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Solar Energy Harvesters – A Review on Fundamentals to Recent Advancements

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Abstract—— ***World demand for energy is projected to more than double by 2050 and to more than triple by the end of the century. Incremental improvements in existing energy networks will not be adequate to supply this demand in a sustainable way. Finding sufficient supplies of clean energy for the future is one of society's most daunting challenges. In this regard, energy conversion from solar is spear heading and promising. Over last three decades, the research efforts on system development for solar energy harvesting is highly encouraging. The current report emphasis on the solar energy harvesting technologies, scientific principle, construction and contemporary development in the solar energy harvesting technologies.***

Keywords—Solar energy harvesters; Solar Photovoltaic; Photovoltaic generator; Solar Cell

1. INTRODUCTION

Global energy crisis and threat of environment disorder has become a common concern worldwide. The demand of electrical energy is growing constantly. The conventional sources of energy like thermal are having serious issue of having limited reservoirs which may end in the next few decades [1]. The carbon emissions from the power plants using conventional sources are adding serious threat to the environment. Also other source of energy i.e. Nuclear is possessing serious threat to the safety of human being [2].

To overcome the above concerns the researchers have paid aggressive attention on renewable energy sources in the past few years. Among all renewable energy sources solar energy is the most acceptable solution as it is available in abundant and free of cost worldwide [3]. The sun provides earth with a staggering amount of energy enough to power the great oceanic and atmospheric currents, the cycle of evaporation and condensation that brings fresh water inland and drives river flow, and the typhoons, hurricanes, and tornadoes that so easily destroy the natural and built landscape. Earth's ultimate recoverable resource of oil, estimated at 3 trillion barrels, contains 1.7 × 1022 joules of energy, which the Sun supplies to Earth in 1.5 days

The amount of energy humans use annually, about 4.6 × 1020 joules, is delivered to Earth by the Sun in one hour. The enormous power that the Sun continuously delivers to Earth, 1.2 × 105 terawatts, dwarfs every other energy source, renewable or non renewable. It dramatically exceeds the rate at which human civilization produces and uses energy, currently about 13 TW [4]. The impressive supply of solar energy is complemented by its versatility, as illustrated in Fig.1.

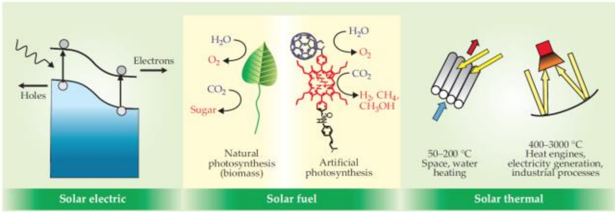

Fig.1. Solar photons convert naturally into three forms of energy—electricity, chemical fuel, and heat—that link seamlessly with existing energy chains [5].

In spite of high specific costs, photovoltaic systems provide an increasingly attractive alternative for electricity supply in particular at remote locations, due to their extremely high reliability, low maintenance requirements, long lifetime and their modularity with flexible system sizing down to very small load demands. The article gives a brief overview over current photovoltaic technology, principle and their applications. In addition, the general components of photovoltaic systems, from the solar cell and the photovoltaic module are also detailed.

2. SOLAR ENERGY BALANCE

More than 99.9% of the energy flow on the earth's surface is due to incoming solar radiation. The rest is from geothermal, gravitational (tidal) and nuclear sources. The sun is an average-size star, with a diameter of 864,000 miles and 93 million miles away from our planet. It is a giant nuclear fusion reactor whose interior and surface temperatures are 35,000,000 and 10,000 °F, respectively. Each second 657 million tons of hydrogen isotopes are converted into 653 million tons of helium. The residual mass of 4 million tons is converted to energy, according to the Einstein equation, E = mc2 [6].

To place this number into perspective, if gasoline were pouring from Niagara Falls, at a rate of 5 billion gallons per hour, and if we had begun collecting it 3.5 million years ago, the combustion of all this accumulated gasoline would liberate the amount of energy equivalent to one minute of the sun's production. Being quite far away from the sun, the earth receives only about half a billionth of this radiation. But it receives it more or less continuously. About 30% of this energy does not reach the surface of the earth because it is reflected from the

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atmosphere. Still, the radiation that does reach the surface is four orders of magnitude larger than the total world's energy consumption. In fact, only 40 minutes of sunshine would be sufficient – if available in adequate forms – to supply the entire annual energy demand on earth. Because solar energy spreads out more or less evenly through space, it reaches the surface of the earth in quite diluted form, at a rate of about 220 W/m2. In other words, if one square meter were available for conversion of solar energy to electricity (at 100% efficiency), the energy produced would be sufficient for just two or three light bulbs. The challenge of solar energy utilization is to concentrate it. Practical ways to achieve this are discussed below. They include direct solar heating, indirect production of electricity and direct production of electricity.

3. SOLAR PHOTOVOLTAIC (PV)

Solar photovoltaic (pv) is used to convert solar energy into electrical energy. The complete solar energy conversion system consists of solar pv, power electronics converters and control unit to regulate the power extracted from solar pv. Harvesting of solar energy by photon absorption in metal nanostructures followed by collection of photo-generated hot electrons via the processes of internal photoemission (ipe) has been recently explored as a promising alternative approach to traditional photovoltaics as well as for catalysis and photo-detection. Traditionally, noble metals such as au are considered as good candidates for gapless photon absorbers, which are potentially capable of full spectrum harvesting.

4. THE GENERAL PHOTOVOLTAIC SYSTEM

The special attraction of photovoltaics, as compared to other power generation technologies, lies in the fact that the solar radiation is converted directly into electric power by an electronic solid state process. In general, no moving parts and no specific thermal stresses are involved. Therefore, photovoltaic systems operate quietly and they can offer extremely high reliability, low maintenance requirements and a long lifetime.

Due to the nature of the conversion process, one can utilize direct as well as diffuse radiation, which also allows applications in moderate climates with higher fractions of diffuse radiation. Another important advantage of pv is its modularity, permitting a very flexible system sizing for integration into buildings and for decentral applications down

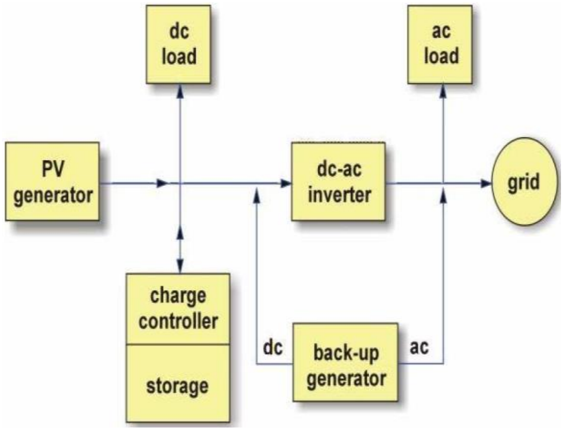

Fig.2. General photovoltaic system [6]

Inverter

For PV systems connected to the public electricity grid an inverter is always required that converts the direct current and voltage produced by the PV generator into an alternating current with appropriate voltage and frequency levels. For stand-alone systems only an inverter is required, if ac-loads are to be operated. This is often the case for larger domestic systems where a variety of loads are connected.

Storage

For stand-alone systems in general a storage battery and/or a back-up generator is required to provide power during cloudy and dark periods. There are however specific applications where storage batteries can be omitted. An example is the photovoltaic pumping system. Here, the pump is operating whenever there is adequate illumination, and storage is achieved by collecting the pumped water in a tank.

PV generator

The principal structure of a PV generator is illustrated in Figure 2. To satisfy a specific power demand by a PV system, a number of solar modules may be electrically interconnected in series and in parallel. The output voltage of the total PV generator is then determined by the number of modules connected in series, and the output current by the number of module strings connected in parallel. The size of PV generators may range from single cells with sub-Milliwatt levels (e.g. in consumer products such as calculators) to single modules and up to module arrays with many Megawatts.

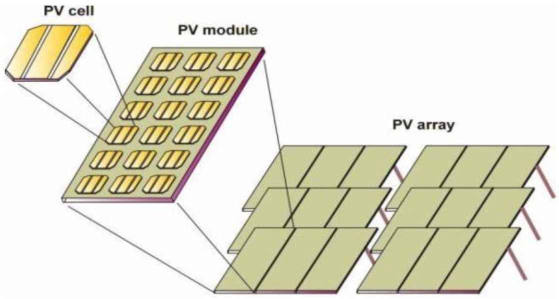

Fig.3. Photovoltaic generator [6]

Solar cell

The smallest independent operational unit of PV systems is the solar cell. The solar cell consists of a specific semiconductor diode, in most cases silicon, with a large aperture area for light absorption. In the photovoltaic conversion process light is absorbed by the semiconductor, and the absorbed photons produce free charge carriers (electrons and holes) which are then separated by the built-in electric field between the n- and p-type region. The charge separation produces a difference in electric potential between the two regions, and an electric current can be drawn through an external load. Depending on the cell efficiency and cell area, the maximum output power for single solar cells is on the order of 1 W, and output voltages are in the range of 0.5-1 Volt. Commercial Silicon cells and modules have conversion efficiencies of 12-16 per cent, high efficiency silicon cellse.g. For concentrator modules have been produced with up to 24 per cent efficiency. For concentrator applications, gaas and related materials are under research, and laboratory efficiencies above 32 per cent have been achieved. Due to the high costs of gaas technology, commercial terrestrial applications however have not yet emerged. The systematic structural representation of solar cell is shown in Fig.4.

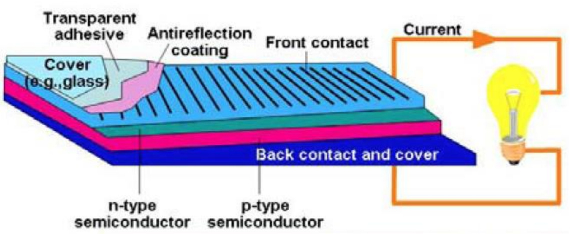

Fig.4. Systematic structural representation of solar cell [7].

Energy of absorbed photons raises the energy of electrons above the Fermi level, creating so-called hot electrons (Fig.5). Photo generated hot electrons typically cool down very fast due to scattering on phonons, lattice defects, and cold electrons. The cooling process occurs on picosecond timescale in most metals. If, however, these hot electrons can be extracted before they cool down, they can contribute to the energy conversion efficiency. Typically, such full-spectrum converters use the Schottky junction that forms at the interface between metal and n-type semiconductor as a frequency-selective filter to extract photo-generated hot electrons (Fig.5). As a result, hot electrons generated by absorption of photons with energies below the semiconductor bandgap can still be harvested by using this approach. This offers the way to potentially increase the conversion efficiency of photovoltaic (PV) cells and to extend the bandwidth of photon detectors. Alternatively, the Schottky junction between metals and p-type semiconductors can be used to harvest hot holes generated by photons absorbed in the metal.

5. SOLAR ENERGY CONVERSION PRINCIPLE

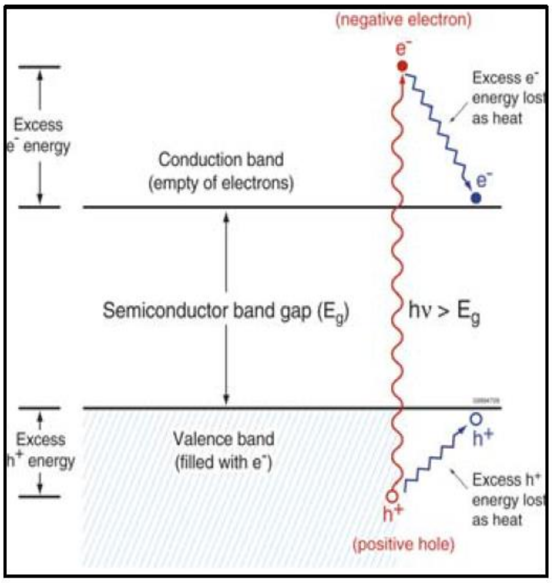

Fig.5. Photovoltaic generator [7]

However, the conversion efficiencies experimentally demonstrated to date have been extremely low. Furthermore, it has been previously shown that the maximum limiting efficiency of the full solar spectrum harvesting and conversion via IPE from noble metals is restricted by the available electron density of states (e-DOS), because their e-DOS favors creation of large population of hot electrons with energies lower than the Schottky barrier height13. Prior theoretical estimate for a model metal with parabolic electron bands found the overall conversion efficiency limit at about 7%. In addition to the limits imposed on the harvesting of high-energy electrons by the available filled and empty electron energy levels, the high dark thermionic current through the Schott KV junction at room temperature prevents the opportunity of lowering the energy barrier to increase the forward current and energy conversion efficiency. Here, we estimate the limiting efficiency of the solar energy harvesting via hot electron photo-injection by using the realistic Au electron band-structure calculated via the first-principles method. Our data shows that the limiting efficiency reduces to a mere 3.6%, indicating the need to develop new photon-to-hot-carrier energy conversion schemes based on synergistic engineering of both photon and electron DOS in the broad energy range14,15. We further discuss possible ways to increase this limit, which include hot holes harvesting, optical concentration, and partial-spectrum conversion. Figure 6 shows the comparison of band gap and efficiency of PV generator.

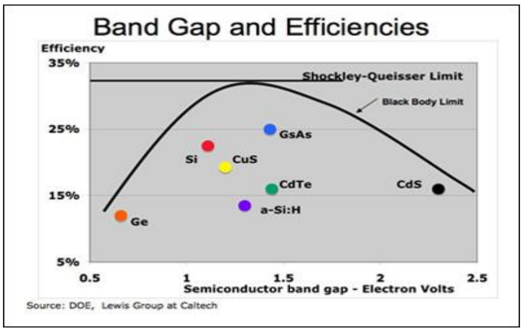

Fig.6. Photovoltaic generator [8]

Inorganic PV and electrochemical PV (EPV) cells operate upon the establishment of an electric potential difference between the n- and p-type regions in an inorganic PV cell or between an n- or p-type semiconductor and redox electrolyte, in the case of an EPV cell. This difference creates an electrical diode structure. The current-voltage behavior of such junctions follows the diode equations, in which the current flow in one direction across the junction is constant with voltage, whereas the current flow in the other direction across the junction increases exponentially with the applied voltage. Hence, the dark current density (J_{dark} [amps/cm^2]), as a function of the voltage (V) applied to this diode (assuming ideal diode behavior), is:

$$J_{dark}(V) = J_0(eqV/kT - 1) \quad (1)$$

where J_0 is a constant, q is electronic charge, k is Boltzman's constant, and T is temperature (K).

If a diode is illuminated, additional charge carriers will be created upon absorption of the light. These carriers will create an additional current flow across the junction, and they must be added to the dark current to obtain the total current in the system. For illumination with light comprising many different wavelengths, the total photo-induced current can be calculated by summing (i.e., integrating) the contributions to the current from excitation at each wavelength. Hence, the short-circuit photocurrent density (Jsc) is:

$$J_{sc} = q \int I_s (E) (QY)(E)\, dE \quad (2)$$

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$$Jsc = q \int I_s (E) (QY)(E)\, dE \quad (3)$$

where I_s = solar photon flux, E = photon energy (inversely proportional to the wavelength of the photon), and QY = quantum yield (electrons collected per incident photon).

The net current density (J) is:

$$J(V) = J_{sc} - J_{dark}(V) = J_{sc} - J0(eqV/kT - 1) \quad (3a)$$

However, ideal diode behavior is seldom seen. This is accounted for by introducing a non-ideality factor, m, into Equation 3a:

$$J(V) = J_{sc} - J_{dark}(V) = J_{sc} - J0(eqV/mkT - 1) \quad (3b)$$

Because no current flows at open circuit, the open-circuit voltage (Voc) for the ideal device is obtained by setting J(V) = 0,

$$V_{oc} = [kT/q] \ln [(J_{sc}/ J_0) + 1] \quad (4)$$

A plot of the net photocurrent density (J) vs. voltage is provided in the figure, which shows the current-voltage characteristic of a PV cell. The conversion efficiency (η) of the PV cell is determined by the maximum rectangle in the figure that can fit within the net photocurrent-voltage characteristic. The maximum power point of the cell, or so-called operating point, is the values of J and V (Jm and Vm) at which the maximum rectangle in the figure meets the J-V curve. This defines a term called the "fill factor" (FF).

$$FF = J_m V_m / J_{sc} V_{oc} \quad (5)$$

that characterizes the "squareness" of the J-V characteristic. The maximum FF value is 1.0; it occurs when Jm = Jsc and Vm = Voc, but in reality, the diode equation limits the maximum FF to 0.83.

The cell conversion efficiency is the electrical power density (JmVm) (watts/cm2) divided by the incident solar power density (Psun), multiplied by 100 to obtain a percent value.

$$\eta = J_m V_m / P_{sun} = 100 * J_{sc} V_{oc} FF / P_{sun} \quad (6)$$

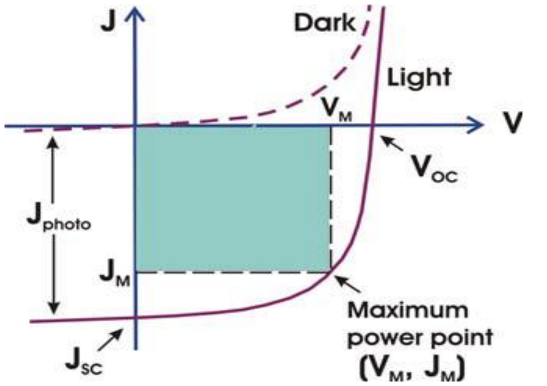

Fig.7. Representation of J-V characteristic of a PV [9]

6.NEED FOR REVOLUTION TO CREATE NEW TECHNOLOGIES

In 2004, the United States consumed approximately 4.0 × 1012 kWh (energy consumed in one year at an average power of 0.46 TW) of electricity (Energy Information Administration [EIA] 2005); this amount represents about 14% of total U.S. energy consumption (EIA 2005). The U.S. electricity produced by solar PV cells currently represents a tiny fraction (<0.02%) of the total electricity supply. The challenge for generators of solar electricity is to produce it at very low cost, ultimately approaching $0.40/Wp, which is equivalent to an energy cost of $0.02/kWh. Achieving this cost would require a reduction in the $/Wp price of about a factor of 15–25 relative to present PV costs. Such a low cost for solar electricity would be expected to result in massive implementation of solar energy systems in the energy infrastructure in the United States and globally. Such a cost breakthrough would also represent a major advance in using solar energy to alleviate the anticipated future problems associated with energy supply, energy security, and unacceptable levels of atmospheric CO2. In addition to satisfying electrical power needs, solar electricity at $0.02/kWh could also contribute to the goal of producing cost-effective non-carbonaceous solar fuels, such as hydrogen (National Academy of Engineering, Board on Energy and Environmental Systems 2004). However, to achieve the latter goal, major advances in suitable and scalable storage and distribution technologies will also be required. Solar electricity can be produced from PV cells or from turbines operating with high-temperature steam produced from concentrated solar power.

This Panel Survey addresses only PV solar cells; the latter method for producing solar power is discussed in the section on Basic Research Challenges for Solar Thermal Utilization.

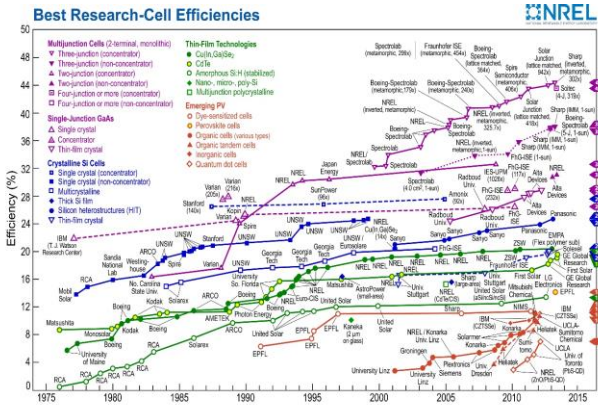

Fig.8. Improvements in solar cell efficiency, by system, from 1976 to 2015 [10]

7. CONCLUSION AND FUTURE PROSPECTUS

Since the 1970s, the PV industry has continually reduced the cost of solar electricity. Over the past three decades, the cost of PV modules has decreased at a rate of 20% for each doubling of module production (see Figure 4). The cost of PV modules per peak watt has declined from about $70/Wp in 1976 to about $3.50/Wp in 2003. The BOS cost (support structures, maintenance, land, etc.) for a grid-tied PV system is about $2.50/Wp. Considering both module and BOS costs, together with present cell efficiencies, the cost of solar electricity has dropped from about $3.65/kWh in 1976 to about $0.30/kWh in 2003. However, if the present learning curve for PV cells is followed, the projected attainment of very-low-cost PV power ($0.02/kWh) and its widespread implementation would lie far in the future (20–25 years depending upon the annual production growth rate; see Figure 5). Therefore, basic research is needed to not only maintain the existing technology path and learning curve in support of evolution, but to also produce a revolution to dramatically change the slope of the historical learning curve and produce dramatic reductions in the PV module cost-to-efficiency ratio (Figure 5). The goal is to reduce the cost per peak watt by a factor of about 15–25 relative to present systems through the use of new designs, materials, and concepts for solar electricity production, and to do so more quickly than would be accomplished by staying on the existing learning curve — thereby materially impacting global energy supply in 10–15 years rather than by the mid-21st century.

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