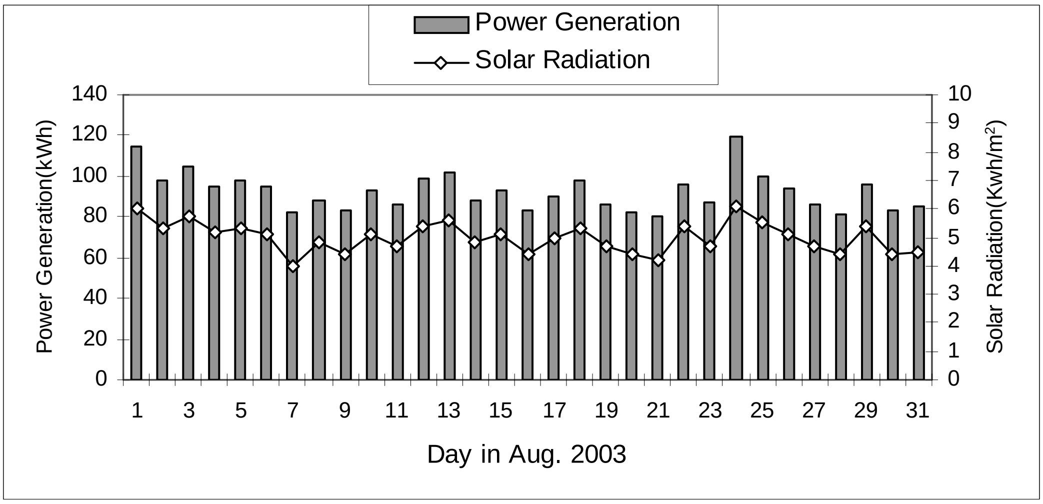

Figure 5.9 PV power generation results for the summer month (August 2003).

	June 2003	July 2003	August 2003	September 2003
Total power generation (kWh)	2465	2686	2868	2440
Total solar radiation (kWh/m^2)	153.2	141.3	154.7	104.7
Efficiency (%)	18.5	20.4	19.1	14.3
Average solar cell temperature	38.2	45.2	42.3	35.1
Average air temperature	33	38	35	28.1
No.of day (days)	30	31	31	30

Table 5.1. Total power generation and the efficiency for summer months.

The average efficiency for summer season is approximately 18.07%, while the average surface temperature and outdoor air temperature during this season is, respectively, 40.2 ^{o}C and 33.5 ^{o}C. It is observed that the over surface temperature of the solar cell panel is relatively higher than one of the other months among summer months, the efficiency of the PV system shows the highest value in the month (July) which has a highest solar altitude. This means that the available shaded area of the solar cell panel should be considered most significant in the design phase. When the electrical power of 90 kWh was generated for 1 day of these summer months, the solar radiation intensity corresponded to 6.2 kWh/m^2 on June 9, 5.7 kWh/m^2 on July 9, 5.0 kWh/m^2 on August 17 and 4.6 kWh/m^2 on September 20.

5.4.2.2 Mid-term results (March, April, May and October)

Among mid-term months (i.e.a month neither cold nor hot), selected as March, April, May and October, Figs 5.10, 5.11, 5.12 and 5.13 show plots of the PV power generation results, respectively, for March 2003, April 2003, May 2003 and October 2003, along with the solar irradiance, as a function of day. Table 3.2 shows shows the total power generation, total solar radiation and the efficiency for the mid-term months.

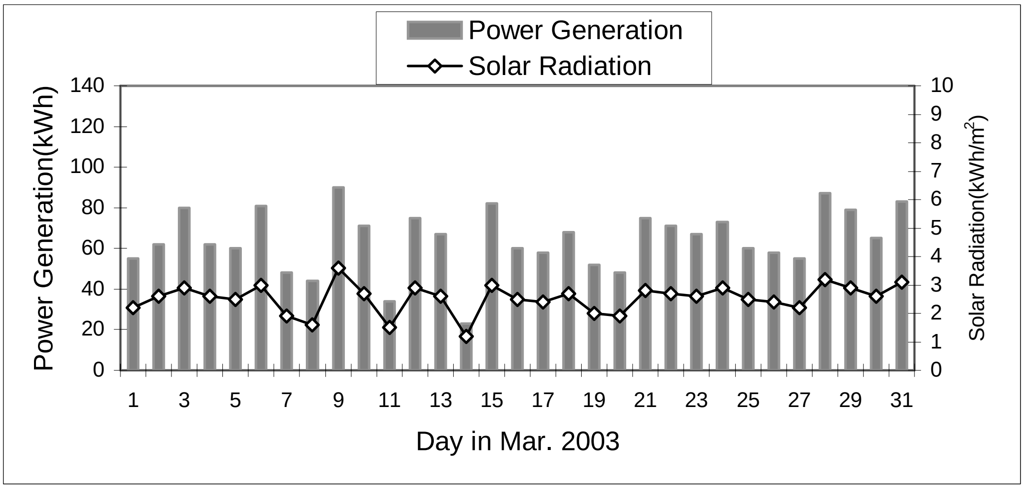

Figure 5.10 PV power generation results for the mid-term month (March 2003).

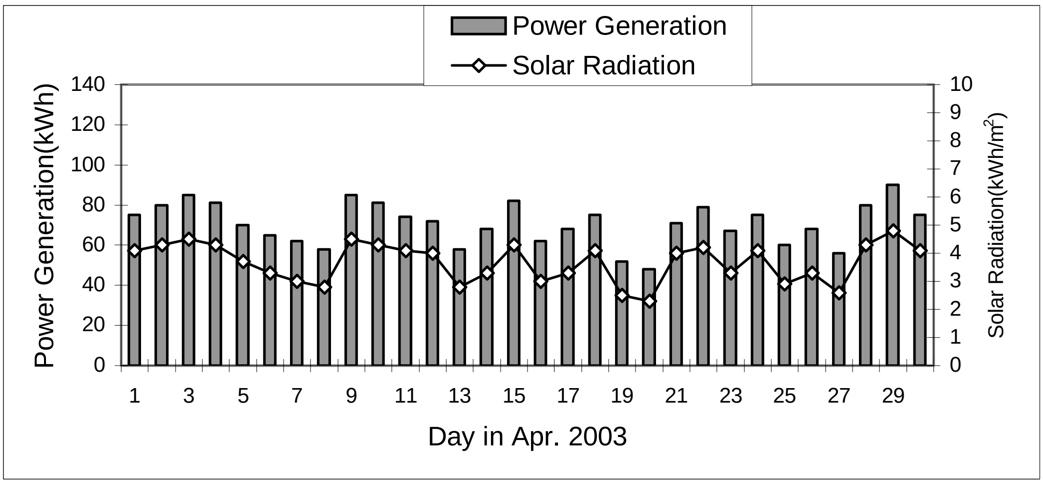

Figure 5.11 PV power generation results for the mid-term month (April 2003).

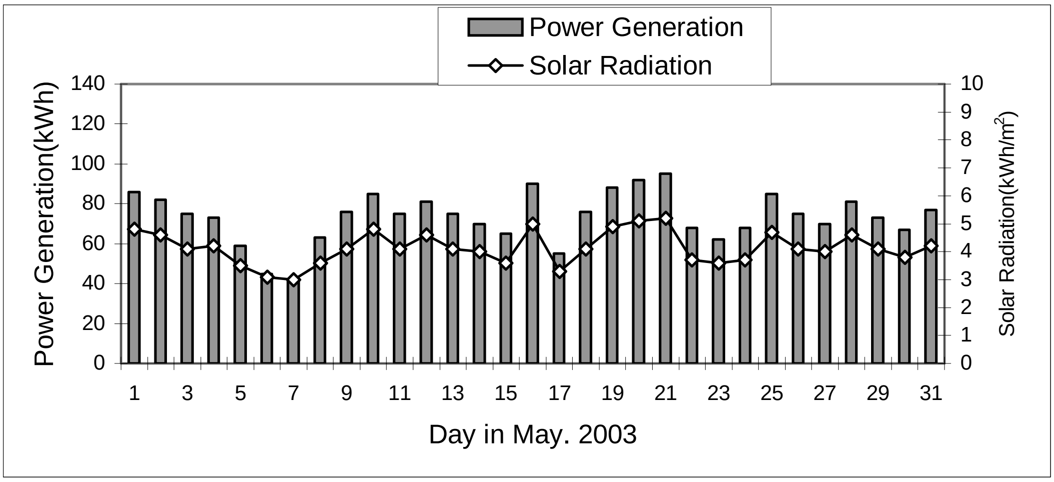

Figure 5.12 PV power generation results for the mid-term month (May 2003).

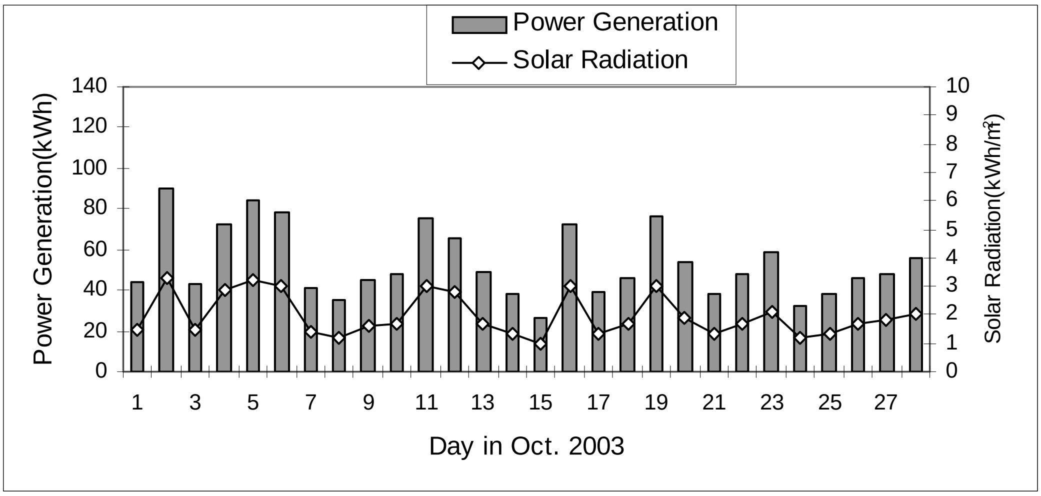

Figure 5.13 PV power generation results for the mid-term month (October 2003).

	October 2003	March 2003	April 2003	May 2003
Total power generation (kWh)	1487	1993	2122	2275
Total solar radiation (kWh/m^2)	55.1	82	110.0	128.3
Efficiency (%)	13.1	9.8	14.7	12.2
Average solar cell temperature	14.8	17.8	20.2	27.3
Average air temperature	9.8	11.2	15.9	21.5
No.of day (days)	28	31	30	31

Table 5.2. Total power generation and the efficiency for mid-term months.

The average efficiency for the mid-term season is approximately 12.4%, while the average surface temperature and outdoor air temperature during this season is, respectively, 20.02 ^{o}C and 14.6 ^{o}C. When the electrical power of 90 kWh is generated for 1 day of this mid-term months, the corresponding solar radiation intensity was 3.6 kWh/m^2 on March 9, 4.8 kWh/m^2 on April 29, 5.0 kWh/m^2 on May 19 and 3.3 kWh/m^2 on October 2.

5.4.2.3 Winter season results (November, December, January and February)

Among winter months, selected as November, December, January and February Figs. 5.14, 5.15, 5.16 and 5.17 show plots of the PV power generation results, respectively, for November 2003, December 2003, January 2003 and February 2003 along with the solar radiation, as a function of day. Table 3.3 shows the total power generation, total solar radiation and the efficiency for winter months.

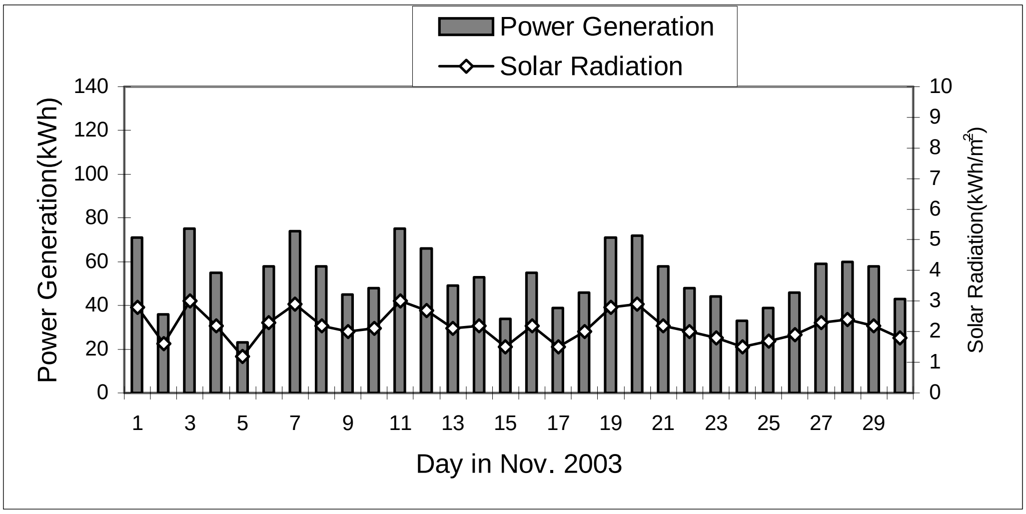

Figure 5.14 PV power generation results for the winter month (November 2003).

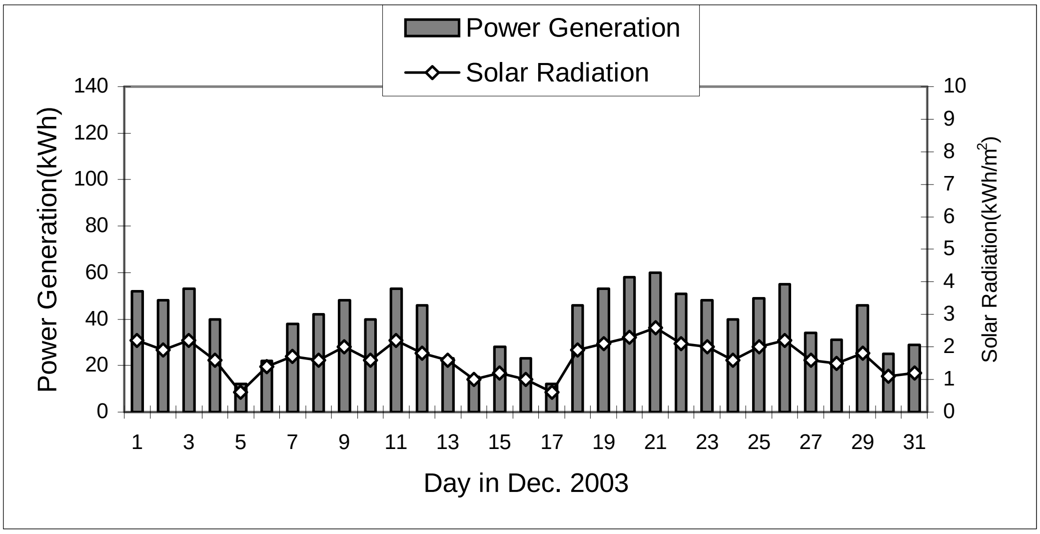

Figure 5.15 PV power generation results for the winter month (December 2003).

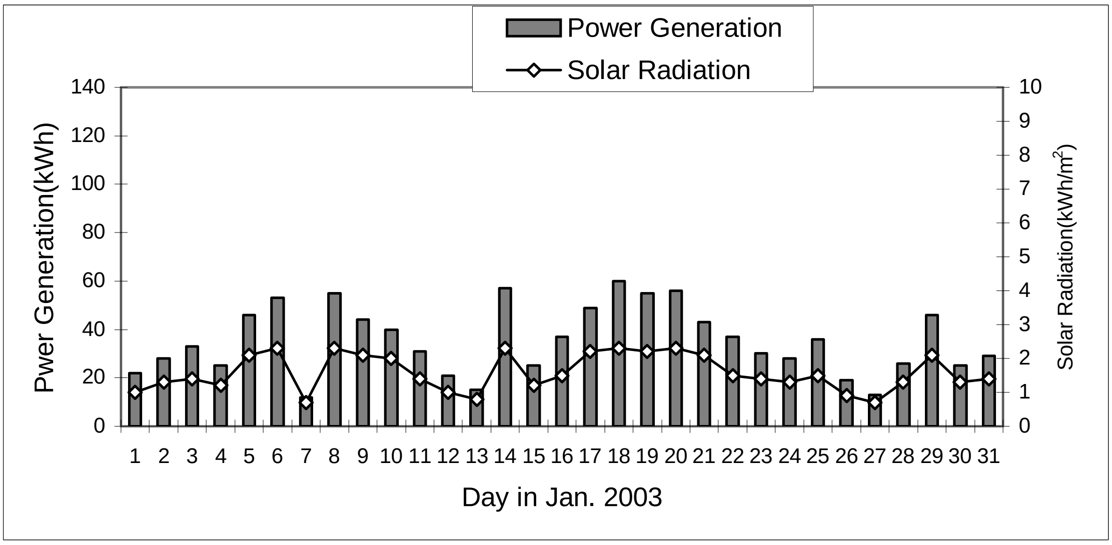

Figure 5.16 PV power generation results for the winter month (January 2003).

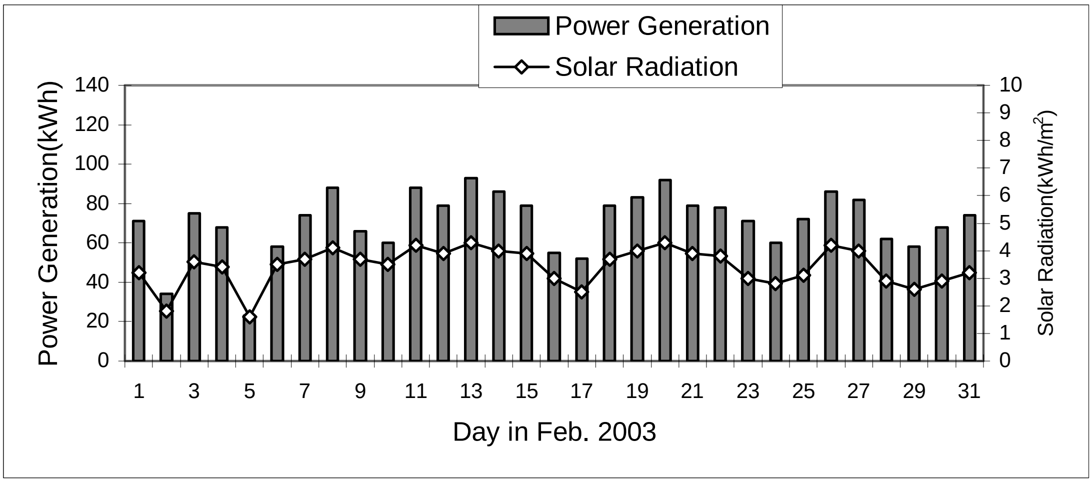

Figure 5.17 PV power generation results for the winter month (February 2003).

	February 2003	November 2003	December 2003	January 2003
Total power generation (kWh)	2195	1595	1220	1094
Total solar radiation (kWh/m^2)	106.3	65	52.2	49.2
Efficiency (%)	11.5	9.2	5.6	4.2
Average solar cell temperature	31.5	28.3	18.4	12.6
Average air temperature	25	22.6	12.5	7.3
No.of day (days)	31	30	31	31

Table 5.3. Total power generation and the efficiency for winter months.

The average efficiency for winter season is approximately 7.6%, while the average surface temperature and outdoor air temperature during this season is, respectively, 22.7 ^{o}C and 16.8 ^{o}C. When the electrical power of 60 kWh is generated for 1 day of these winter months, the solar radiation intensity was corresponding to 2.4 kWh/m^2 on November 28, 2.6 kWh/m^2 on December 22, 2.3 kWh/m^2 on January 18 and 2.8 kWh/m^2 on February 24. Thus It is seen that the efficiency of the PV system was obtained the lowest value in the month (January), which has a lowest solar altitude, because the shaded area is less than that of the other months. Therefore, the efficiency of the summer is higher than that of the winter season.

CHAPTER 6

CONCLUSIONS

We present a subjective perspective of PV materials and panels. The most important and widely used material is silicon. It dominates the present world market, particularly in its crystalline form but amorphous silicon is also of importance. Silicon solar cells are still heavily dependent on the materials base of the semiconductor industry. Crystalline silicon still has a large potential for cost reduction in its conventional form and even more so in the crystalline thin film and PV panel version. Solar electric, a process whereby electricity is created directly by sunlight, holds exceptional promise now for the future. Energy from the sun will, by photovoltaic transformation, supply an ever-increasing amount of the world's power needs, and this unending form of energy will be produced without degrading the environment. Partly because of its perceived energy self-sufficiency, Turkey has been slow to appreciate the significance of photovoltaics, however, other countries are very much alert to the benefits that electricity through PV can offer.

The BIPV used as exterior solar shading devices is a means of producing electricity on site and of reducing cooling loads and peak loads in buildings. Designing and assessing such a BIPV system, which acts as both a shading element and a power generation element, requires a multidisciplinary approach. The BIPV system gives rise to gains in terms of heat and light in winter, spring and autumn, and it controls such gains in summer, when they are less desirable.

The efficiency of the sunshade module varies considerably depending on the month and the season, due to the shadows cast by other PV panels and the tilt, the orientation and the surface temperature variation of the PV panel. Therefore, the influence of the shadow cast by other PV panels should be carefully considered during the design phase. Precisely, the maximum and minimum values of the efficiency in July and January are, respectively, 20.4% and 4.2%.

The yearly average efficiency of the sunshades is 12.7%, while the average over surface temperature is 27.6 ^{o}C. The average efficiency of the sunshades according to the season is shown below.

Season	Average Efficiency(%)	Average over surface temperature
Summer	18.07	40.2
Mid-term	12.4	20.02
Winter	7.6	22.7

Table 6.1. The average efficiency of sunshades

Based on this investigation, the key point we suggest is that a photovoltaic system should be applied, not just for generating electricity, but also for improving general aspects including the use of thermal energy behind the panel during the summer, daylight provision inside the room, shade provision for the interior of the building during the winter, and aesthetical contribution to the interior view and exterior of the building.

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