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Solar Photovoltaic Technologies: An Approach to Sustainable Energy

Shikha Sharda and Derminder Singh*

Punjab Agricultural University, Punjab, India

**Corresponding author*

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A B S T R A C T

The environment awareness and increase demand for energy along with remarkable progress of inexhaustible energy technologies, has given up new opportunities for utilization of renewable energy resources. Since the beginning of this era, people have been allured by the sun that is the ultimate source of energy. The power received by Earth is many times larger than the present rate of all the energy consumption. Photovoltaic technology is one of excellent ways to use the solar power. There is an immense increase in solar power technologies. Solar power systems provide an optimal solution for generating power for residential, commercial and industrial applications. This paper aims at providing a great help to researcher to deal in solar power technologies and gives an idea regarding performance efficiency of different solar photovoltaic cell.

Introduction

The immense use of energy causes the significant change in environment(1). In 21st century, growing of energy crisis is the alarming situation (2). Over many years, fossil fuels have been used for energy generation, but in today's world using these fuels to meet our energy needs is becoming a problem. As reported by International Energy Agency, the current share of fossil fuels is at 82% in the global energy mix. It is same as it was 25 years back. Due to increase in use of renewable energy sources, the dependency on fossil fuels for energy production is likely to be declined up to 75% by the year 2035(3). Now, people are more aware about the environmental challenges that they are facing in their day to day lives. The burning of non-renewable energy resources (petroleum, coal) produces harmful pollutants in air and water which results in environmental degradation. Another issue with fossil fuels is that the energy generated is limited. With the passage of time, the supply of fossil fuels is fast running out making it difficult to meet the energy requirement each year. To protect our planet, there is great need to switch to a clean energy which must be environment friendly. Nowadays, renewable resources of energy are in great demand. The major advantage of renewable energy resources is the environmental friendly and inexhaustible. But there are few challenges as well. One is its dependency on climate. These energies continuously change with the variation in climatic conditions (4-5). Hence, the power drawn from them is not constant every time. Sometimes, the power reduces to zero at night or in adverse environmental conditions. For continuous operation of the system, the batteries can be used which store the power generated by solar panel for future use. Second is the high cost of generation (6).

Power generation with the help of Solar Photovoltaic (SPV) has gained more interest as it is free of cost and doesn't harm the environment. The word "Photovoltaic" refers to "photo" means light and "voltaic" means voltage. SPV directly converts solar energy into electricity. The electricity generated by photovoltaic produces no harmful pollutants as it doesn't require any gaseous fuel and liquid for combustion. Hence results in clean energy. The Photovoltaic (PV) systems are quite reliable and easy to maintain. The performance of solar power system is measured in terms of its efficiency.

It has been observed that photovoltaic industries are growing at rapid rate. So in order to maintain this growth rate, a widely new approach has to be followed for PV material selection, device design, as well to increase its overall efficiency (38). Numerous existing photovoltaic technologies like silicon based, thin film, multi junction based systems needed some improvements and innovation for an efficient power generation system (39). In near future, Solar PV based electricity generation will become a modular approach for meeting energy demand of major cities of India namely Chennai, Delhi, Jodhpur, Mumbai, Kilkata and Trivandrum(40). However, SPV technology provides a platform to researchers to work in this field in order to get better system's efficiency while keeping the cost down.

This paper deals with the different types of Solar Photovoltaic (SPV) modules, highlighting their performance efficiency. It discusses the practical model of a photovoltaic cell and its VI characteristics. After that, market trends of PV are reviewed in the later part of the paper.

Basic principle of solar cell

A solar cell is device that converts optical input (sunlight) into current. Its operation is similar to photodiode which is made of semiconductor, but both have a qualitative difference like photodiode operates in narrow range of wavelength whereas solar cell works over a broad spectral range (solar spectrum). Many researchers have proposed mathematical model of the PV cell. This model is used to interpret the nonlinear behavior of semiconductor in order to determine the PV cell performance (7). The model represented in (8-13) included only series resistance R_s but not shunt resistance R_{sh} in order to reduce complexity.

Some of the research workers have not included both the resistances in their work. Further, many papers are reviewed (14-19) in which they have considered these two internal resistances as the essential part of the electrical model to determine the performance of PV cell accurately.

Equivalent model of solar cell

The voltage and current characteristics of a solar cell depict an exponential behavior (24). The ideal equivalent circuit of a solar cell is composed of a current source in parallel with a diode (as shown in Fig. 1). Figure 2 represents the practical equivalent model of solar cell with internal resistances (series and shunt). This resistance R_{se} is encountered due to the flow of electrons between the bulk material and metal contact.

Shunt resistance R_{Sh} is due to in between recombination of electron and hole pairs which occurs before going to the load. This will affect the current flowing through the load. V_L represents the voltage across external load and I_L is the load current. Solar cell operates similar to pn junction diode. When sunlight strikes the surface of solar cell, it excites the electrons in n side region. The movement of electrons from 'n' region to 'p' region results in generation of photo current I_{Ph}.

For practical electrical model of solar cell, current equation is defined by Kirchhoff's Current Law (KCL) and given as:

$$I_{Ph} - I_D - I_{Sh} = I_L \quad (1)$$

As we already know, diode current (I_D) and V_D is given as

$$I_D = I_o\left(e^{\frac{qV_D}{nkT}} - 1\right)$$

$$V_D = V_L + I_L R_{se}$$

From equation (1)

$$I_L = I_{Ph} - I_o\left(e^{\frac{q(V_L + I_L R_{se})}{nkT}} - 1\right) - \frac{V_L + I_L R_{se}}{R_{Sh}}$$
(2)

For the sake of simplicity, shunt resistance can be ignored. Therefore, under constant illumination and temperature conditions, I_{SC} (known as short circuit current) is the largest current drawn from the cell and V_{OC} (known as open circuit voltage) is the largest voltage exhibited at the cell terminals (24). They can be calculated by following equations:

Calculation of VOC

For open circuit voltage, $I_L = 0$
Therefore, from equation (2) neglecting R_{Sh} we will get

$$V_{OC} = \frac{nkT}{q}\ln\left(\frac{I_{Ph}}{I_o} + 1\right)$$

Calculation of I_{SC}

For short circuit current, $V_L = 0$
As series resistance is very small, from equation (2)

$$I_{SC} \approx I_{Ph}$$

Behavior of solar cell

The operation of solar cell is similar to photodiode. The pn junction operated in fourth quadrant can act as power source. This corresponds to the basic principle behind the solar cell. It has been noticed that the product of voltage and current in fourth quadrant yield negative power which corresponds to a power source. The voltage and current relationship of solar cell is presented in Figure 3. This graph depicts the behavior of solar cell with respect to solar radiation.

Fill factor and conversion efficiency

From the above graph, the maximum value of power P_m is obtained by the product of maximum value of current I_m and voltage V_m. This maximum value of power is traced by Maximum Power Point Tracking (MPPT) technique (25). The performance of the solar cell is determined by two parameters namely: Fill Factor (FF) and Conversion Efficiency. The value of FF lies between 0 and 1.Mathematically, FF is given as:

$$FF = \frac{I_m \times V_m}{I_{SC} \times V_{OC}}$$

The conversion efficiency (η) of a solar cell is defined as the ratio of the generated power P_m and the incident power P_{in}.

$$\eta = \frac{P_m}{P_{in}}$$

Factors affecting the performance of solar PV cell

There are many conditions that influence the output of SPV system. One must consider these factors to get a realistic idea of the system output. Few factors are being discussed below.

Temperature effect

Temperature has negative affect on system performance. With the increase in temperature, the band gap of a solar cell is reduced. This affects the open circuit voltage V_{OC} that decreases with the increase in temperature due to the temperature dependency of reverse saturation current. Graphically, the effect is shown in Figure 4(a).

Solar irradiation effect

The term irradiation is referred to the power density of sunlight received at a particular location on the earth. It is measured in W/m^2. Figure 4(b) shows the effect of solar irradiation on VI characteristics of a solar cell. It has been observed that higher is the irradiation, greater is the current and there is less variation in voltage. As irradiations increases from 400 W/m^2 to 800 W/m^2, correspondingly current increases from 1.6 A - 3.6 A.

Series resistance effect

The slope of VI curve gives the resistance. As the value of resistance increases, it results in decrease in the value of short circuit current. But there is no impact on open circuit voltage, its value remains same. The influence of series resistance on a solar cell is depicted in Figure 4(c).

Shunt resistance effect

The effect of shunt resistance on the performance of solar cell is shown in Figure 4(d). It has been noticed that the value of current increases with the increase in shunt resistance. It restricts the flow of current between the terminals of solar cell hence, resulting in larger current through the load.

Solar photovoltaic technology

Focusing on solar power technology, photovoltaic has gained immense progress in the field of power generation over the last years and in future, the growth is likely to be continued at the same rate (20).

The process of direct conversion of sunlight into electricity without any external interface is known is photovoltaic conversion. SPV systems are simple and rugged in construction. The major advantages of SPV system include less maintenance required, last longer, modular and high power output in megawatts. Hence, these systems are successfully used for power generation, solar home system, water pumping, remote building, communication, satellites and space vehicles (21). Solar panels that are utilized for power generation are mainly composed of different types of photovoltaic material like monocrytalline silicon, polycrystalline silicon and thin film (Cadmium telluride (CdTe), Gallium arsenide (GaAs), amorphous silicon). Table 1 compares these most widely used solar cell technologies (12-13). Different technologies are represented in Figure 5.

A single solar cell produces electricity at small scale. For larger scale electricity production, solar cells are combined to form a module of multiple cells. As stated in (9), these modules are arranged in such a manner that they form PV array of length up to several meters and hundreds of these arrays are used for utility-scale solar electricity generation (Fig. 6).

Solar photovoltaic power generation

The basic principle of PV array is to convert the solar irradiations into DC power. SPV system consists of numerous components like Photovoltaic cells forming an array, battery (if needed), MPPT controller(26-29)to ensure the maximum power output, electrical and mechanical connections and mountings. The expected power generated by the system is in Peak Kilowatts (KWp) when the sun is directly overhead on a clear day. Solar energy has come out to be an emerging technology for electricity production comprising many advantages like pollution free, renewability etc. There are few factors that restrict the usage of solar energy like its dependency on time. For continuous flow of energy, system requires some kind of energy storage to provide energy in the absence of sunlight (30). A comprehensive research is being done in the field of fuel cell technology. The main focus is to provide an economical and efficient mechanism for storing energy. For energy storage, solar system uses conventional lead acid battery. SPV systems are broadly classified into three main categories based on their functionality and operational requirement: grid-connected photovoltaic system, stand-alone photovoltaic system and hybrid systems.

A grid-connected system is the cost efficient PV design for many cites. The fundamental element of this system is the inverter (power conditioning unit). Inverter converts the DC power generated by solar array into AC power. There is a bi-directional flow of power between PV system output circuits and utility grid. When power produced by solar array is more than the load requirement then the excess power is supplied to utility grid. At night or on any cloudy days, when the power needed by the load is more as compared to power generated by PV system then power requirement of onsite load is met with utility grid. Further, this system is categorized as grid connected system with or without battery. The main purpose of the battery is to provide energy backup in the absence of sunlight. A research on optimization of the electrical load pattern based on grid connected Photovoltaic systems was carried out in Kuwait. Power requirement is fulfilled from both PV array and the utility grid (31). A significant reduction in peak load can be attained with grid connected SPV system.

A stand-alone system on the other hand, comprises of solar array, charge controller, batteries and inverter. This system don't require utility grid for its functioning. Such systems are used in remote areas where electricity is not available. The power generated by PV array is used to charge batteries and that stored power is further utilized by onsite load at night. Feasibility of stand-alone PV system is tested in remote and rural areas of India. A comparative study of renewable generators with non-renewable generators was carried out based on some parameters like life cycle cost etc. It has been found that life cycle cost of PV energy is lesser as compared to the cost of energy from generated diesel or petrol generators (32). Among the different renewable energy resources, solar energy represents the largest energy source. Figure 7 represents the estimates of technical potential of different renewable energy resources (35-37).Solar energy has undergone remarkable progress in recent years.

Two types of PV technology exits in the market: (a) Crystalline silicon (mono and polycrystalline) based PV solar cell (b) Thin-Film comprises of different material like amorphous silicon, cadmium–telluride and copper indium gallium diselenide. The estimate of PV cell efficiency determined by using laboratory solar cell is shown in Figure 8. From this figure, it has been noticed that maximum efficiency of 25.6% is obtained by mono crystalline silicon, whereas other PV cells (multi crystalline and thin) have efficiencies nearly 20%. As the year passes, there is noticeable increase in efficiency of PV cells. Figure 8 shows that still there is a scope of improvement in this field. High efficiency with lesser initial cost of PV systems is one of the major challenges that the researchers are trying to overcome.

Table.1 Comparison of solar cell technologies

Types Parameters	Monocrystalline	Polycrystalline	Thin-Film		
			Amorphous silicon	**CdTe**	**CIS/CIGS**
Typical module efficiency	15-20%	13-16%	6-8%	9-11%	10-12%
Best research cell efficiency	25.0%	20.4%	13.4%	18.7%	20.4%
Area required for 1 kWp	6-9 m^2	8-9 m^2	13-20 m^2	11-13 m^2	9-11 m^2
Temperature resistance	Performance drops 10-15% at high temperature	Less temperature resistant than monocrystalline	Tolerates extreme heat	Relatively low impact on performance	

Fig.1&2 Ideal model of solar cell & Practical model of solar cell

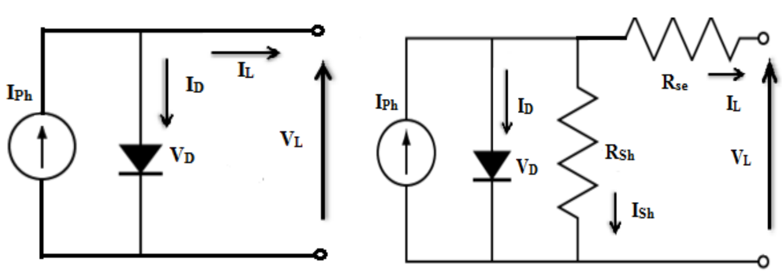


Fig.3 VI characteristics of solar cell

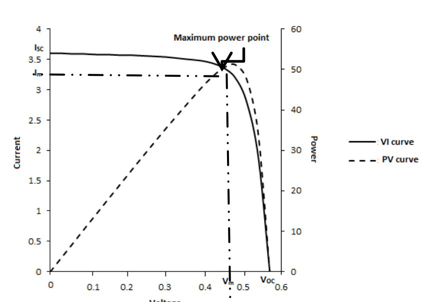
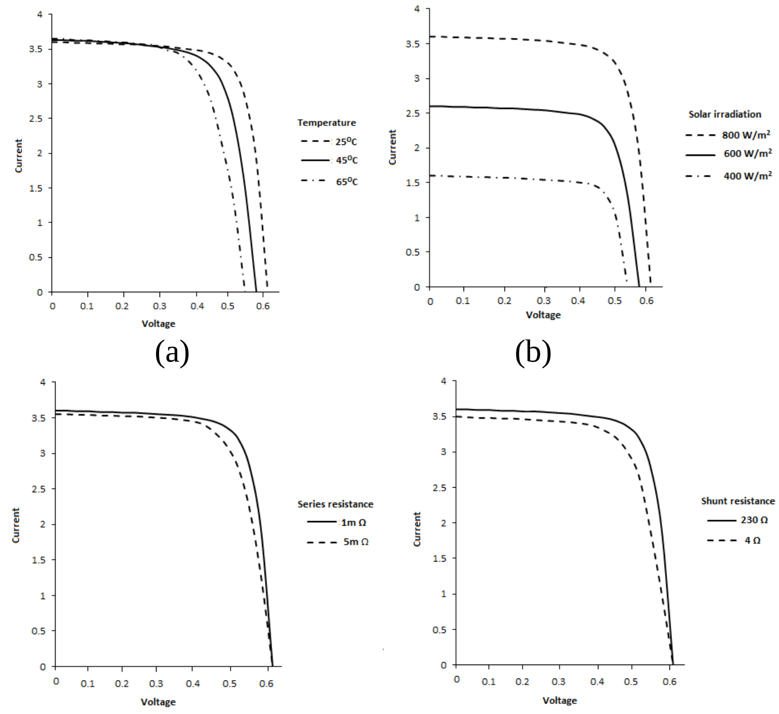


Fig.4 Represents the response of SPV under different factors



(a) (b)

(c) (d)

Fig.5 Different photovoltaic technologies (a) Monocrystalline Module (b) Polycrystalline Module (c) Thin film module (42)

(a) (b) (c)

Fig.6 Solar Array (42)

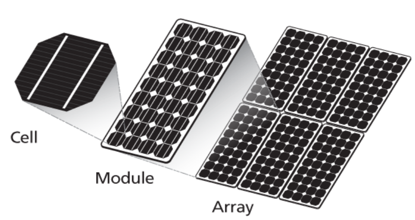


Fig.7 Technical potential of renewable energy resources

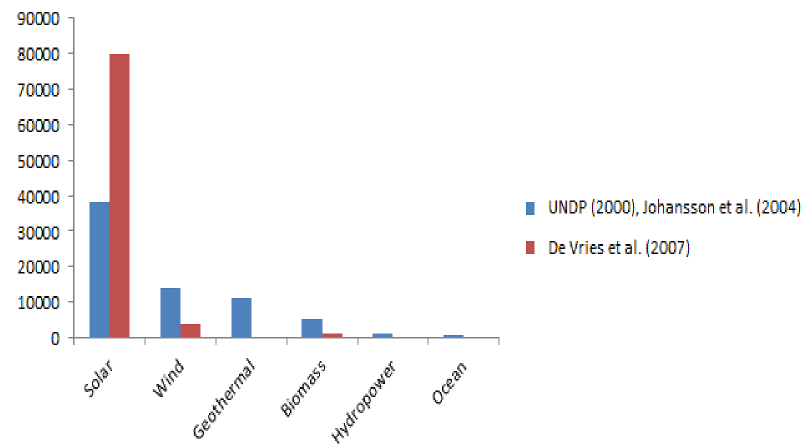
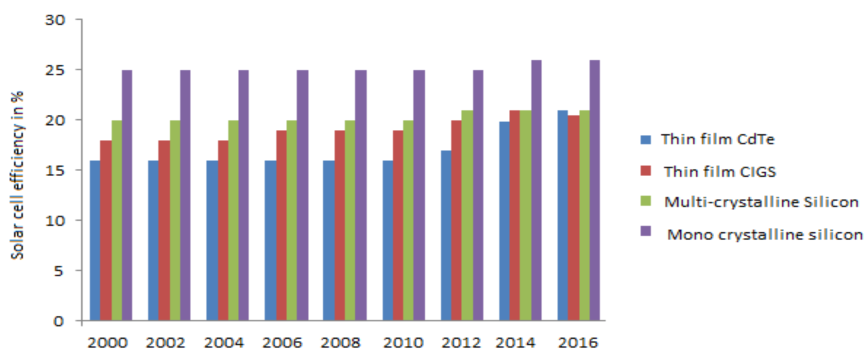


Fig.8 Represents solar PV cell efficiency over the years



The adequate amount of solar irradiance received at the earth's surface ranges from the 0.06 kW/m^2 at the highest latitudes to the 0.25 kW/m^2 at low latitudes. The demand of multi-megawatt PV plants for power generation results in a tremendous growth of the PV industry in 1980s. In 2009, a remarkable increase of 10.66 GW has been noticed in world PV production (33). In the end of year 2010, the global installed capacity for PV was about 40 GW. This included 85% grid connected systems and rest 15% were off grid (34). In year 2010, 80% of the market was occupied by crystalline silicon based PV cells and the rest of the market was taken up by thin film technologies. Globally, PV industry is growing at the fastest rate. In 2015, the solar cell production volume increased by 200 times as compared to year 2000. Compound Annual Growth Rate (CAGR) is incremented by 40%. Due to the speedy annual production rate in China, there is a tremendous increase in solar production in other countries like Malaysia, Thailand and India. In last few years, the prices of PV modules have fallen significantly. Due to decrease in PV module price, most of the countries prefer PV technology for electricity production.

Conclusion and Future perspective of the study are as follows

By every passing year, energy consumption is increasing. Numerous technologies have been developed to meet the energy demand. Among various other technologies, solar PV technology has proven to be a reliable, clean and affordable source of energy for the society (41). While considering this fact, government is now encouraging the development of solar PV technology. Based on the reviewed literature, monocrystalline modules showed highest efficiency of 20%. Moreover, the performance of photovoltaic cell is depended on various factors like illumination, temperature etc. This results in shifting of maximum power point on VI characteristics curve which can change the power output. In order to get maximum power, MPPT and PWM controllers are used. Apart from these factors, few parameters like easy maintenance, fault tolerant operation and installation cost are need to be considered while developing PV system.

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