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Solar cells: Types, Modules, and Applications–A Review

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Abstract

The basic operating principle of photovoltaic (PV) devices is the conversion of solar irradiation into electricity. There are various applications of this principle in many countries such as Egypt, Nigeria and Denmark. Most of the solar PV projects are designed for street lighting, water pumping and water desalination. However, we hope about wide range of using the appropriate components and best technical procedures, standard PV projects with maximum performance output. The present systems now provide 20% to 40% only of the community's heat or lightness on annual basic needs. These include innovative and alternative ways to reduce material uses and module degradation, and opportunities to reuse and recycle PV panels at the end of their lifetime because of the installations of photovoltaic solar modules which are growing extremely very fast.

Keywords: Solar cells; renewable energy; photovoltaic; free energy; solar panel cost; solar battery.

Introduction

A solar cell is, in principle, a simple semiconductor device that converts light into electric energy (Figure 1). The conversion is accomplished by absorbing light and ionizing crystal atoms, thereby creating free, negatively charged electrons and positively charged ions. If these ions are created from the basic crystal atoms, then their ionized state can be exchanged readily to a neighbor from which it can be exchanged to another neighbor and so forth; that is, this ionized state is mobile; it behaves like an electron, and it is called a hole. It has properties similar to a free electron except that it has the opposite charge. Solar cells can be made from single crystals, crystalline and amorphous semiconductors. Each photon of the light that has a high enough energy to be absorbed by the crystal's atoms will set free an electron hole pairs (Bagher et al. 2015).

The electron and hole are free to move through the lattice in a Brownian motion; however, on average they will never move too far from each other. On the other hand, when they experience an electric field, this will tend to separate the electrons from the holes; the electrons will drift toward the positive pole (the anode), and the positively charged holes will drift toward the cathode. Photo conductors are passive devices; they react to light by changing their electric conductivity. In order to activate them, an external electric power source, such as a battery is required (Bagher et al. 2015).

Figure 1: Shape of solar cell.

Photovoltaic system (PV) is the best-known renewable energy technology to produce electrical energy as the PV systems use sunlight. In addition, photovoltaic systems can be applied to small or large applications without restriction in individual homes, housing developments, and public and industrial buildings and generate energy.

A solar cell, also known as a photovoltaic cell, is any device that converts the energy of light directly into electrical energy via the photovoltaic effect. The vast majority of solar cells are made of silicon, which is becoming more efficient and less expensive as the materials progress from amorphous (noncrystalline) to polycrystalline to crystalline (single crystal) silicon forms. Figure 2 shows a basic diagram of a photovoltaic solar cell. Solar cells, unlike batteries or fuel cells, do not use chemical reactions or require fuel to generate electricity, and, unlike electric generators, they do not have any moving parts (Yuan and Huang 2016).

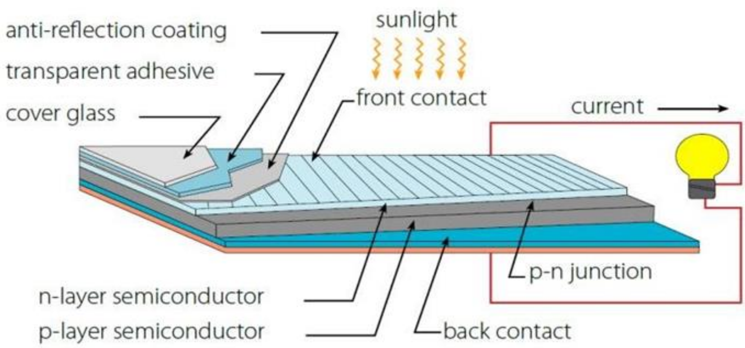

Figure 2: Basic diagram of a photovoltaic solar cell.

Materials and Methods

A review was conducted on published articles, reports, and other materials on solar cells, which were searched on scientific databases and the general internet using combinations of keywords: Solar cells; solar cells types; solar cells modules; and solar cells applications. Search results were thoroughly evaluated. Databases of scientific research included Science Direct, Springer Link, and Google Scholar.

Results and Discussion

PV technologies

Different types of photovoltaic cells and panels have been created over time in order to improve the performance, to reduce the cost and the amounts of the materials used, and to increase the application possibilities.

The photovoltaic cells are classified into four groups, generally referred to as generations. For the first generation, the most representative is the monocrystalline silicon (mSi) photovoltaic cell, whose theoretical efficiency limit is around 32%. The second generation photovoltaic cells include the polycrystalline silicon (pSi), amorphous silicon (aSi), CdTe and CIGS, which are the most important photovoltaic cells. The third generation include the organic or polymer, dye-sensitized solar cell DSSC and multijunction photovoltaic cells. The fourth include the "inorganics-in-organics". The newest now are nanotube and graphene, with improvement of the performance of the PV (Atesin et al. 2019).

CdTe solar cells are the second most common photovoltaic (PV) cells in the world after crystalline silicon (Table 1). CdTe thin-film solar cells can be manufactured quickly and inexpensively, providing an alternative to conventional silicon-based technologies (Figure 3). The record efficiency for a laboratory CdTe solar cell is 22.1% by First Solar at the end of 2020.

Table 1: Results of room temperature Hall measurements on CdTe:Cu crystals (Compaan et al. 2001)

Carrier concentration (10^{14} cm^{-3})	Resistivity (kΩ-cm)	Mobility (cm^2/Vs)	Condition
1.18	16.5	3.22	1 week after the 1st anneal.
5.3	13.5	0.9	Immediately after re-anneal.
0.7	21.4	4	1 week after re-anneal
6.4	12.3	0.8	2nd re-anneal
0.46	35.3	3.8	1 wk. after 2nd re-anneal
5.87	25.1	0.4	3rd re-anneal

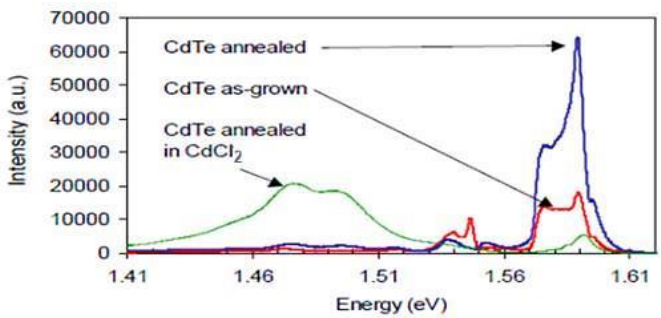

Figure 3: Photoluminescence from CdTe single crystals as-grown, annealed at 387 °C, and annealed at 387 °C in $CdCl_2$ (Compaan et al. 2001).

The benefits of CdTe thin-film solar cells include**:**

High absorption: Cadmium telluride is a direct-bandgap material with bandgap energy that can be tuned from 1.4 to 1.5 eV, which is nearly optimal for converting sunlight into electricity using a single junction (Li et al. 2019).

Low-cost manufacturing: Cadmium telluride solar cells use high throughput manufacturing methods to produce completed modules from input materials in a matter of hours (Compaan et al. 2001, Li et al. 2019).

Materials of solar cells

Monocrystalline silicon/monocrystalline silicon (mono-Si) solar cells have a single-crystal composition, allowing electrons to move more freely than in a multi-crystal configuration. As a result, monocrystalline solar panels are more efficient than their multicrystalline counterparts. Because the wafer material is cut from cylindrical ingots, which are typically grown using the Czochralski process, the corners of the cells appear clipped, like an octagon. Solar panels made with mono-Si cells have a distinct pattern of small white diamonds (Thopil et al. 2020).

Polycrystalline silicon/multicrystalline silicon, also known as polysilicon or poly-Si, is a high purity polycrystalline form of silicon used as a raw material in the solar photovoltaic and electronics industries. A chemical purification process known as the Siemens process is used to produce polysilicon from metallurgical grade silicon. This method entails distilling volatile silicon compounds and decomposing them into silicon at high temperatures. A fluidized bed reactor is an emerging alternative refinement process. The photovoltaic industry also produces upgraded metallurgical-grade silicon (UMG-Si), using metallurgical instead of chemical purification processes (Figure 4).

When produced for the electronics industry, polysilicon contains impurity levels of less than one part per billion (ppb), while polycrystalline solar grade silicon (SoG-Si) is generally less pure. In 2013, a few companies from China, Germany, Japan, Korea, and the United States, including GCL-Poly, Wacker Chemie, OCI, and Hemlock Semiconductor, as well as the Norwegian-based REC, accounted for the majority of the global production of about 230,000 tonnes (Rizwan et al. 2021).

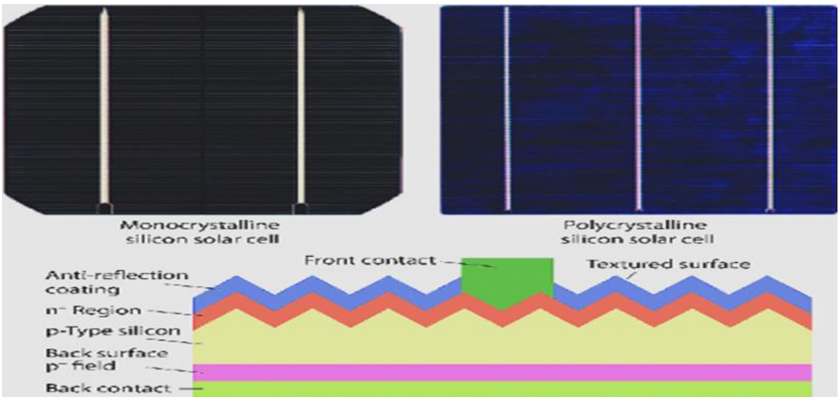

Figure 4: Typical mono- and polycrystalline silicon solar cells (top), and simplified cross-section of a commercial monocrystalline silicon solar cell (bottom). Reprinted with permission of Saga T (2010).

Ribbon silicon is a type of polycrystalline silicon–it is formed by drawing flat thin films from molten silicon and results in a polycrystalline structure. These cells are cheaper to make than multi-Si, due to a great reduction in silicon waste, as this approach does not require sawing from ingots, however, they are also less efficient (Kim et al. 2003). Mono-like-multi silicon (MLM) was developed in the 2000s and commercially introduced around 2009. This design, also known as cast-mono, employs polycrystalline casting chambers with small "seeds" of mono material. As a result, a bulk mono-like material with polycrystalline edges is formed. When sliced for processing, the inner sections are high-efficiency mono-like cells (but square rather than "clipped"), while the outer edges are standard poly. This method of production yields mono-like cells at poly-like prices (Omer 2009). Thin film/thin-film technologies reduce the amounts of active materials in a cell. Most designs sandwich active materials between two panes of glass. Since silicon solar panels only use one pane of glass, thin film panels are approximately twice as heavy as crystalline silicon panels, although they have a smaller ecological impact (Figure 5).

Gallium arsenide thin film/gallium arsenide (GaAs) is a semiconductor material that is also used in single-crystalline thin film solar cells. Despite their high costs, GaAs cells have the world's highest efficiency for a single-junction solar cell at 28.8 percent (Płaczek-Popko 2017).

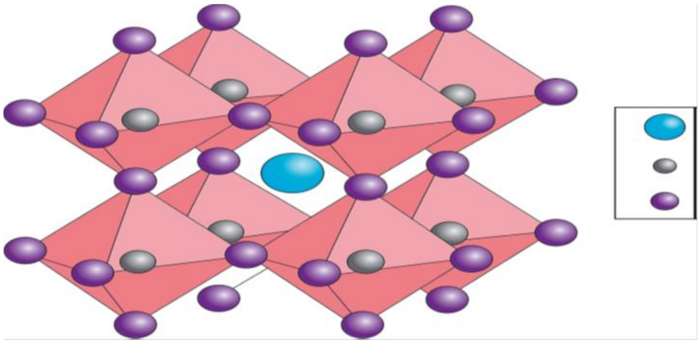

Figure 5: Cubic perovskite crystal structure. For photovoltaically interesting perovskites, the large cation A is usually the methylammonium ion (CH_3NH_3), the small cation B is Pb and the anion X is a halogen ion (usually I, but both Cl and Br are also of interest). Reprinted with permission of Green et al. (2014).

Types of solar photovoltaic systems

Solar PV generates DC electricity, which is not the common form to be used for home appliances and the utility grid in general, which usually uses AC electricity. So in order to be able to connect the PV system to the grid it is needed to change the DC to AC, and that is done using a power conditioning units AKA "inverter. So Not all energy the PV system generates is used right away, especially when we talk about off-grid systems. Solar photovoltaic systems can be of three types–grid-tied, grid-tied with battery back-up and off-grid system but we must know what is the best and the right (Li et al. 2019).

Grid-tied (On-grid system

The solar PV system is integrated with the grid. 'Grid' is what they call the conventional electricity infrastructure. This is the most popular mode of going solar. This is the cheapest mode of going solar of all the three types. On an average, up to 20% of the energy needs might still be fulfilled by the grid (Gay et al. 2018).

Grid-tied with battery backup

The solar PV system be integrated with the grid, and will have its own battery back-up. Batteries are meant to store excess electricity that gets generated by the solar PV systems. The batteries used in solar PV systems tend to be very expensive; the grid will be much less when the on-grid system is backed up with the battery as well. This is because the batteries act as the primary source for power when the system is not generating electricity, during night time (Nshimiyimana 2018).

Off grid system

Batteries are a must here unless the solar power is combined with other renewable energy. This tends to involve higher initial investment and installation costs. But is not that a good price to pay for energy self-sufficiency (Nshimiyimana 2018).

Different modules of solar cells

USA module

AGM and flooded batteries have been designed to meet the needs of long-term residential systems that do not have access to power grids. Furthermore, Trojan's deep-cycle batteries enable homeowners to improve their renewable energy systems while significantly lowering operating costs when powering their homes in remote areas (Figure 6). Whether homeowners use solar panels, windmills, or a combination of different resources in their systems, Trojan's battery backup products enable cost-effective and optimal energy storage that can be relied on when living off the grid. Our main and industrial lines have been designed specifically for renewable energy applications (Shadmand et al. 2010):

- Monocrystalline silicon cells - Highest efficiency and highest cost;
- Cast mono silicon cells - High efficiency and lower cost;
- Polycrystalline silicon cells - Lower efficiency and lowest cost (Gu et al. 2012).

Figure 6: Trojan's lines of deep-cycle gel.

Germany module

Solar energy is converted to electrical energy by organic photovoltaic (OPV) devices. A typical OPV device is made up of one or more photoactive materials sandwiched between two electrodes. Figure 7 shows an example of a bilayer organic photovoltaic device. Sunlight is absorbed in photoactive layers composed of donor and acceptor semiconducting organic materials in a bilayer OPV cell to generate photocurrents.

The donor material (D) donates electrons while primarily transporting holes, whereas the acceptor material (A) withdraws electrons while primarily transporting electrons. As shown in Figure 6, photoactive materials harvest photons from sunlight to form excitons, which contain electrons. The excitons diffuse to the donor/acceptor interface (Exciton Diffusion) and separate into free holes (positive charge carriers) and electrons (negative charge carriers) as a result of the concentration gradient (charge separation). When holes and electrons move to the corresponding electrodes by following either the donor or acceptor phase, a photovoltaic is produced (charge extraction) (Bajenescu 2015).

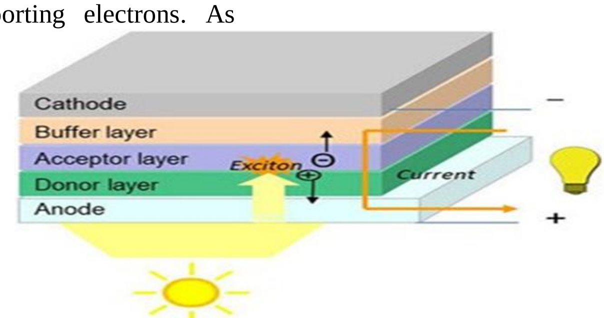

Figure 7: Structure of a bilayer organic photovoltaic device.

Taiwan module

Several monitoring devices were installed to investigate the system's actual operating conditions. A precision spectral pyranometer (Eppley Laboratory, Inc., model PSP) is placed near the system to measure incident solar radiation values, while a Vector Instruments low-power anemometer (ModelA100L2) measures the local wind speed. Two Macnaught flow metres (Model M2SSP-1R) are installed in the cold water supply line to the hot water storage tank (hot water consumption) and the circulation line from the bottom of the storage tank to the collectors' inlet (circulation flow rate) (Figure 8).

To monitor the local water temperature, 14 platinum resistance thermometers (Izuder Enterprise, 1/10 DIN Class B) have been installed. The power metre also records the energy consumption of the auxiliary electric heater. The data from monitoring devices is sampled every 10 seconds by a National Instrument (NI) data acquisition system (Model cFP-AI-110 and cFP-RTD-124) and transmitted synchronously via the Internet to the host computer at the Energy Research Center, National Cheng Kung University (Lin et al. 2012).

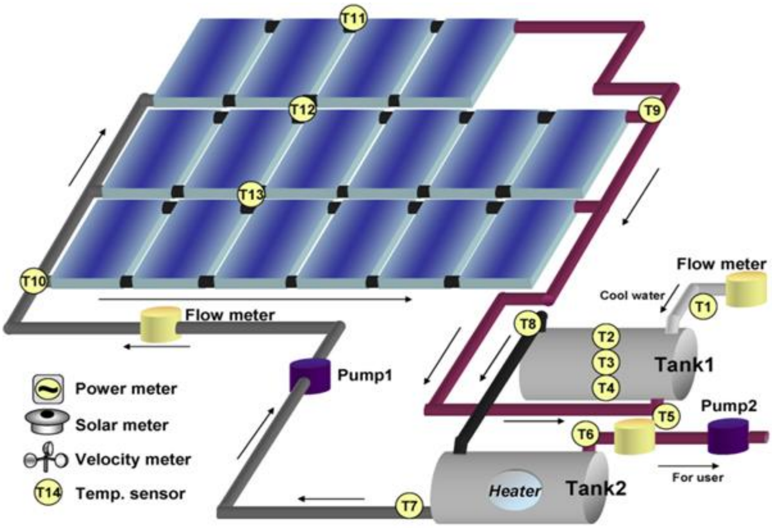

Figure 8: Schematic drawing of monitoring devices.

Japan module

Hyogo Prefecture in Japan has floating solar power plants, two floating solar power plants have been completed in two reservoirs in Kato City, Hyogo Prefecture, Japan. This is a collaborative effort. Kyocera and Century Tokyo Leasing, which specialises in equipment leasing, are the two companies involved. Construction has begun. They use 255-watt Kyocera modules, totaling 11,256 modules. The Sanyo-designed bus is a hybrid diesel-electric vehicle whose rooftop solar cells power the interior LED lights (Figure 9) (Owano 2015).

Figure 9: Floating solar power plants in Hyogo Prefecture.

Applications of solar cells

Classification of all the solar cell technologies discussed here based on the structural materials. It should be noted that among all the listed cell technologies within the classification. Now scientists around the world are working hard on combining different PV technologies to create multi-junction cells. The utilization of different materials allows the cells to achieve a much higher efficiency than the maximum theoretical limit (33.5%). Research is mainly focused on thin-film silicon tandem cells, which yield a theoretical efficiency of 43%. The maximum theoretical efficiency of multi-junction cells is greater than 50% (Rodriguez et al. 2021).

Solar cells are frequently electrically linked and encapsulated as modules. Photovoltaic modules frequently have a sheet of glass on the front (sun up) side, which allows light to pass while protecting the semiconductor wafers from abrasion and impact caused by wind-driven debris, rain, hail, and so on. In addition, solar cells are typically connected in series in modules, resulting in an additive voltage (Julajaturasirarath et al. 2012).

Connecting cells in parallel results in a higher current; however, parallel connections have serious drawbacks. Shadow effects, for example, can cause the weaker (less illuminated) parallel string (a number of series connected cells) to shut down, resulting in significant power loss and even damage to the weaker string. For example, due to the excessive reverse bias applied to the shadowed cells by their illuminated partners, shadow effects can shut down the weaker (less illuminated) parallel string (a number of series connected cells), causing significant power loss and even damaging the weaker string (Sdeeq et al. 2015).

The availability of electricity in rural areas provides significant social and economic benefits to remote communities all over the world. Power distribution to remote homes or villages, electrification of health-care facilities, irrigation, and water supply and treatment are just a few examples of such applications. PV-powered rural applications have enormous potential.

The output of PV power systems is affected by many parameters such as changes in irradiation, variations in temperature and dust deposition. When the temperature increases, efficiency drops. Efficiency can be improved by reducing the surface temperature of panels which will also prevent thermal deterioration of panels, so the efficiency of PV systems is also influenced by range and selection of batteries, charger controller, inverter and power electronic devices.

The future for solar cells

Different scientific disciplines are frequently well separated, so it is critical to build bridges between them, which this review paper attempts to do. There are numerous aspects of solar cell development using nanoparticles as a novel concept that can play a significant role. This is especially intriguing, in terms of industrial feasibility, as opposed to lithographic techniques that are currently limited to proof-of-concept designs (Di Vece 2019).

There are two main methods for producing nanoparticles and solar cells: 1) physical fabrication/deposition, which frequently employs vacuum techniques, and 2) chemical fabrication/deposition, which requires the presence of liquids and is not always compatible with physical fabrication/deposition. In contrast to conventional wafer-based solar cells, these fabrication processes can be carried out at room temperature, significantly lowering the fabrication cost (Di Vece 2019).

The integration of cluster sources with research fields such as solar cells is currently not far from being realized. The commercial availability of gas aggregation cluster sources will accelerate the maturation of using cluster sources for photovoltaics in the near future.

Nanoparticles are likely to find their ways into photovoltaics via various techniques and approaches. For many years to come, light management will be of interest in increasing the efficiency of thin-film solar cells. Thin-film solar cell compositions, including promising perovskites, will provide decades of research opportunities for nanoparticle implementation. Nanoparticles are inexpensive to produce and simple to combine with existing fabrication methods in PV technology.

Conclusion

The use of PV system will significantly reduce CO_2 gas emission from environmental point of view. The PV system with battery is the most economical PV system. The photovoltaic community is not only to further improve the solar photovoltaic cells, it has more benefits for society than just generating electricity from the sun. The important task is how to spread the message and public support of solar photovoltaic cells.

Solar energy is a locally available renewable resource. It does not need to be imported from other regions of the country or across the world. This reduces environmental impacts associated with transportation and also reduces our dependence on imported oil. And, unlike fuels that are mined and harvested, the use of solar energy to produce electricity does not deplete or alter the resources.

Different types of available PV cells are monocrystalline, multicrystalline, multi-junction and concentrating solar PV cells. High efficiency is a major advantage in case of monocrystalline cells, but these types of cells require a complex method for fabrication till now. Polycrystalline cells are cheaper compared with the monocrystalline cells, but they are slightly less efficient. The efficiency of PV cells can be increased by concentrating sunlight using lenses and mirror arrangement as application methods.

The output of PV power systems is affected by many parameters such as changes in irradiation, variations in temperature and dust deposition. The efficiency of PV systems is also influenced by range and selection of batteries, charger controller, inverter and power electronic devices.

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