Photovoltaics Technology & Its applications in Saudi Arabia

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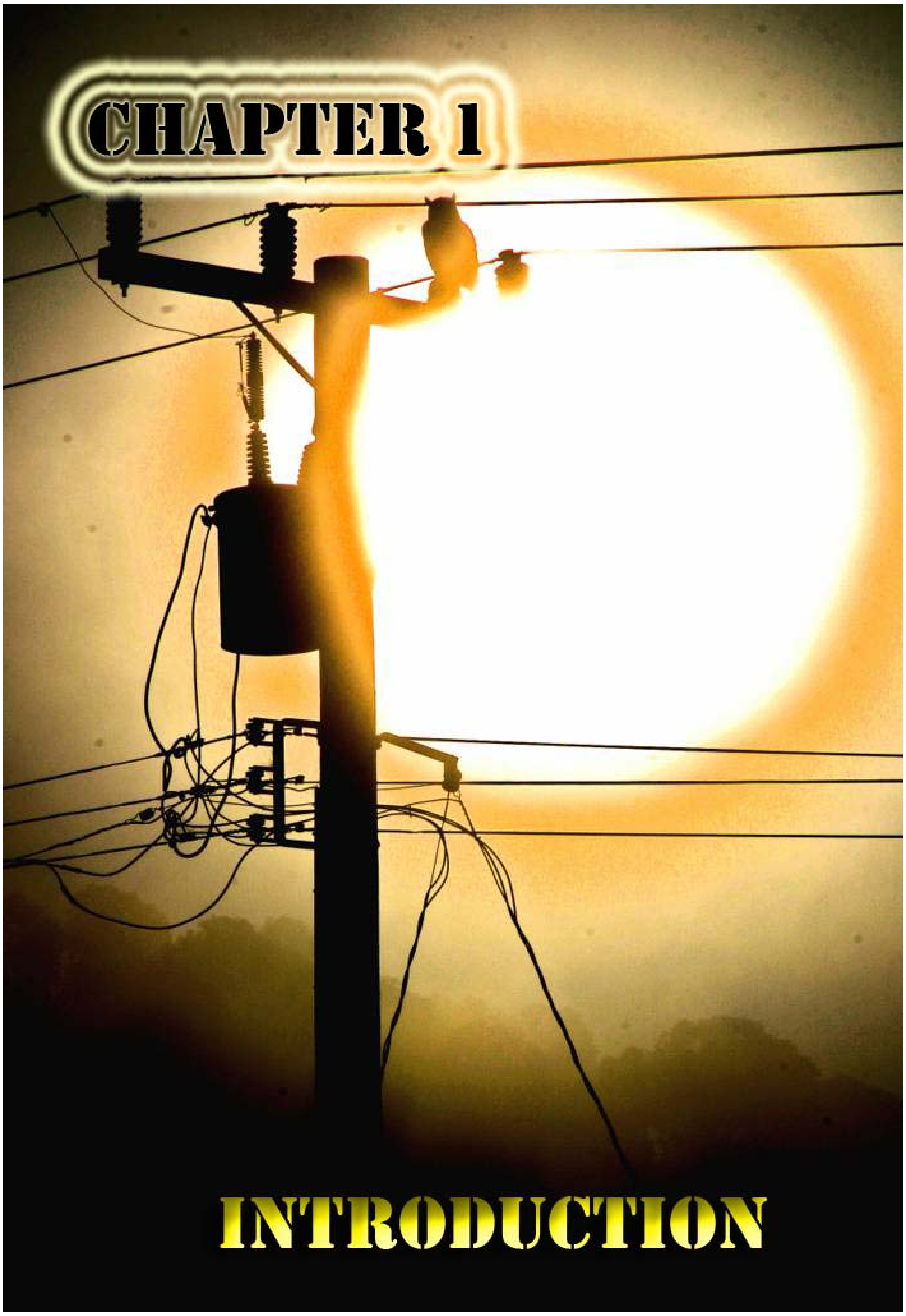


CHAPTER 1

INTRODUCTION

Introduction:

Energy is an essential factor for the development of any society. Nowadays, the production of global energy is dominated by the use of fossil fuel such as coal, oil and natural gas but this type of source of energy is going to consume. Global warming ever depleting natural resources, and public concern over using nuclear energy, are limiting the world options. Therefore, *renewable energy* sources must be studied as a matter of urgency.

Renewable energy is defined as "energy derived from resources that are regenerative or for all practical purposes can not be depleted". The prime source of renewable energy is solar radiation, i.e. sunlight. The Earth-Atmosphere system supports approximately 5.4×10^{24} joules per year in the solar radiation cycle [1].

Sunlight can be converted directly into electrical energy through a process known as a *photovoltaic* (PV). A device that used to do such process is called a (PV) cell or, *a solar cell*.

In 1839, nineteen-year-old Edmund Becquerel, a French experimental physicist, discovered the *photovoltaic effect* while experimenting with an electrolytic cell made up of two metal electrodes. Becquerel found that certain materials would produce small amounts of electric current when exposed to light. One century after that, Albert Einstein received the Nobel Prize for his theories explaining this *photovoltaic effect*.

According to the encyclopedia *Britannica* the first genuine solar cell was built around 1883 by Charles Fritts, who used junctions formed by coating selenium (a semiconductor) with an extremely thin layer of gold. The silicon solar cell was invented in 1941, by Russell Ohl. In 1954, three American researchers, Gerald

Pearson, Calvin Fuller and Daryl Chapin, designed a silicon solar cell capable of 6% energy conversion efficiency with direct sunlight. The three inventors then created an array of several strips of silicon (each about the size of a knife blade), to capture as much photons as possible and turn them into electrical current. In fact, they created the first solar panels [2].

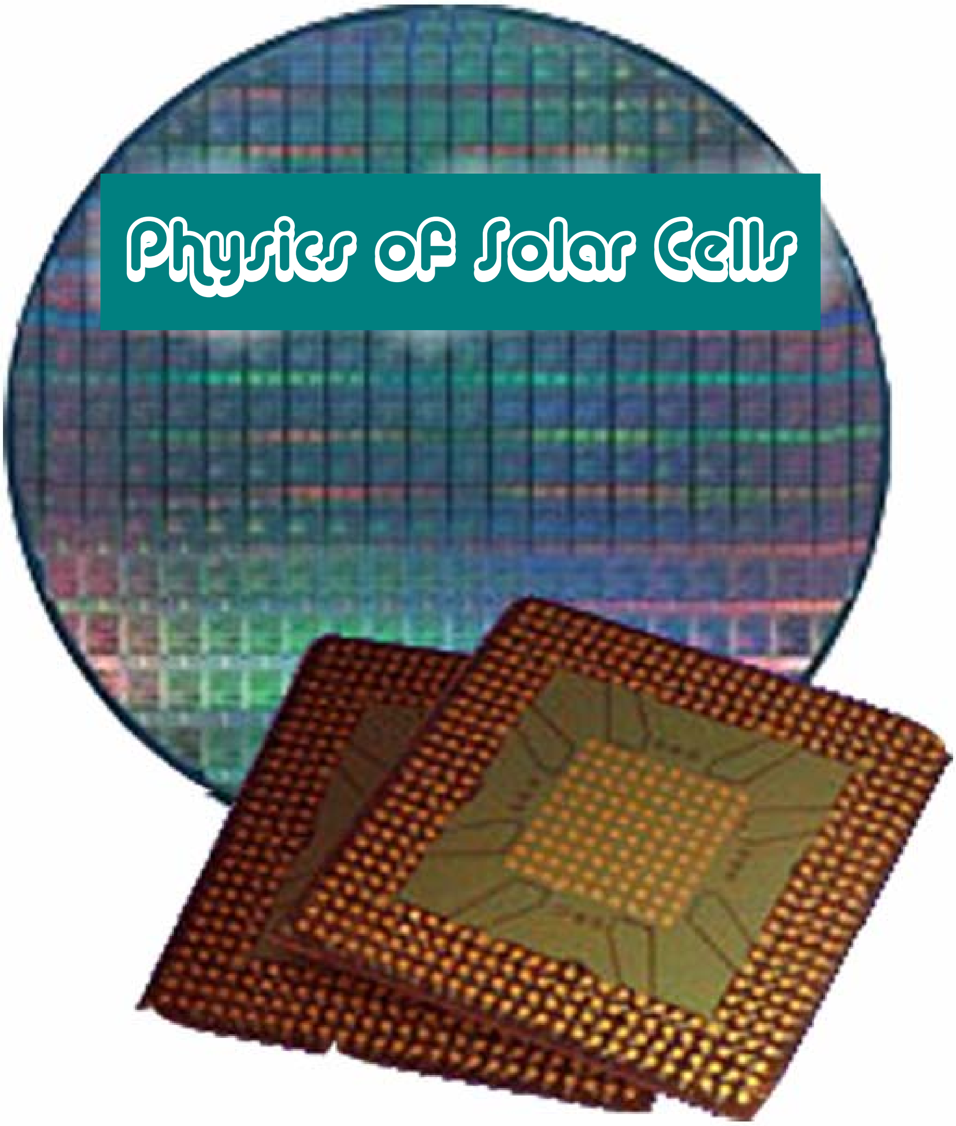
Since then a numerous developments had been done to the solar cell to be at high efficiency with an affordable cost. The individual solar cells are usually arranged together in a PV *module* and the modules are grouped together in an *array*. Some of the arrays are set on special tracking devices to follow sunlight all day long. The electrical energy from solar cells can then be used directly, or it can be stored in batteries to uses when the sun is not shining.

Fortunately, the Kingdom of Saudi Arabia receives some of the most intense sunlight in the world. It is listed on the map of the top five places for potential photovoltaic generation of electricity around the world. The Kingdom of Saudi Arabia extends from Azimuth 50 to Azimuth 35 and from latitude 17 in the south to latitude 32 in the north [3]. A Solar Radiation Atlas developed by the King Abdulaziz City for Science and Technology (KACST) in collaboration with the US National Renewable Energy Laboratory indicates, that direct normal radiation in the Kingdom exceeds 30MJ/m^2/day in some regions in the summer, and is not less than 24 MJ/m^2/day anywhere in the country even in the month of January [4]. These figures highlight the fact that solar insulation is uniquely available in all the areas of Saudi Arabia at high intensity all year round. This makes Saudi Arabia one of the most likely candidates for a country run by solar energy.

In this thesis we aim to spot the main characteristics and applications of solar cells and how that would be suitable to a country such as Saudi Arabia. First, we will discuss the physics of the solar cell in **chapter 2.** This is including the p-n junction properties, the solar cell's efficiency factors and the classification of solar cells according to their structure. Description of photovoltaic systems along with their different applications will be the subject of **chapter 3**. Factors that limit the uses of solar cells will be discussed as well in this chapter. Finally, in **chapter 4,** we will report the main solar energy programmes in Saudi Arabia, which can be divided mainly into international joint and local programmes.

CHAPTER 2

Physics of Solar Cells



2.1 About the Chapter:

On a bright, sunny day the sun shines approximately 1,000 watts of energy per square meter of our planet's surface. If we could collect all of that energy we could easily power our homes and offices for free. The devices that used to convert sunlight directly into electricity are known as **photovoltaic** (PV) **cells.** PV cells are made of special materials called **semiconductors** such as silicon, which is currently the most commonly used. Basically, when light strikes the cell, a certain portion of it is absorbed within the semiconductor material. This absorbed energy allows some electrons to flow freely. PV cells also have one or more electric fields which act to force those free electrons to flow in a certain direction. This flow of electrons is a *current*, and by placing metal contacts on the top and bottom of the PV cell, we can draw that current off to use externally. This current, together with the cell's voltage (which is a result of its built-in electric field or fields), defines the power that the solar cell can produce. [5]

In this chapter we are going to discuss the main physical principles of the photovoltaic cells. In particular we will talk about the p-n junction, the I-V characteristics and the efficiency of the solar cell. Then we will show the different types of solar cells along with their basic properties.

2.2 Semiconductors:

Semiconductors are the elements that located in the fourth column of the periodic table , they have four valance electrons such like Ge and Si. The crystal structure of these elements follows the tetrahedral pattern, where each atom sharing one valence electron with each of four neighboring atoms.[6]

According to Band theory which states that : *a band which is completely full carries no electric current, even in the presence of an electric field,* it follows that a solid behaves as *metal* only when some of bands are partially occupied.

If the gap between the valence band and the conductor band is small, the electrons could thermally be excited across the gap, both bands become partially filled and hence both contribute to the electric current. Such materials are known as *semiconductors*.

If the gap between the valence band and the conductor is too large that the electrons could not cross the gap, the element is *insulator*.

Figure (2.1) shows the difference between those three type of solid.[7]

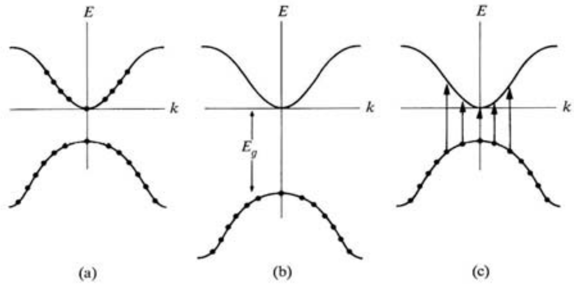


Figure (2.1) : The main types of solid: a) metal, b) semiconductor and c) insulator.

2.2.1 Physical Properties of Semiconductors:

i) Intrinsic (Pure) Semiconductors:

At temperature close to absolute zero, perfect crystal of a pure semiconductor is considered as insulator.

As the temperature increasing, electrons are thermally excited from the valence band to conduction band. Both electrons in conduction band and holes left behind in the valence band contribute to the electrical conductivity.[8]

Since the conduction in this case is an intrinsic property, the material is called *intrinsic semiconductor* .

ii) Extrinsic Semiconductors:

If we add an element from the fifth column of the periodic table (donor impurity) to a tetravalent element we will get an *n-type* semiconductor. Similarly, adding elements from the third column (acceptor impurity) gives a *p-type* semiconductor. The conduction in such substances will be by electrons impurities in the n-type and by holes impurities in the p - type.[9]

iii) Organic Semiconductors:

They are the polymers semiconductors such as (3-hexylhiophene).[10] The main differences between organic and extrinsic semiconductors are :

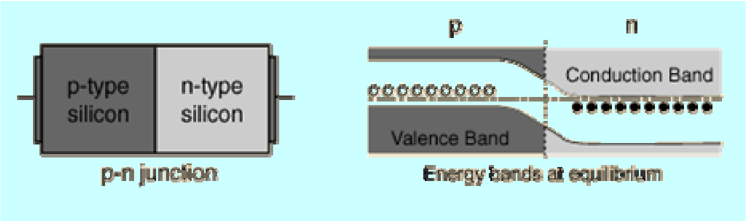
1- Organic have different bounding system from conventional inorganic semiconductors which have strong covalent bonds. On the other hand, organic materials are held together by the weak intermolecular Van der Waals bonds.

2- The optical excitations of organic semiconductor create electron-hole pairs (called exciton) that not effectively split by electric field we need to driving force to separated. But in inorganic semiconductor the interaction between an electron-hole pair is less than thermal energy kT and no additional force needed to separated carriers.

3- The absorption - spectrum bandwidth of organic semiconductor is narrower than that in inorganic materials. Thus, organic material can be potentially photoactive only in a narrow optical-wavelength range of solar spectrum. [11]

2.3 The P - N Junction:

The p-n junction in figure (2.2.a) is a single semiconductor crystal that has been selectively doped so that one region is n-type material and adjacent region is p-type material. Such junctions are the heart of all semiconductor devices.



(a) **(b)**

Figure (2.2): a) The p-n junction. b) Energy bands at equilibrium.

We assume, for simplicity, that the junction has been formed mechanically, by jamming together a bar of n-type semiconductor and a bar of p-type semiconductor. Thus, the transition from one region to the other is perfectly sharp, occurring at a single junction plane.

Let us discuss the motions of electrons and holes just after the n-type bar and the p-type bar, both electrically neutral, have been jammed together to form the junction. We first examine the majority carriers, which are electrons in the n- type material and holes in the p-type material.

2.3.1 Motion of the Majority Carriers:

In the same way, Electrons on the n side, that are close to the junction plane tend to diffuse across it (from right to left in the figure) and into the p side, where there are very few free electrons. Similarly, holes on the p side that are close to the junction plane tend to diffuse across that plane (from left to right) and into the n side, where there are very few holes. The motions of both the electrons and holes contribute to a **diffusion current** I_{diff}.

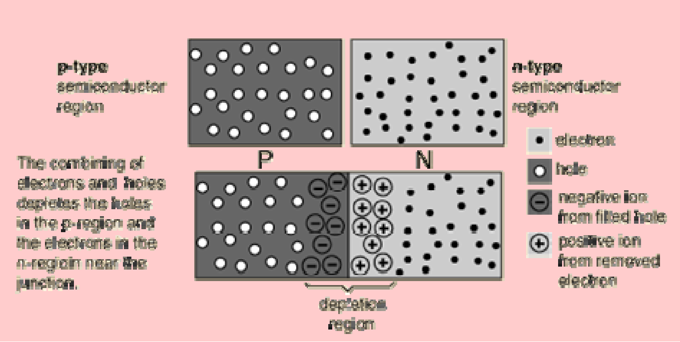
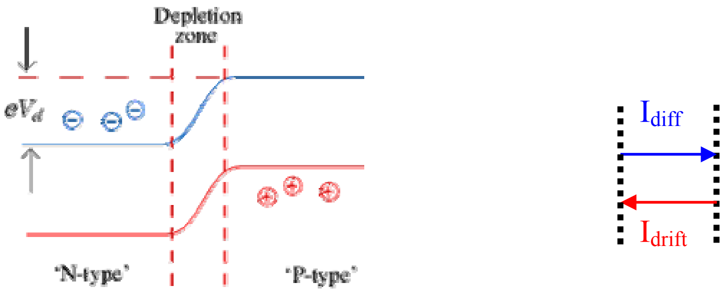


Figure (2.3): Formation of the depletion zone in the p-n junction.

When an n-side electron diffuses across the junction plane, it leaves one positive ion behind. Then when this diffusing electron arrives on the p side, it quickly combines with an acceptor ion which lacks one electron, holes diffusing through the junction plane from left to right have exactly the same effect. The motion of both majority carriers, electrons and holes, contributes to a buildup of two space charge regions, one positive and one negative. These two regions form a **depletion zone** its width is shown as d_0 in figure (2.3). The buildup of space charge generates an associated contact potential difference V_0 across the depletion zone.

2.3.2 Motions of the Minority Carriers:

Although the majority carriers in n-type material are electrons, there are nevertheless, a few holes. Likewise in p-type material there are also a few electrons. These few holes and electrons are known as the **minority carriers** in the corresponding materials.



(a) (b)

Figure (2.4): a) The potential barrier and, b) the two types of currents through it.

Although the potential difference V_0 in figure (2.4.a) acts as a barrier for the majority carriers, it is a downhill trip for the minority carriers, i.e. electrons on the p side or holes on the n side. Positive charges (holes) tend to seek regions of low potential; negative charges (electrons) tend to seek regions of high potential. Thus, both types of carriers are swept across the junction plane by the contact potential difference and, together, constitute a **drift current** I_{drift} across the junction plane from right to left, as figure (2.4.b) indicates.

Thus, an isolated p-n junction is in an equilibrium state in which a contact potential difference V_0 exists between its ends. At equilibrium, the average diffusion current I_{diff} that moves through the junction plane from the p side to the n side is just balanced by an average drift current I_{drift} that moves in the opposite direction. These two currents cancel each other because the net current through the junction plane must be zero; otherwise charge would be transferred without limit from one end of the junction to the other. [12]

2.4 Photovoltaic Solar Cell:

2.4.1 Nature of Light :

Light is a form of the radiant energy, which is propagated through space or matter as electromagnetic waves. Light differs form other kinds of electromagnetic radiation such as radio waves, heat ,and X- rays only in wavelength or frequency (1). The Sunlight is composed of packets of energy which is known as *photons*. These photons contain various amounts of energy corresponding to the different wavelengths of light. When photons strike a semiconductor, they may be reflected or absorbed, or they may pass right through. When a photon is absorbed, its energy is transferred to an electron in the semiconductor. The electron with its newfound energy will be able to escape from its normal position associated with that semiconductor to become part of the current in an electrical circuit.[13]

2.4.2 Photovoltaic Effect:

The photovoltaic (or PV) effect is the basic physical process through which sunlight converts into electricity. The word photovoltaic is a joining of two words *Photo,* meaning light, and *voltaic*, meaning electricity. And this is the phenomenon by which certain materials, properly processed and fabricated into suitable devices; generate a voltage when they are exposed to light. The photovoltaic cell or *self generating photocell* is one that generates an output voltage in proportion to the intensity of incident light.

2.4.3 I-V Characteristics of the Solar Cell:

Consider an isolated p-n junction as that shown in Fig. (2.5)**.** It is fabricated of a wafer of p-type silicon on which a thin layer of n-type silicon has been deposited. The wafer is calls the base and the deposition the surface layer. Electrodes are affixed to the outer surfaces of the device. The electrode for the surface layer is composed of an extremely thin metallic deposition. This electrode is essentially transparent so that sunlight reaches the surface layer with little attenuation. The surface layer is also thin so that solar radiation can reach the junction**.**

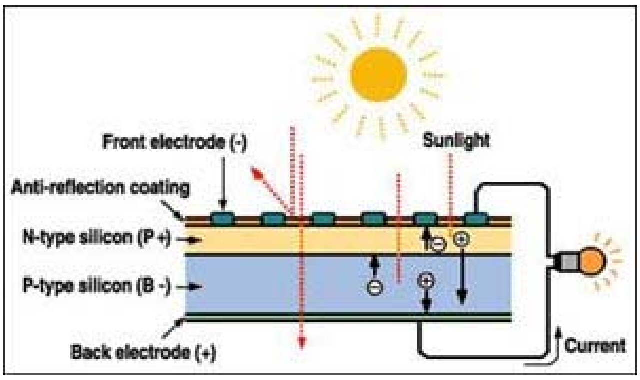


Figure (2.5): Typical model of PV solar cell.

The sun light have a power, it is can operates the photovoltaic cell or 'solar cell' without an external bias, These moving charges can be detected as an external photo current and a produced photo voltaic can be measured at the diode terminals ,like the same charge separation mechanism in the bias .

When photons with energy $hv \geq E_g$ are absorbed near a p-n junction in a semiconductor crystal; some minority carriers (electron and holes) will be excited and then promoted from the valence band to conduction band, creating electron-hole pairs. The excited electron -hole pairs that are in the depletion layer, can sweep to the n and p regions respectively. While those that lie outside the depletion region will diffuse towards the junction and once they reach the depletion region, they drift rapidly across. Fig. (2.6).

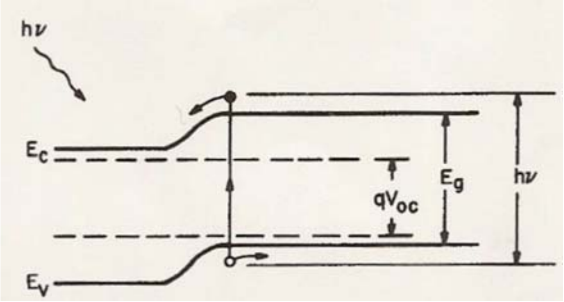


Figure (2.6): The movement of carriers of an illuminated junction.

These moving carriers will produce an additional current ($-I_L$) called photocurrent (I), and it has given a negative sign because it flows in the opposite direction of the forward current of the diode. This current depends on the minority carrier lifetime (τ) which is defined as the rate of electron-hole recombination. When (τ) is large enough to avoid the electron-hole recombination while they diffuse, the photocurrent increases. The lifetime (τ) is a sensitive function of the crystal perfection and the diffusion length L, as the following

$$L = \sqrt{D\tau} \qquad (2\text{-}1)$$

Where D is the diffusion's constant, Eq (2-1) means that only carriers which are generated within the distance L of the junction are collected at the junction; the rest is lost by recombination. Thus, we can ensure that nearly all the excited carriers cross the junction by making the depletion layer wide or by increasing the minority carrier lifetimes.

The presence of the additional photocurrent shifts the Characteristics by the amount (I_L), hence the current equation can be represented by:

$$\mathrm{I}=\mathrm{I}_{\mathrm{O}}-\mathrm{I}_{L}\left[\exp\left(\frac{eV}{k_{B}T}\right)-1\right] \qquad (2\text{-}2)$$

And the voltage is given by:

$$V=\frac{k_{B}T}{e}\ln\left(\frac{\mathrm{I}+\mathrm{I}_{L}}{\mathrm{I}_{0}}+1\right) \qquad (2\text{-}3)$$

There are many important quantities we can determine, **firstly**, the short-circuit current (I_{SC}) which is, by setting $V=0$, in Eq (2-2) equal to the light generated current (I_{L}).

$$I=I_{sc}=I_{L} \qquad (2\text{-}4)$$

Secondly, the open - circuit voltage (V_{OC}) which can obtain by setting $I=0$ in Eq (2-3):

$$V_{oc}=\frac{k_{B}T}{e}\ln\left(\frac{\mathrm{I}_{L}}{\mathrm{I}_{0}}+1\right) \qquad (2\text{-}5)$$

At high intensities of light the open circuit voltage can approach the semiconductor band gap. In the case of Si solar cells for solar illumination (without atmospheric absorption) the value of V_{0c} is roughly 0.7 eV.

A plot of the current in the solar cell as a function of the voltage provides the curve shown in Fig. (2.7). In general, the electrical power delivered to the load is given by:

$$p=IV=\mathrm{I}_{o}V\left[\exp\left(\frac{eV}{k_{B}T}\right)-1\right]I_{L}V \qquad (2\text{-}6)$$

The maximum power P_{m} is delivered at voltage and current values of V_{m} and I_{m} as shown in. Fig. (2.7).

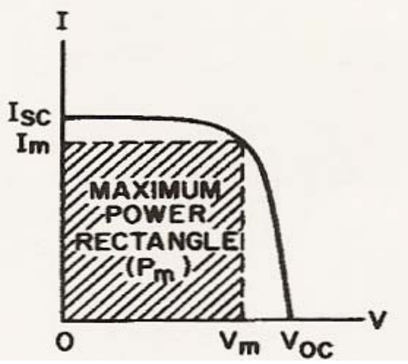


Figure (2.7): The I.V characteristics of the solar cell.

The open circuit voltage is V_{0c} and the short circuit current is I_{sc} the maximum power is delivered at the Rectangle shown in Figure (2.7). [14, 15]

2.4.4 Equivalent Circuit of Solar Cell:

An ideal solar cell may be modeled by a current source in parallel with a diode. In practice no solar cell is ideal, so a shunt resistance and a series resistance component are added to the model. The result is the *equivalent circuit of a solar cell* shown in. Fig. (2.8). [13]

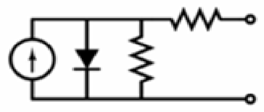


Figure (2.8): Equivalent circuit of the solar cell.

2.5 Types of the Solar Cell:

Solar cells can be classified according to their structure to three main types: bulk, thin film and quantum dot cells.

2.5.1 Bulk Solar Cells

These *bulk* technologies are often referred to as wafer-based manufacturing. In other words, in each of these approaches, self-supporting wafers between 180 to 240 micrometers thick are processed and then soldered together to form a solar cell module. [13]

By far the most prevalent bulk material for solar cells is crystalline silicon.

Two types of crystalline silicon are used in the industry. The first is **monocrystalline**, produced by slicing wafers (up to 150mm diameter and 350 microns thick) from a high-purity single crystal boule. The second is **multicrystalline** silicon, made by sawing a cast block of silicon first into bars and then wafers. The main trend in crystalline silicon cell manufacture is toward multicrystalline technology. [16]

2.5.2 Thin Film Solar Cells

The high cost of crystalline silicon wafers (they make up 40-50% of the cost of a finished module) has led the industry to look for cheaper materials to make solar cells.

The various thin-film technologies - currently being developed - reduce the amount of light absorbing material required in creating a solar cell. This can lead to reduce the processing costs from that of bulk materials but in the same time it tends to reduce the efficiency. [13]

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

The selected materials are all strong light absorbers and only need to be about 1 micron thick, so materials costs are significantly reduced. [16]

The most common thin film solar cells are:

i) Amorphous Silicon devices:

Amorphous silicon (a-Si) absorbs solar radiation 40 times more efficiently than does single-crystal silicon, since Amorphous silicon has a higher bandgap (1.7 eV) than crystalline silicon (c-Si) (1.1 eV), which means it is more efficient to absorb the visible part of the solar spectrum, but it fails to collect the infrared portion of the spectrum. So a film only about 1 micron thick can absorb 90% of the usable light energy shining on it. This is one of the chief reasons that amorphous silicon could reduce the cost of PV cells. Other economic advantages are that it can be produced at lower temperatures and can be deposited on low-cost substrates such as plastic, glass, and metal. This makes amorphous silicon the leading thin-film PV material. [13, 17]

ii) Heterojunction Devices:

This structure is often chosen for producing cells made of thin-film materials that absorb light much better than silicon. The top and bottom layers in a heterojunction device have different roles. The top layer, or "window" layer, is a material with a high bandgap selected for its transparency to light. The window allows almost all incident light to reach the bottom layer, which is a material with low bandgap that readily absorbs light as it is shown in figure (2.9). [18, 19]

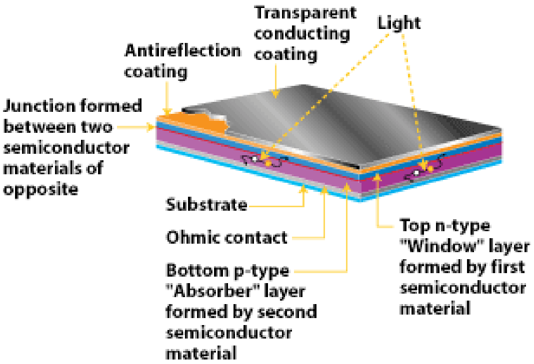


Figure (2.9): Structure of a heterojunction solar cell.

An example of this type of device structure is **copper indium gallium selenide** (**CIGS**). Such structure gave the best efficiency of a thin-film solar cell in December 2005 which was 19.5%. Higher efficiencies (around 30%) can be obtained by using optics to concentrate the incident light.

Another example of the heterojunction is **Cadmium Telluride** (**CdTe**). Cadmium telluride is another famous polycrystalline thin-film material. With a nearly ideal bandgap of 1.44 eV, **CdTe** also has a very high absorptivity. Although **CdTe** is most often used in PV devices without being alloyed, it is easily alloyed with zinc, mercury, and a few other elements to vary its properties. Films of CdTe can be manufactured using low-cost techniques. [13, 19, 20]

iii) Multijunction Devices:

This structure, also called a cascade or tandem cell, can achieve higher total conversion efficiency by capturing a larger portion of the solar spectrum. Each type of semiconductor will have a characteristic band gap energy which causes it to absorb electromagnetic radiation over a portion of the solar spectrum. Photons not absorbed in the first cell are transmitted to the second cell, which then absorbs the higher-energy portion of the remaining solar radiation while remaining transparent to the lower-energy photons. These selective absorption processes continue through to the final cell, which has the smallest band gap as it is shown in figure (2.10). **GaAs** multijunction devices are the most efficient solar cells to date, reaching as high as 39% efficiency. They are also some of the most expensive cells per unit area (up to $ 40/cm²). [13, 18]

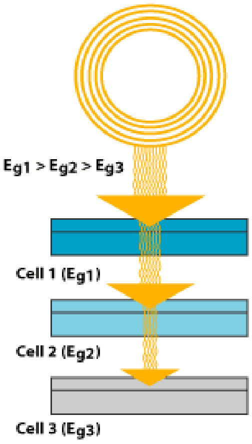


Figure (2.10): A schematic diagram of the multijunction device

2.5.3 Quantum Dot Solar Cells:

Quantum dots or nano-particles are semiconductors crystals of nanometer dimensions. They have quantum optical properties that are absent in the bulk material due to the confinement of electron-hole pairs (called excitons) in a region of a few nanometers.

The first advantage of quantum dot cells is their tunable bandgap. The greater the bandgap of a semiconductor solar cell, the more energetic the photons absorbed, and the greater the output voltage. There is an optimum bandgap that corresponds to the highest possible solar-electric energy conversion, and this can also be achieved by using a mixture of quantum dots of different sizes to collect the maximum proportion of the incident light.

Additionally, in quantum dot cells it possible to generate multiple excitons from the absorption of a single photon.

Therefore, quantum dots are offering the possibilities for improving the efficiency of solar cells in at least two respects, by extending the band gap of solar cells for collecting more of the light in the solar spectrum, and by generating more charges from a single photon. [21]

2.5.4 Organic/Polymer Solar Cells:

Organic solar cells and Polymer solar cells are built from thin films (typically 100 nm) of organic semiconductors such as polymers and small-molecule compounds like polyphenylene vinylene, copper phthalocyanine and carbon fullerenes. Energy conversion efficiencies achieved to date using conductive polymers are low at 4-5%. However, these cells could be beneficial for some applications where mechanical flexibility and disposability are important [13]

(i) Polymer solar cell:

Polymer solar cells are a type of solar cells that is now commercially available. They are durable and find common application in small devices, such as pocket calculators. Polymer solar cells also suffer from huge degradation effects, i.e. the efficiency is decreased over time due to environmental effects. Good protective coatings are still to be developed.

(ii) Poly (phenylene vinylene):

Poly phenylene vinylene is capable of electro-luminescence, producing yellow-green for construction of organic light emitting diodes.

2.5.5 Dye-Sensitized Solar Cells (DSSCs):

In 1991, dye-sensitized nanocrystalline titanium dioxide TiO_2 solar cells (**DSSCs**) were first reported by Grãtzel et al. They based on the mechanism of a fast regenerative photo-electro-chemical process, The overall efficiency of this new type of solar cell was 7.1—7.9% under simulated solar light. The main difference between this type of solar cell and conventional cells is that in the new cells the functional element, which is responsible for light absorption (the dye), is separated from the charge carrier transport. Such a feature makes it possible for **DSSCs** to use low- to medium-purity materials through low-cost processes, and exhibits commercially realistic energy-conversion efficiency. In addition, it is of great importance that the materials used in **DSSCs** are environment-gentle.

DSSCs based on liquid electrolytes have reached efficiency as high as 10%. The main problem is that the liquid electrolytes may limit device stability because the liquid may evaporate when the cell is imperfectly sealed. A liquid electrolyte also makes the manufacture of multi-cell modules difficult because cells must be connected electrically yet separated chemically.

A schematic diagram of the structure of solid-state DSSCs is given in figure (2.11). At the heart of the system is a mesoporous TiO_2 film, which is placed in contact with a solid-state hole conductor. A monolayer of a charge transfer dye is attached to the surface of the nanocrystalline TiO_2 film. [22]

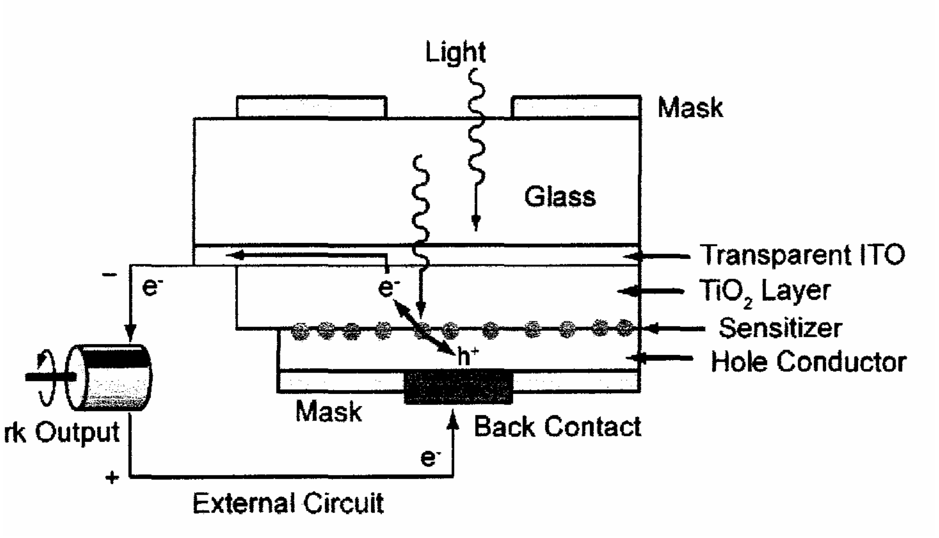


Figure (2.11): A schematic diagram of the dye-sensitized device.

DSSCs use a dye sensitizer to absorb the light and create electron-hole pairs in a nanocrystalline titanium dioxide semiconductor layer. This is sandwiched in between a tin oxide coated glass sheet (the front contact of the cell) and a rear carbon contact layer, with a glass or foil backing sheet.

2.6 Efficiency of Solar Cell:

Solar cells are characterized by some important factors, namely; its fill factor (*FF*), the maximum power output of the device (P_m), the conversion efficiency of the device (η) and the quantum efficiency.

2.6.1 Maximum Power Point:

The cell can be worked for a large range of voltages and currents. This occur by changing the load resistance from zero (a short circuit) to infinity (an open circuit), then we can find maximum power point. Since the power is the product of voltage times current, the maximum-power point (P_m) occurs on the I-V curve (see figure(2.11)) when the product of current times voltage is a maximum. Power can not be produced neither in the short-circuit current because there is no voltage, nor in the open-circuit voltage because there is no current.

Maximum power is created at only one point on the power curve, at about the "knee" of the curve. This point represents the maximum efficiency of the solar cell in converting sunlight into electricity. [23]

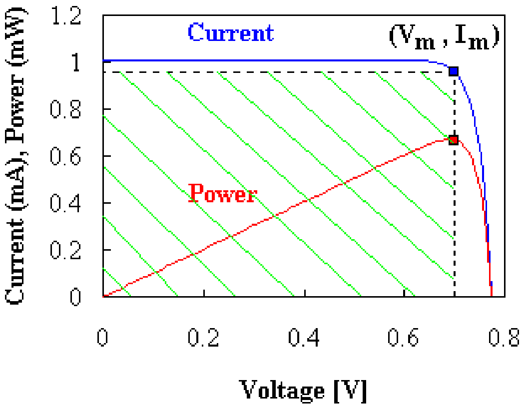


Figure (2.11): Maximum power point in the IV characteristics. [24]

2.6.2 Energy Conversion Efficiency:

The solar cell's energy conversion efficiency (η) is the ratio of the power converted (from light to electrical energy) to the power collected, when the cell is connected to an electrical circuit. Therefore, □ can be calculated by the ratio of P_m, to the input light *irradiance* (E) in W/m^2 and the surface area of the solar cell (A_c) in m^2, i.e.;

$$\eta = \frac{P_m}{E \times A_c} \qquad (2.7)$$ [13]

2.6.3 Fill Factor:

Fill factor (FF) is a factor measures the "squareness" of the I-V curve. It is the ratio of the maximum power point to the open circuit voltage (V_{oc}) and the short circuit current (I_{sc}):

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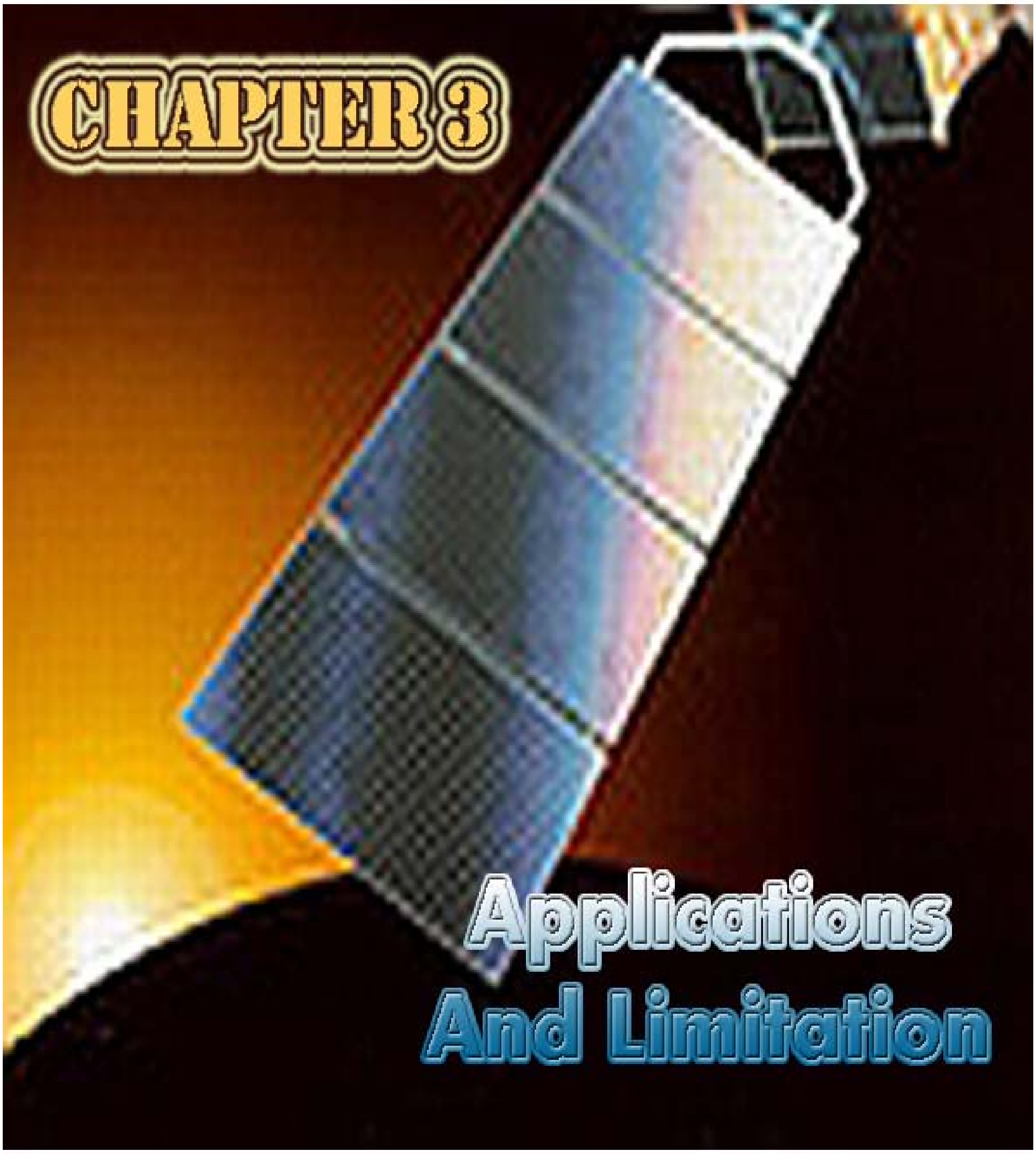
$$FF = \frac{P_m}{V_{oc} \times I_{sc}} = \frac{\eta \times A_c \times E}{V_{oc} \times I_{sc}} \qquad (2.8)$$

[23,13]

2.6.4 Quantum Efficiency:

Quantum efficiency (QE) is the ratio of the number of charge carriers collected by the solar cell to the number of photons — or packets of light — of a given energy shining on the solar cell.

QE depend on the response of a solar cell with various spectrum wavelengths of light shining on the cell. QE is a function of either wavelength or energy. If all the photons of a specific wavelength are absorbed, and all the resulting minority carriers are gathered, the QE at that specific wavelength will have a value of one. The QE for photons with energy below the band gap is zero. [23]



CHAPTER 3

Applications And Limitation

3.1 About the chapter:

Photovoltaic is an important energy technology because it makes use of the abundant and free energy in the sun, also it has little impact on our environment. This technology can be used in a wide range of applications. But the single PV cell is unbeneficial; it must be added to some other components within a system known as *the Photovoltaic System*, before it can be used in any applications.

In the first part of this chapter, we will discuss the components of the photovoltaic system. Then we will show some important applications of this system in our life. Finally, the limitations which get in the way of the solar energy applications will be considered.

3.2 Photovoltaic Electrical System:

An individual solar cell generates a low voltage, approx 0.5V, and only DC current, which is not enough for many applications. Therefore, solar cells must be used through an electrical system known as *Photovoltaic electrical Systems, or PV Systems,* for short. PV Systems have two general types of electrical designs; o*ff-grid and grid-connected* systems. *Off-grid*, or *Stand-alone*, systems are those which use photovoltaic technology only, and they are not connected to a utility grid. Such systems need a battery backup. On the other hands, *grid-tied* systems interact with the utility power grid and have no battery backup capability.

Both types need many components to make the entire system fully functional to supply the needed electricity. These components can be divided into essential and optional ones. [26. 27]

3.2.1 The Essential Components:

i) PV Modules and Arrays:

Solar cells, composed of semiconductor materials such as silicon are the basic of building of PV technologies. An individual PV cell typically produces between 1 and 2 Watts, hardly enough to meet household needs. To increase the power output, a number of cells are connected in series or parallel to form larger PV modules. The module is the smallest commercially available unit for power applications. PV modules range in power output from about 6 watts to about 300 watts with supposed output voltages from 6 to 90 volts. Connecting modules together in series will increase the output voltage, while parallel connection increases the output current. These groups of modules form PV panels or arrays. System designers can create PV arrays that have power outputs of 15kW or more. A typical PV module consists of a protective weatherproof enclosure for the semiconductor materials and the electric wiring, as it is shown in Fig (3.1). [27.28]

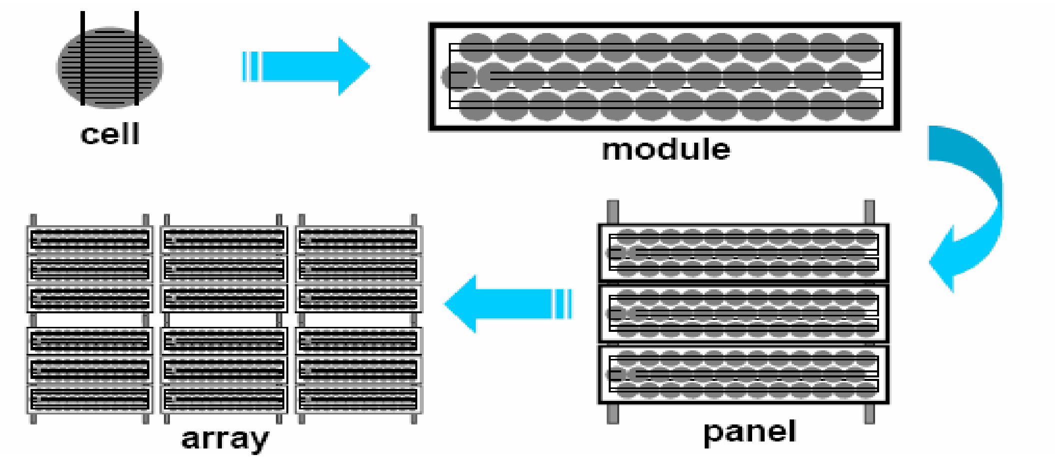


Figure (3.1): Photovoltaic cells, modules, panels and arrays

.

ii) Inverters:

PV cells produce direct current DC, rather than alternating current AC, which is required to run most common household appliances and electronic devices. The inverter converts the DC power produced by the PV array into AC power consistent with the voltage and power quality requirements of the utility grid, and automatically stops supplying power to the grid when the utility grid is not energized. The inverter must be carefully selected to insure proper operation with other system components, for most net metering applications inverters will range in size from 100 Watts, small inverters, to 4kW, large inverters. Large inverters typically contain built in battery chargers. This allows the inverter to operate as a battery charger when power is available from another AC source such as a generator.

There are two classes of inverters. Sine wave inverters supply clean, utility-grade power. Modified sine wave inverters supply a *stepped* sine wave output. This power is not as *clean* as pure sine wave inverters; however, they can operate well in most stand-alone applications and are less expensive than pure sine wave inverters. [29]

iii) Batteries (off-grid):

Batteries are an essential component for off-grid or emergency backup power systems. Several batteries linked together comprise a battery "bank", which collects and stores energy produced by the PV array for periods. Several factors can be used to help determine the size of the battery bank. These include the electric load, the duration of required reserve power, and the availability of a source of backup power, grid or generator. A good quality, lead-acid battery bank will last from 500 to 1,000 charge-discharge cycles depending on depth of discharge and attention to maintenance considerations. Other types of batteries are available such as Nickel Cadmium. These batteries are longer lasting, but quite a bit more expensive than lead acid batteries. A battery box is needed to enclose the battery bank. The battery box must provide adequate ventilation of explosive hydrogen gas that produced during battery charging to the outside. This includes careful attention to charge and discharge levels, periodic watering, and inspection of cables and connections for tightness and corrosion. [29]

iv) Wiring:

Connecting PV panels to the household requires properly sized wiring, installed according to code standards. All systems also require fuses for protection of people and equipment. Interconnection requirements in Vermont include a utility accessible, lockable, load break rated, visible break disconnect switch for all grid connected PV installations. [29]

v) Charge Controller:

A charge controller regulates the amount of energy flowing from the PV array to the batteries. This is essential to avoid the damaging situation of overcharging the batteries. Figure (3.2) shows how this controller works. [29]

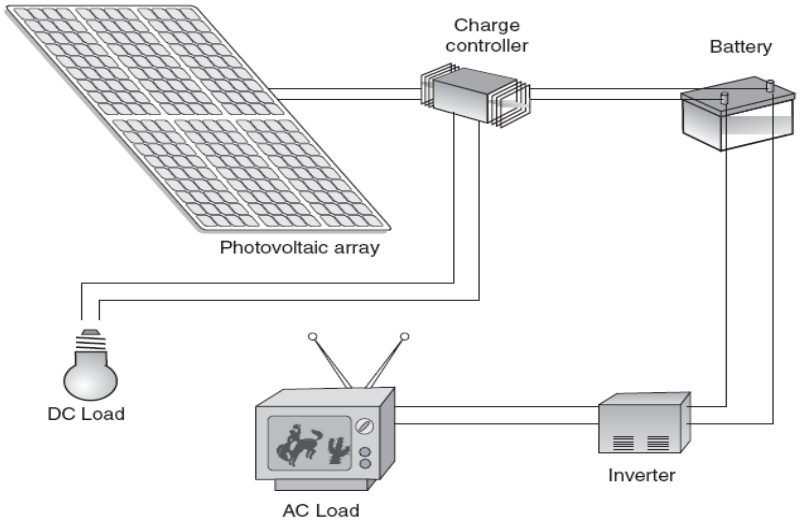


Figure (3.2): Diagram of *stand-alone* PV system.

3.2.2 The Optional Components:

i) Metering:

Grid connected households will most commonly use a single meter set up, whereby the utility meter registers the net difference between the household's load and PV system output. When the PV output is greater than the house's consumption, the meter will spin backwards. If the sun is shining, and the household load is greater than the PV output, then the meter will spin forward, but more slowly than it would if there was no contribution of solar electricity. When the sun is not shining, the utility meter operates as usual in a non-solar house. The single meter set up is attractive because there is no additional cost for PV metering. However, it is difficult to know how much solar electricity is actually generated each month. [29]

ii) Generator:

Some off grid home owners need to install a generator to supplement the PV system during cloudy periods, or for when high-power equipment such as washing machines, water pumps or power tools are being used. [29]

iii) Concentrating Photovoltaic (CPV):

To concentrating photovoltaic systems use a large area of lenses or mirrors to focus sunlight on a small area of photovoltaic cells. These systems use single or dual-axis tracking to improve performance as it is shown in figure (3.3). The primary attraction of CPV systems is their reduced usage of semiconductor material which is expensive and currently in short supply. Additionally, increasing the concentration ratio improves the performance of general photovoltaic materials and also allows for the use of high performance materials such as gallium arsenide. Despite the advantages of CPV technologies their application has been limited by the costs of focusing, tracking and cooling equipment. The sunflower is a CPV system currently in development. [30]

Figure (3.3): A parabolic solar collector concentrating the sun's rays on The solar cells (Solar Stirling Engine)

3.3 Applications of the solar cell:

Anything that requires electricity could potentially be powered by solar energy.

However, there are some specific fields in which solar energy is mainly used today. Some of these fields are shown in figure (3.4).

3.3.1 Uses in Space:

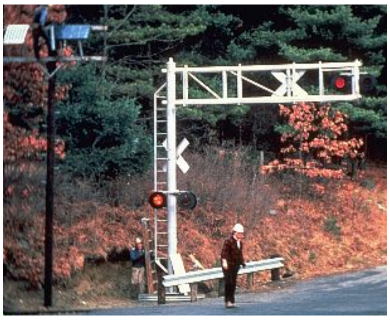
Solar cells have been and will remain the best choice for providing electrical power to satellites to orbit around the Earth. The first practical application of photovoltaic power was on the U.S. satellite Vanguard I in 1958. Since then, the satellite power requirements have evolved from few Watts to several kilowatts, with arrays approaching 100 kW being planned for a future space station. Photovoltaic modules have proved to be a good source of power in this field.

It was shown practically that the lifetime of satellites powered by solar cells is longer than those use normal batteries. [31]

(a) In Space.

(b) In ocean.

(c) In desert.



(d) In Lighting.

Figure (3.4): Some uses of the solar energy.

3.3.2 Industrial Uses:

Photovoltaic modules have proved to be a good source of power for high-reliability remote industrial use in inaccessible locations, or where the small amount of power required is more economically met from a stand-alone PV system than from mains electricity. Examples of these applications include:

i) Ocean navigation: many lighthouses and most buoys are now powered by solar cells.

ii) Telecommunication systems: radio transceivers on mountain tops or telephone boxes in the country can often be solar powered.

iii) Remote monitoring and control: scientific research stations, seismic recording, weather stations, etc. use very little power which, in combination with a dependable battery, is provided reliably by a small PV module.

iv) Cathodic protection: this is a method for shielding metalwork from corrosion, for example, pipelines and other metal structures. A PV system is well suited to this application since a DC source of power is required in remote locations along the path of a pipeline. [31]

v) PV Systems: can be used to pump water in remote areas e.g. as part of a portable water supply system. Specialized solar water pumps are designed for submersible use (in a borehole) or to float on open water. Usually, the ability to store water in a tank means that battery power storage is unnecessary. Large-scale desalination plants can also be PV powered. Larger off-grid systems can be constructed to power larger and more sophisticated electrical loads by using an array of PV modules and having more battery storage capacity. [32]

3.3.3 Domestic Uses:

Solar cells are already viewed as the best option for electricity supply in many fields such as:

i) Lighting: which can be considered as the biggest application of photovoltaic tens of thousands of units installed world-wide, to provide lighting for domestic or community buildings, such as schools or health centers. PV is also being increasingly used for lighting streets and tunnels, and for security lighting. [31]

ii) Solar energy: is also frequently used on transportation signaling e.g. offshore navigation buoys, lighthouses, aircraft warning lights on pylons or structures, and increasingly in road traffic warning signals advertising boards. [32]

iii) A part from off-grid homes: other remote buildings such as schools, community halls, and clinics can all benefit from electrification with Solar Energy. This can power TV, video, telephony…etc. [32]

3.4 Solar Cell Limitation:

Solar cells have a lot of applications but they are limited by three main factors; efficiency, cost, and Lifetime

3.4.1 Efficiency:

Solar cells are characterized by the percentage of the incident power that they convert into electric power. This characteristic factor is called the *power conversion efficiency* or just *efficiency*. The efficiency is given by a percentage and it is depend on many factors. [33]

i) Energy Losses:

Light is composed of photons—or packets of energy—that range in wavelength. The energy of photons can be expressed in term of wavelength by the relation $E = hc/\lambda$. When light strikes the surface of a solar cell, some photons are reflected and the other photons pass through the material, some are absorbed but only have enough energy to generate heat, and some have enough energy to exciting an electron from the valence band to the conduction band, leaving behind a positively charged hole. If these excited carriers can be separated before they spontaneously recombine, voltage and current can be derived, hence power can be provided to a load. . [34,37]

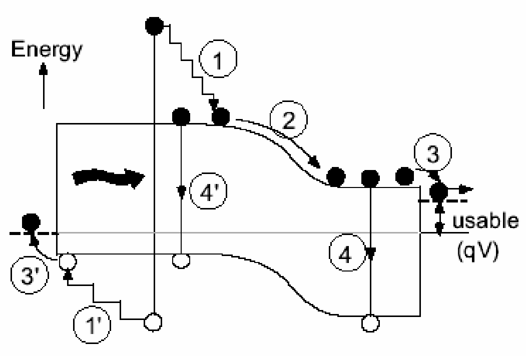


Figure (3.5): Processes through which energy can be lost in the solar cell.

In stander solar cell, there are four processes through which energy can be lost. Namely;

1) If the light energy is lower than the semiconductor band gap simply passes through unutilized, which represents a significant loss. . [34]

2) If an electron is excited to the conduction band by a photon with energy greater than the bandgap, it will lose energy as heat (thermalization of photogenerated carriers) until the energy of the electron is reduced to the bandgap energy, (see figure (3.5), case.1). [34]

3) When N and P-type silicon come into contact, they create their own electric field. This electric field is created when the electrons on the N-type silicon close-by fall into the holes in the P-type silicon. The result is a barrier between the positive and negative sides, called diode, which allows electrons to travel one way. The barrier is called a diode. The diode allows electrons to travel from the P-type silicon to the N-type silicon, but not the other way around (figure (3.5), cases 2 & 3).[38]

4) An electron in its excited state will spontaneously return to its ground state, and in doing so it will release energy as heat or light. This is known as recombination of the photoexcited electron-hole pairs (figure (3.5), case 4). [34]

ii) Natural electrical Resistance:

The natural resistance to electron flow in a cell decreases cell efficiency. These losses control in three places: in the bulk of the primary solar material, in the thin top layer typical of many devices, and at the interface between the cell and the electrical contacts leading to an external circuit. [37]

Larger electrical contacts can minimize electrical resistance. But covering a cell with large, opaque metallic contacts would block too much incident light. Typically, top-surface contacts are designed as grids, with many thin, conductive spread over the cell's surface as it shown in figure (3.6). The back-surface contact of the cell is simpler, it often being just a layer of metal. [37]

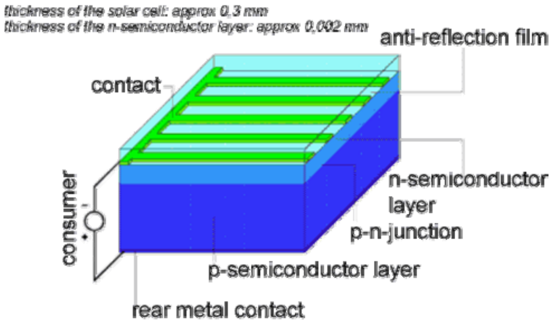


Figure (3.6): Front and rear contacts of the solar cell.

iii) Temperature:

Solar cells work best at low temperatures, as determined by their material properties. All cell materials lose efficiency as the operating temperature rises. Much of the light energy shining on cells becomes heat, so it is good to either match the cell material to the operation temperature or continually cool the cell. [37]

iv) Reflections:

A cell's efficiency can be increased by minimizing the amount of light reflected away from the cell's surface. For example, silicon reflects more than 30% of incident light. We can use antireflection (AR) technologies in the top layer of solar cell to optimize light absorption. A single AR layer will reduce reflection only at one wavelength. The best results with use multiple AR layers over a wider range of wavelengths.

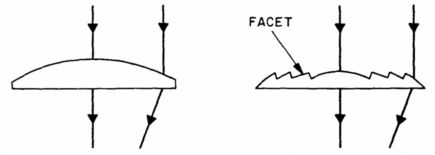


Figure (3.7): Reducing reflection by texturing the top surface of the cell.

Another way to reduce reflection is to texture the top surface of the cell as shown in figure (3.7), which causes reflected light to strike a second surface before it can escape, thus increasing the probability of absorption. If the front surface is textured into pyramid shapes for antireflection, all incident light is bent so that it strikes the polished—but otherwise untreated—back surface of the cell at an angle. This texturing causes light to be reflected back and forth within the cell until it is completely absorbed. [37]

v) Light intensity:

The best result of solar cells electricity in the daylight, whereas the result is not good at sunrise or sunset as a result of smallness of light intensity. A higher light intensity will be focused on the solar cells by the use of mirror and lens systems. [35]

Silicon as a semiconductor has many limitations. While the limit on conversion of sunlight to electricity is 95%, the theoretical upper limit for the standard single junction silicon solar cell is just 33% and the research or laboratory efficiency of these is close to 25% as a result of previous limitations. The theoretical efficiency rises to 40.8% under concentrated light. [34]

3.4.2 Cost:

Solar cells in commercial production today are expensive; they cost around $6 per watt. To understand what that means, consider this: If you install $600 worth of solar cells, you can power a typical light bulb for 25 years. That is about twice the cost of coal-based electricity.

Through various technological improvements, solar-cell prices have typically fallen by 5% to 6% a year, but no more, because cells are manufactured through complex processes similar to those employed for making PC processors and memory cards. [36]

The photovoltaic industry has achieved impressive improvements in solar cell efficiencies and significant cost reductions. Mostly photovoltaic cells today achieve efficiencies between 12 and 20 percent, well above what they were just 15 years ago. The price of photovoltaic panels has declined from $100/watt in the 1970s to the current price of approximately $3 /watt. The global photovoltaic industry is expanding rapidly; global manufacturing of solar cells stood at 58 megawatts per year in 1992 and has risen to over 1,600 megawatts per year in 2005 - an increase of almost 30% per annum over the past 15 years. Analysts believe that the photovoltaic industry will continue to see impressive gains in efficiencies and cost reductions.

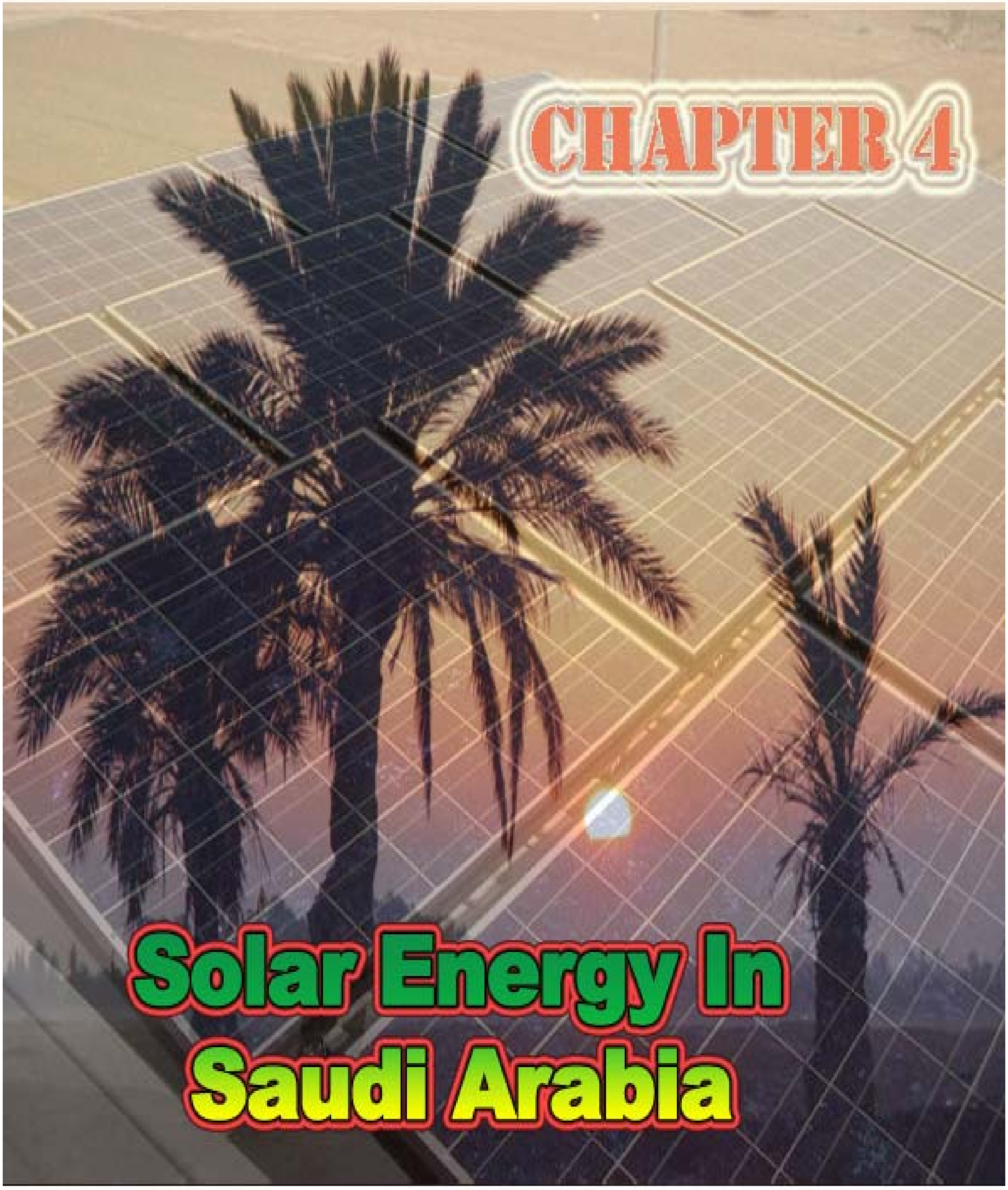
In recent years, most solar production has been going to Europe and Asia, even from US-based manufacturing facilities. Countries like Germany have had government motivation programs that have made the installation of solar systems attractive. In the US, some states have instituted financial motivations that have played an important role in starting to boost the use of solar electricity in the US.

The price of electricity produced from solar cells is still significantly more expensive than it is from fossil fuels like coal and oil, especially when environmental costs are not considered. Photovoltaics can be cost-competitive for utility companies today, especially in areas where photovoltaic installations can defer or avoid costly upgrades to the transmission and distribution system. [40]

3.4.3 Lifetime:

Solar cells lifetime depends on some factors such as temperature, materials and the recombination rate that occurs inside the junction. It is found that lifetime slowly increases with temperature over the range of 10 to 80 C under constant irradiance. On the other hands, lifetime decreases with the recombination that occurs inside the solar cell. [39]

Modules from crystalline cells have a lifetime of over twenty years, while thin-film modules will last at least ten years. [38]


CHAPTER 4
Solar Energy In
Saudi Arabia

4.1 About the Chapter:

The Kingdom of Saudi Arabia is one of the major players in the energy (oil) field. As a matter of fact, it is the largest oil producing and exporting country in the world.

However, the government of Saudi Arabia is fully aware that they cannot depend on oil for their income forever, especially in the current situation of price fluctuations. Therefore, their 5 year plans call to diversify the sources of the country's revenue. In fact, investments in the petrochemical industries have come through this trend. The Saudi Arabian Basic Industries, "SABIC", now produces about 3—4% of the petrochemical products of the world.

The oil producing and exporting countries should understand that there have been changes in energy sources throughout history. Energy has come from horsepower and hydropower, to coal, oil, nuclear, solar and hydrogen. These countries, including Saudi Arabia, should be ready for any transition in the energy technologies and should have a long term energy strategy.

The Kingdom of Saudi Arabia has a variety of natural resources for energy, namely underground (oil and gas), in the air (wind) and from the sky (solar), and different industrial minerals and raw materials, such as quartz, sand, iron, copper, zinc, lead, underground water, sea water etc. With good vision and a flexible strategy, Saudi Arabia may rationally utilize these resources and play a more effective role in the energy world in the coming decades. Even in the transition toward clean energy technologies, the Kingdom of Saudi Arabia could become an "Energy Kingdom", rather than just an "Oil Kingdom" [41].

In this chapter we will shed more light on the solar energy programmes in Saudi Arabia. These programmes can be divided mainly into international joint and local programmes.

Two major joint international cooperation programmes were introduced to which the Saudi government provides one-half of the funds needed, while the other half is provided by developed countries, such as United States and the Federal Republic of Germany. These joint programmes have been directed towards projects that are of mutual interest to both countries and which have concentrated on large demonstration plants, such as electricity generation, desalination, agriculture and cooling systems.

4.2 Joint Program with the USA

This program, which is called **SOLERAS** (**SOLE**ar **E**nergy **R**esearch - **A**merican / **S**audi), addressed solar energy technological and economical related issues. SOLERAS began in 1977 and concluded in 1987. A second program, started in 1989 with US Department of Energy (DOE) to address the other technologies of renewable energy, in addition to solar energy [42].

4.2.1 SOLERAS

In the SOLERAS program, each country contributed US$50 million to the budget. The program was focused on the following fields of solar energy utilization:

i) Rural Agricultural Applications

The major goal was to examine the feasibility of using solar technologies in remote areas. These included the Saudi Solar Village Project and the Saudi Controlled

Environment Agricultural Project, which aimed to control agriculture with solar energy in climate zones similar to those of Kingdom of Saudi Arabia.

ii) Urban Applications

The objective of the Urban Applications was to investigate the use of solar energy in the active cooling of buildings, under typical conditions of hot-arid and hot-humid environments. Such project could improve the quality of life for the inhabitants in a hot environment.

iii) Industrial Applications

The goal of this program was to use solar technologies in industrial applications that require thermal or electric energy. The major project was the development of solar-powered sea-water desalination technologies.

The total cost of these programmes was roughly US$35.3 million. In this application, a solar-powered sea-water desalination pilot plant was installed by SOLERAS in Yanbu in December 1984. The plant uses an indirect contact heat transfer freeze process to produce 200 cubic meters of potable water per day. This plant, however, was later closed down for economic reasons.

iv) Resource Development Activities

Several activities supported resource development, which includes the collection and analysis of solar resource data, granting universities multi-year funding to conduct basic solar energy research, organizing and sponsoring major international technical solar workshops and annual short courses in solar-related fields, and disseminating the technical knowledge acquired during the program. The total cost in this area was US $5.1 million.

4.2.2 Renewable Energy Research Program

A second program of collaboration between the (DOE) and King Abdulaziz City for Science and Technology (**KACST**), is currently addressing the other technologies of renewable energy, namely, wind, geothermal, bio-mass, etc., in addition to solar energy. The main activities included in this program are:

i) Solar Energy for Remote Applications

In remote areas, water is very important for the life of the community, for watering stock and for irrigation. In Saudi Arabia, the major source of water is underground, and supplies are drawn to the surface using diesel engines. These engines need a continuous fuel supply for regular operations. Fuel supply to remote areas can be very costly. Solar energy can, therefore, be a competitive alternative source for water pumping and desalination. The first PV powered water pumping and desalination plant was installed in 1994 at Saudis village, approximately 70 km from Riyadh.

ii) Assessment of Solar Radiation Resources in Saudi Arabia

Reliable quantitative data on the daily and annual distribution pattern of solar energy at given locations are essential not only for assessing the economic feasibility of solar energy, but also for the thermal design and environmental control of buildings and greenhouses. Therefore, a Saudi Atlas Project has been initiated, and 12 locations have been selected in the following cities throughout the Kingdom: Riyadh, Gassim, Al-Ahsa, Al-Jouf, Tabuk, Madinah, Jeddah, Qaisumah, Wadi Al Dawasir, Sharurah, Abha and Gizan. All these stations are connected to a central unit for data collection, and all the instruments are calibrated from time to time in order to provide reliable and accurate data.

4.3 Joint Program with Germany

Under the umbrella of the Saudi-German Joint Commission on Economic and Technical Cooperation, this program is devoted to addressing several solar energy related issues through a joint international Research and Development (R&D) program. It started in 1982 with the *Solar Thermal Dish Project*, and it was then expanded to include sizable projects dedicated to the advancement of solar hydrogen technologies [42].

i) The Solar Thermal Dish Project

The Solar Thermal Dish Project is a joint program between KACST and the Federal Ministry of Research and Technology, Bonn, BMFT (Germany). This Program is aimed at the production of 50 kW of electrical power from each thermal dish. It involves the development, construction, and testing of two 17 meter diameter large-scale membrane solar concentrators. It uses a large hollow reflector that tracks the sun. The units are coupled with Stirling engines to convert the solar thermal energy collected into mechanical energy to drive 50-60 kW peak electrical A/C generator. These are both dishes to be connected with the electric utility grid to evaluate cogeneration mode, and those used in a stand-alone mode to demonstrate the system's capability of providing electric power for remote sites. The Solar Thermal Dish Project, which has succeeded in generating 50 kW of electricity from a single concentrator dish, is still considered the largest dish of its type in the world. The project's budget was approximately 8 million Deutsche marks.

ii) Solar Hydrogen (HYSOLAR)

The Saudi interest in solar hydrogen arose about ten years ago when it was envisaged that hydrogen might become the main source of energy in the next century. In 1986 both the Kingdom of Saudi Arabia and the Federal Republic of Germany agreed to cooperate in a research, development and demonstration program called HYSOLAR (Hydrogen from SOLAR energy) with the following main objectives:

1-To attain sufficient scientific knowledge for the future commercial production and use of hydrogen in Saudi Arabia.

2-To demonstrate the use of these technologies to the general public of Saudi Arabia.

The HYSOLAR program is funded jointly with a total budget of 60 million Deutsche marks [42].

4.4 KACST Solar Programmes

Solar Energy research in Saudi Arabia is being conducted by King AbdulAziz City for Science and Technology (**KACST**). The major work in this field is connected by the Energy Research Institute (ERI) at KACST. The main solar energy projects executed by ERI are: [42]

4.4.1 Saudi Solar Village

i) The Objective

The objective of this project is to use solar energy to provide power to remote villages not serviced by an electric power grid. The long-range goal is to install a solar energy system capable of delivering up to 1 MV of electrical power to the villages.

ii) The Location

The Solar Village Project site is located near the villages of Al-Jubaiylah and Al Uyaynah, which are about 50 km northwest of Riyadh, the capital city of Saudi Arabia as shown in figure (4.1). [42]

Figure (4.1): The location of the solar village in Saudi Arabia

iii) General Description

A 3 kW photovoltaic power system has been established at the Solar Village in order to evaluate the resulting effects of changing direction, rotation, dust and temperature on photovoltaic measurements as well so test the efficiency and output of a photovoltaic system.

The Photovoltaic power system is developed, fabricated and installed to provide electrical energy to the villages of AL- Uyaynah, Al-Jubaiylah and AL-Hajrah.

The entire Photovoltaic Project site occupies an area of approximately 67,180 square meters [42].

The major parts of the project are the following:

- The Array Field: It consists of 160 photovoltaic arrays (of 350 KW) and covers an area of 40.000 square meters.
- The Control System: It consists of the signal termination cabinets, a control computer, a data recording system computer and a control and display panel with associated electrical wiring.
- The Energy Storage System: It is furnished with 1100 KWH lead acid batteries. The batteries will provide electrical load power during the night hours of non-insulation and during inclement weather.
- Solar Data Collection System: It is an automatic weather data gathering system.

4.4.2 KACST Independent Programmes

i) Wind Energy Resource Assessment

A separate study has been initiated for wind energy assessment in Saudi Arabia. Five locations, namely; Abha, Arar, Dhahran, Solar Village and Yanbu. Have been selected for this purpose. The installation of monitoring equipment at those sites is in hand.

ii) Assorted Project

Energy building research has produced several studies on the basic factors which affect energy in buildings and or energy conservation principles using the behavior of a solar house, e.g. cooling, heating and lighting. Research, development and demonstration work on photovoltaics, solar cookers and solar stills has also been carried out at KACST [42].

iii) Solar Dryers

Drying immature dates is a problem for many countries where the relative humidity is high during the drying season.

The Energy Research Institute, KACST in cooperation with the Ministry of Agriculture and Water, has conducted various research studies to develop the most efficient system drying dates using solar energy. In this connection, a number of solar dryers have been designed, installed and experimentally rested at the Al-Hassa and Qatif agricultural experimental test [42].

iv) Solar Thermal Dish Project

The Solar Electric Stirling Engine Concentrator (the Solar Thermal Dish Project) is a joint program between KACST and the Federal Ministry of Research and Technology, BMFT, Bonn (Germany), which was mentioned before in sec(4.3). [43]

v) 350 kW Solar Hydrogen Production Project

Production Hydrogen by PV methods, and storing it, is effective way of exploiting solar energy desirable time. The Solar Hydrogen Production Project in solar village is the Worlds first 350 kW solar powered hydrogen generation plant.

This plant uses the DC electricity being produced by the 350 kW PV field and the AC power from grid supply through the rectifier. The electricity is used by advanced alkaline water electrolyze (0.25m^2 of electrode area, 120 cells) to produce 463 cubic meters of hydrogen per day at normal pressure [43].

Results show that following improvements are required:

1. Hardware improvement of PV-field and electrolyze.
2. Improvement of the AC power supply for the rectifier.
3. Installation of a new pressurized air system and adaptation of specific measurement techniques.

vi) Solar-Powered Hydrogen Utilization Project

The development of hydrogen for domestic, agriculture and industrial applications, (cooking, cooling, lighting, and electrical energy generation for example) is one of the aims of the **HYSOLAR** program. Hydrogen used to power fuel cells also represents an exciting power generation technology for the coming decades. Fuel cells are universally applicable due to their high efficiency (75% to 80%), modularity, optimum environmental characteristics, sitting feasibility and for their direct use of hydrogen or natural gas as a fuel and air as an oxidant [43].

vii) Solar Water Heating Project

It has recently been observed that consumption of electricity is increasing significantly in Saudi Arabia, which is creating an imbalance between demand and supply. One way to reduce electricity consumption in water- heating sectors is to introduce solar water heating systems (**SWHS**) for different hot water applications (for domestic and industrial use for example). A study on the development of SWHS is under way, through which a number of suitable SWHS (for different climatic areas) will be designed, fabricated (by utilizing locally available material) and field tested for all seasons.

The largest application of solar water heating project in Saudi Arabia is the solar powered compound of the King AbdulAziz Airborne Training School in Tabuk. To heat 14 of the 22 buildings of the school, solar collectors (covering total surface area of 4370 m^2) were used. The solar heat collected is used to supply 40% of the building heat and 100% of the domestic water needs.

The Royal Commission for Jubail and Yanbu installed a number of thermosyphon type solar domestic hot water units. At **MYAS** Medical Center staff housing campus in Yanbu, comprising 132 solar flat-plate collectors of 490 m^2 total surface area were used [43].

viii) Solar Powered Highway Device

Due to the difficulties in the use of electric power from the national grid for illuminating the highway networks, the Ministry of Communication requested that KACST conduct experiments, with the goal of determining the economic feasibility of using solar energy for highway illumination. In order to conduct this exercise, KACST has used PV systems to power highway devices in various remote locations within the country. The most significant projects are the lighting systems for two remote tunnels located in the southern mountains of Saudi Arabia [43].

4.5 Lessons Learned

As a result of Saudi Arabia's efforts in research and development of renewable energy sources, valuable lessons have been learned, which are also believed to be very useful to other countries with similar climatic conditions, as well as to the scientific community in general. The overall lessons gained are listed as follows: [43]

1) In the developing countries, it is not worth spending hinds on basic research for developing renewable energy sources. Instead, such efforts should be directed to finding applications of those systems that have already been developed by industrialized nations.

2) Researchers in the field of renewable energy have responsibilities beyond the scientific and technical aspects of research and beyond the efforts made for publication of their findings. These include dissemination and utilization of scientific knowledge gained in laboratories; and interaction with potential users, policy makers, planners, and manufacturers.

3) Seawater desalination by solar energy is still not seen as cost effective when compared with conventional energy sources (gas and oil) as implemented in Saudi Arabia.

4) Assessment projects on renewable energy resources have helped Saudi staff gain valuable experience, especially in the fields of instrumentation, calibration, data collection, and monitoring and analysis.

5) The solar-thermal dish project revealed that development of thermal dishes with a smaller diameter would be more practical for remote applications because the operational and maintenance problems of large-scale dishes are complex and they are not cost effective.

6) Hydrogen production by PV systems can be used to store solar energy in a convenient form that can subsequently be used at a time of need; for example
Power generation and domestic applications.

7) The need to regularly clean the PV array in dusty weather in order to maintain an acceptable level of system output. It was found that the dust effect, which in some parts with low rainfall can reduce solar energy by 10% to 20%.

8) PV systems have proven cost effective in Saudi Arabia in supplying the peak demand of the electricity grid as well as in supplying energy for small loads at remote Sites.

9) Close contacts and effective interaction need to be maintained between researchers and local industry in order to bring the new developed product to practice.

10) There is a need to promote proper education and technical training on renewable energy applications within academia, as well as a need to increase public awareness about the benefits of using these sources of energy.

11) The availability of governmental subsidies for oil and electricity generation and non-availability of similar subsidies for solar energy programs. Such subsidies inhibit the chances for solar energy to compete with the commercial energy sources that are available. If such subsidies continue then solar energy will require incentive programs.

References:

[1] 'Renewable energy'(online),Wikipedia http://en.wikipedia.org/wiki/Renewable_energy ,

[2] 'Definition of a Solar Cell – History of Solar Cells'(online), about, http://inventors.about.com\od\sstartinventions\a\solar_cell.htm?terms=solar+cell, January, 2007.

[3] 'Best Locations for Photovoltaic Generation of Electricity Around The World'(online), Hydrogen UK, 2001. http://www.hydrogen.co.uk\h2\world_map.htm, Feb, 2007.

[4] Alnatheer, O. “The Potential contribution of renewable energy to electricity supply in Saudi Arabia” .Energy Policy, Vol. 33 (2005)2298-2312

[5] Scott, A. 'How Solar Cells Work'(online), how stuff works, http://www.howstuffworks.com\solar-cell.htm,

[6] Judson, S. ‘Electronics : Circuits& Devices’, Canada: john Wiley & Sons, ink. 1976, pg.121, 124-126.

[7] Omar, M. “Elementary Solid State Physics : Principles & applications” ,United State of America: Addison-Wesley Publishing Company, Ink .1997,pg.210-211.

[8] Kittel, C. “Introduction to Solid State Physics”, United State :John Wiley & Sons, Ink.1976.pg207-208.

[9] 'Organic Semiconductor devices' (online), RICE Information technology, http://www.ruf.rice.edu\~natelson\p_osc.html,

[10] Chiatzun Goh, Michael and D.McGehee, 'Organic Semiconductor for Low Cost Solar Cells ' (online), National Academia of Engineering, http://www.nae.edu\nae\bridgecom.nsf\Multi+Database+Search\AC1BCED1C0B00F5685257111006F5BDB ,October,2006.

[11] Halliday, D. et al. Fundamentals of Physics, New York: John Wiley & Sons, Ink.2001,pg.1050-1051.

[12] 'solar cell' (online), Wikipedia, http://en.wikipedia.org/wiki/Solar_cell, October,2006.

[13] Sze, S. “semiconductor Devices Physics and Technology”, Canada: Wiley,1985.pg.289-292.

[14] Wieder, S. “An introduction to Solar energy for scientists and Engineers”, New York , NY: Wiley, 1992. Pg.8.

[15] 'Solar Cell Technologyies' (online), Solarbuzz, http://www.solarbuzz.com\Technologies.htm,

[16] 'Polycrystalline Thin Film' (online), Solar Energy Technologies Program, U.S.Department of Energy, http://www1.eere.energy.gov\solar\tf_polycrystalline.html, November,2006.

[17] 'Silicon' (online), energy efficiency and renewable energy, U.S.Department of Energy , http://www1.eere.energy.gov\solar\silicon.htm, November, 2006.

[18] 'Solar Cell Structures' (online), energy efficiency and renewable energy, U.S.Department of Energy, http://www1.eere.energy.gov\solar\index.html , November, 2006.

[19] 'polycrystalline Thin Film'(online), energy efficiency and renewable energy , U.S.Department of Energy, http://www1.eere.energy.gov\solar\tf_polycrystalline.html, November,2006.

[20] 'semiconductors & Electro ceramics' (online), University of Durham, http://www.dur.ac.uk\~dph0www5\solar.htm , October,2006.

[21] Mae-Wan Ho 'Quantum Dots and Ultra-efficient Solar Cells' (online), Institute of science in society, http://www.i-sis.org.uk\QDAUESC.php .

[22] Li.B et al. 'Review of recent program in solid-state dye-sensitized solar cells' in solar Energy Materials & solar cells. Vol. 90, (2006), pp.549-573.

[23] 'Current-Voltage Measurements' (online), U.S. Department of Energy, Energy Efficiency and Renewable Energy,

http://www1.eere.energy.gov\solar\current_voltage.html , October, 2006.

[24] 'Photodiodes and Solar Cells' (online), University of Colorado at Boulder, http://ece-www.colorado.edu\~bart\book\solar.html , October, 2006.

[25] 'Photovoltaic Power System: What Inspectors Need to Know'(online), IAEI, http://www.iaei.org\subscriber\magazine\04_b_wiles.htm , October, 2006.

[26] 'perspective on PV: Photovoltaic Power Systems and the NEC'(online), IAEI, http://www.iaei.org\subscriber\magazine\99_a\wiles.htm , October, 2006.

[27] 'cells, modules & Array'(online), Florida solar energy center, http://www.fsec.ucf.edu\en\consumer\solar_electricity\basics\cells_modules_arrays.htm, November, 2006.

[28] 'Education' (online), Solar Connecticut, http://www.solarconnecticut.org\education.htm, October, 2006.

[29] 'solar cell' (online), Wikipedia, http://en.wikipedia.org\wiki\solar_power#concentrating_collector_with_stirling_enging , November, 2006.

[30] 'Applications – contents' (online), solar electricity, http://www.soton.ac.uk\~solar\intro\appso.htm , November, 2006.

[31] 'Uses of solar energy '(online), solarbuzz, http://www.solarbuzz.com\Applications.htm , November, 2006.

[32] Honsberg, Christiana 'FAQ List for Solar Cells'(online), Electrical and Computer Engineering at The University of DEIAWARE, http://www.ece.udel.edu/~honsberg/FAQListforSolarCellsv2.pdf , November, 2006.

[33] 'absorption of light, Separation of Electric Charge' (online), Evident Technologies, http://www.evidenttech.com\applications\solar-cell-white-paper\solar-limitations.php , November, 2006.

[34] 'photovoltaics: Solar Electricity and Solar Cells in Theory and Practice' (online), the solar server Forum for solar Energy,

http://www.solarserver.de/wissen/photovoltaik-e.html#nat , December, 2006.

[35] Olga Kharif, January 31, 2006 'Solar Cells: The New Light Fantastic'(online), business week, http://businessweek.com/technologh/content/jan2005/tc2005131_1084_tc024.htm , December, 2006.

[36] 'Current-Voltage Measurements'(online), U.S. Department of Energy, Energy Efficiency and Renewable Energy, http://www1.eere.energy.gov/solar\current_voltage.html , November, 2006.

[37] 'solar Technology'(online), Solar Electrical Light Fund Powering a Brighter 21st century, http://www.self.org/shs_tech.asp , November, 2006.

[38] Dondero, R.C.; Schroder, D.K. and Backus, C.E., 'Minority carrier lifetime measurements on silicon solar cells under concentrated sunlight'(online), Smithsonian/NASA ADS, http://adsabs.harvard.edu/abs\1987pvsp.conf.1374D , December, 2006.

[39] 'Solar Electricity'(online), Northeast Sustainable Energy Association (NESEA), http://nesea.org/buildings/info/solarelectricity.html , December, 2006.

[40] Abaoud, H.A.' Energy Kingdom ', Energy conversion and Management. Vol.43, 2002, pg. 855-861.

[41] Al-Athel, Saleh A. 'solar energy in the kingdom of Saudi Arabia '. International Journal of Global Energy Issues. Vol.9.No.1/2, 1997, pp.53-67.

[42] Alawaji, Saleh H.' Life after oil: solar Energy Research and Applications in Saudi Arabia', Renewable Energy. Vol. 22 March2001, pp.14-19.

[43] 'Solar village' .Saudi Arabian National Center for Science and Technology, Riyadh, 1982.

[44] Said, S.A.M., El-Amin, I.M. and Al-Shehri, A.M.' Renewable Energy Potentials in Saudi Arabia' King Fahd University of Petroleum & Minerals Dhahran Saudi Arabia.

[45] Alawaji, S.H 'Evaluation of Solar Energy Research and its Applications in Saudi Arabia-20 Years of Experience' Renewable and Sustainable Energy Reviews 5(2001), pp.59-77