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Generations of Solar Photovoltaic Power Technology

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Abstract: ***The exponential expansion of global energy consumption in daily life incentivizes to solicit a green and cost-effective alternative source of energy for power generation and storage. Since the advent of photovoltaic cells, crystalline silicon-based photovoltaic technology has monopolized the market, accounting for approximately 80% of the market share in 2022. Most standard second-generation technologies have efficiencies of 20-25% and they are highly priced. The cost of silicon cells has decreased and silicon technology is now one of the growing key research directions. Production-scale prototypes have also been constructed and tested with 10-17% efficiency. Third-generation multi-junction solar cells, on the contrary are already commercially available and have accomplished exceptional conversion factors from 40% to over 50%, making this technology the best. Technological breakthrough in multi-junction solar cells based on n-type silicon and functional nanomaterials like graphene provide a promising strategy to low-cost, high-efficiency cells. Multi-junction cells, benefit from nanotechnology advancements, are currently breaking efficiency records of nearly 45%. This paper addresses the recent applications of PV- technology including the super-capacitors and energy storage devices in addition to their future potentials.***

Keywords: Solar photovoltaic, multijunction cells, conversion factor, nanotechnology, supercapacitors, energy storage devices.

1. Introduction

Great strides, greater convenience, increased mobility and an expanding global population are all contributing to the tremendous annual increase in energy consumption. In the energy crisis, coal, oil and gas are among the fossil fuels vying to satisfy the world's energy demands. Environmental contamination is also a significant issue of pollution because of the extensive use of fossil fuels. Furthermore, renewable energy technologies have a promising possibility for meeting the world energy demands as presented in Figure 1. Solar energy in abundance is widely recognized as the most promising renewable energy source [1].

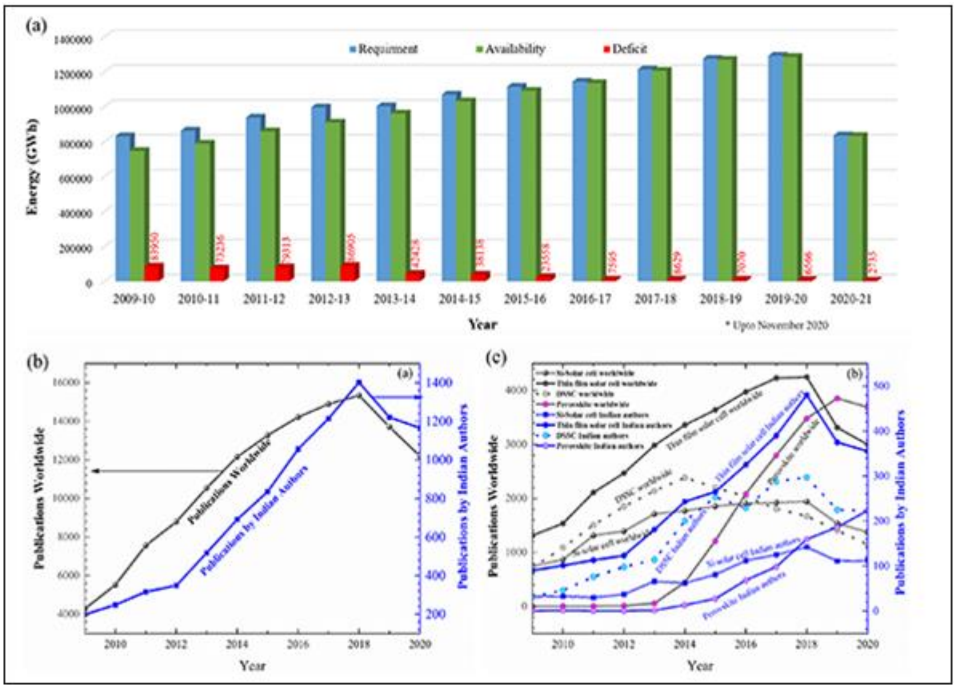

Figure 1: (a) Energy demand-supply scenario in India; (b) Annual publication trend on solar cells and (c) Annual publication trend on different technologies of solar cells [1].

Most countries have access to reasonably priced, dependable power and the government is encouraging the installation of solar energy-based power plants. The direct conversion of solar radiation into electricity is known as photovoltaics (PV) power. Cells in a photovoltaic system directly convert the sunlight into electricity. Each cell comprises a layer of semiconductor materials. When light strikes on the PV-cell, it creates an electric field across the layer, exacerbating current to flow. The amount of electrical energy produced by each cell is dictated by the intensity of incident sun light on solar cells. Methods for appreciating renewable technologies have been developed over decades but there is a consistent need to implement more comprehensive and effective technologies. The traditional approach of implementing technical and economical methods in the evaluation process remains fundamental but criteria related to environmental, social and political constraints becoming increasingly important for public opinion and regulation. Current global trends show that renewable energy is becoming more important than traditional energy sources (coal, gas, oil, nuclear, etc.) due to their environmental benefits [2].

Alexandre-Edmond Becquerel discovered the photovoltaic effect in 1839. Following that, Russel Ohl [3] concocted the first modern silicon solar cell in 1946. Photovoltaic solar cells, as originally highlighted, are thin silicon wafers that convert sunlight into electrical power. Modern photovoltaic technology is based on the principle of electron hole configuration in each cell composed of two different layers (p-type and n-type) of a semiconductor material. When a photon with sufficient energy impinges on the p-type and n-type junctions in the structure, an electron is ejected and moves from one layer to another by gaining energy from the striking photon. This creates an electron and a hole in the process and by this process electrical power is generated.

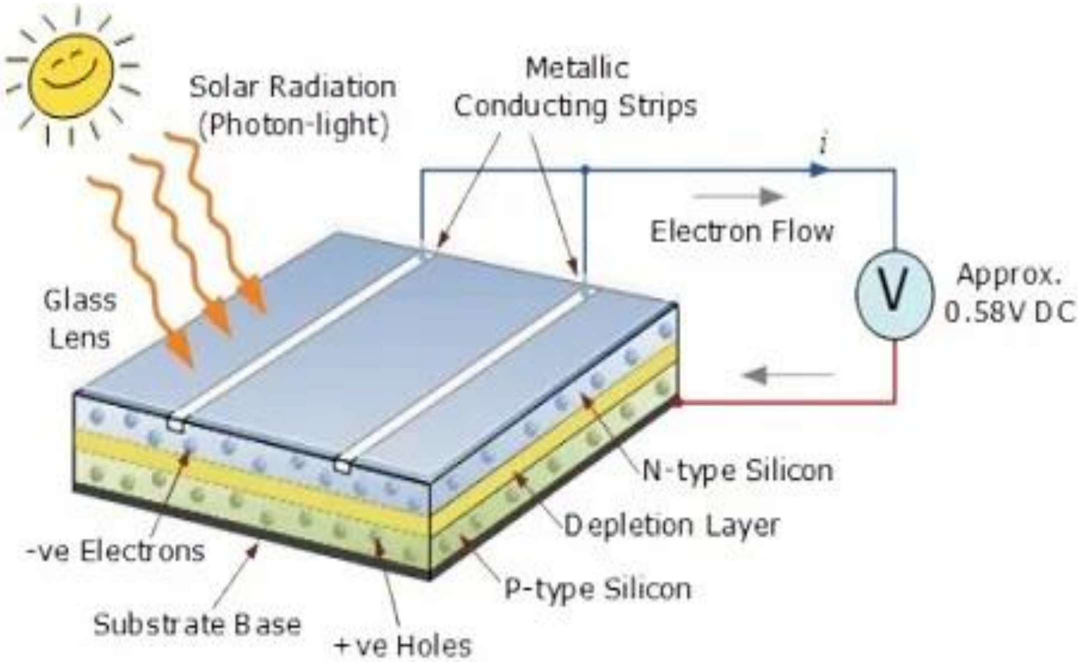

Figure 2: Solar photo-voltaic power generation [3].

When light strikes on a P-N junction (N type semiconductor region facing sunlight), incident photons with energy ($E = h.\upsilon$) equal to the energy band gap of the semiconductor material are absorbed, producing electron and hole pairs as charge carriers. Because of the inherent potential, these electrons and holes pairs are separated. This voltage is measured as it develops across the P-N junction as shown in Figure 2. This direct current-voltage is converted into alternating current-voltage with the alternator to feed power to the various household appliances or commercial, transportation and industrial applications. Different types of materials used in solar cells are classified into different categories [4].

2. Different Technologies of Solar Cells

Technology is accrescent in nature hence the change of materials and synthesis process, we are able to understand the gradual yet firm development of the solar PV-technology.

2.1 First generation solar cells

This innovation is premised on crystalline Si-wafers, is crafted from crystalline Si which is the most expensive method of obtaining pure Silicon crystal. These solar cells are used worldwide and have the highest commercial efficiency. Single-crystalline made of Czochralski process, solar cells make up approximately 80% of the solar cell market. Polycrystalline solar
cells with honeycomb-like structures have been reported in the literature which have cell efficiency of around 19.8%. Polycrystalline silicon-solar cells are less efficient than crystalline silicon cells [5].

2.2 Second generation solar cells

The thin films (1 μm) of Silicon cells are considered in second generation. The major economic shortcomings of wafer technology could be circumvented in this generation. Furthermore, thin film technology gobbles up far less silicon than wafer-based first-generation technology [6]. The second generation of solar cells consist of the following type cells;
1) Amorphous Silicon solar cells
2) Copper Indium Gallium Di-Selenide [CIGS], V-I characteristics in Figure 3.
3) Thin-Film Cadmium Telluride Solar cells
4) Copper Zinc Tin Sulphide thin film solar cells
5) Compounds of group III-V

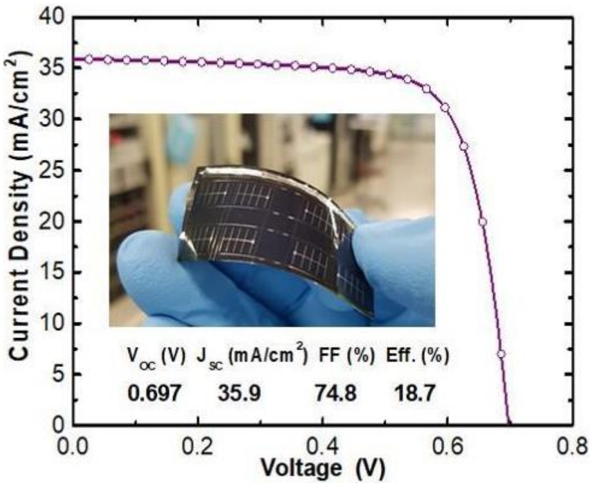

Figure 3: Thin film, lightweight CIGS cell and its characteristics [6]

2.3 Third generation solar cells

The third-generation solar cells refer to single junction solar cells that can outperform the Shockley-Queisser limit of 31-41% cell power conversion efficiency. The third generation of solar cells consists of the following type cells:

1) CZTS solar cells including materials CZTSe and CZTSSe
2) Dye sensitized solar cells, schematic in Figure 4.
3) Quantum Dot solar cells
4) Perovskite solar cells, schematic in Figure 5.
5) Organic solar cells

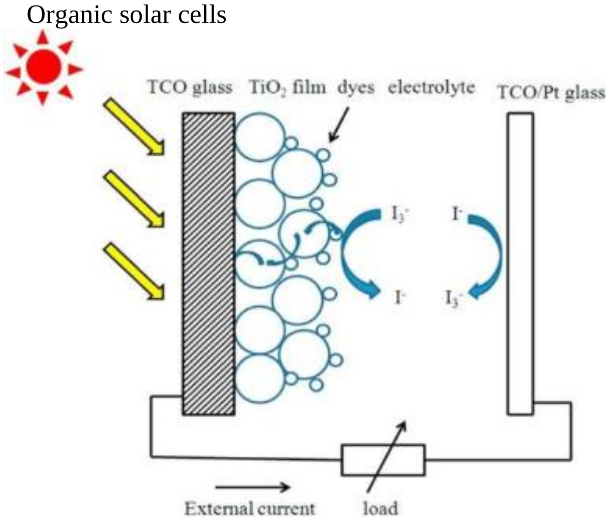

Figure 4: Schematic diagram of a dye-sensitizing solar cell [6]

To enhance solar cell efficiency, all photons of incident sunlight must be assimilated. This cannot be accomplished with a single junction solar cell. As a direct consequence, multi-junction solar pv-cells are being considered as a solution to this problem [6].

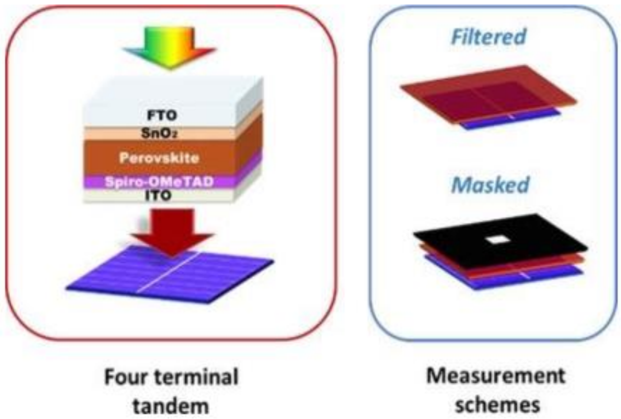

Figure 5: Schematic diagram of four terminal Perovskite Tandem cell [6]

2.4 Fourth-generation solar cells

The groundbreaking inorganic nano-structures as metal oxides and metal nanoparticles or organic-based nanomaterials such as graphene, carbon nanotubes and graphene derivatives [7] in addition to low flexibility and low cost of thin film polymers. The conversion efficiency of graphene-based Perovskite solar cells exceeded 25.5% and attained 10% for BHJ organic solar cells as given in Figure 6.

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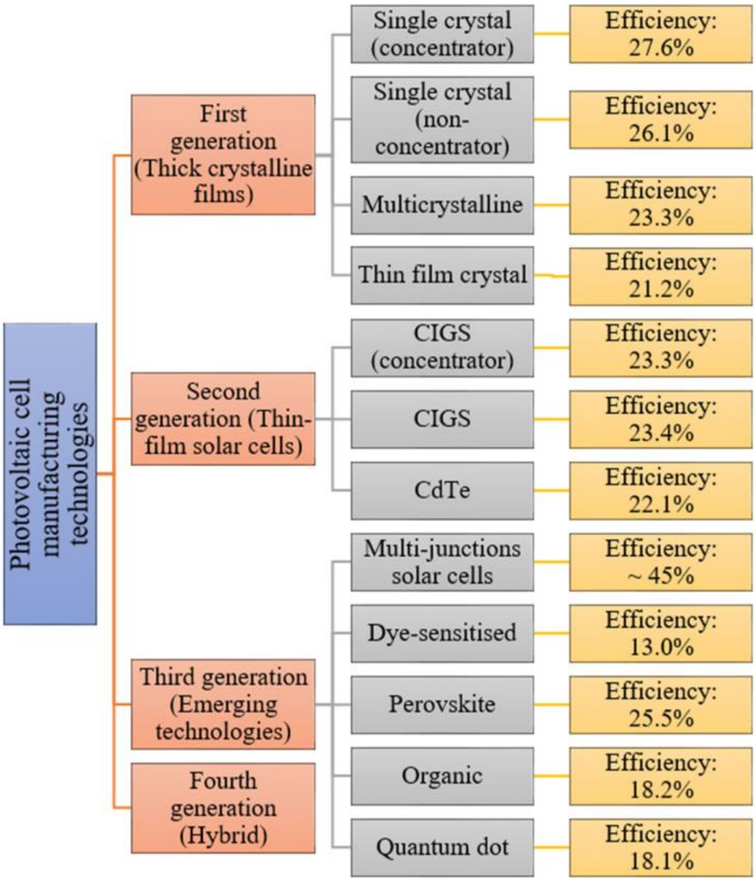

Figure 6: Generations and efficiencies of photovoltaic cells [9]

In additament to extracting and transporting charge to the electrodes, graphene performs another unique function as it safeguards the device from environmental degradation via its packed 2D lattice structure, ensuring the long-term environmental stability of photovoltaic devices [8]. One dilemma for graphene applications is the scarcity of a simpler, more reliable method for depositing a well-ordered monolayer with low- cost flakes on target substrates with varying surface properties.

The other concern is the adhesion of the deposited graphene thin film, which has yet to be investigated thoroughly. The major downside of graphene is its low hydrophilicity, which has a negative impact on the design of devices that are processed in solution, but this can be overcome by modifying the cell by super hydrophobic coating on the surface through non-covalent chemical functionalization [9].

Nanotechnology and revolutionary new multifunctional nanomaterials have the potential to dramatically enhance the solar energy generation and conversion via photovoltaic techniques. However, when these technologies are incorporated into PV panel manufacturing, the challenges associated with them remain a concern. Carbon nanoparticles and their allotropic forms [5], such as graphenes are expected to provide high efficiency in comparison to traditional silicon solar cells in the near future, creating new opportunities in the solar energy market. Carbon nanoparticles and their allotropic forms, as graphene are expected to provide high efficiency in comparison to conventional silicon solar cells in the near future, resulting in new opportunities in the solar energy pv-technology [10].

3. Energy Storage and Future of PV-Technology

Since sunlight is not available throughout the day, so the solar PV-cell businesses may not operate at night or off sun-shine hours. As a matter of fact, energy storage is a critical factor in the solar cell market. There are several energy storage devices in the market. Battery energy storage is the oldest and most familiar storage device. There are several type of batteries such as primary batteries (non-rechargeable), secondary batteries (recharge- able) further classified as aqueous (flooded) or nonaqueous electrolytes [11]. Multiple batteries connected together form a battery bank but they are costly and have a short life span. The secondary chemical batteries are,

1) Lead Acid batteries,
2) Ni-Iron and Ni-Cadmium,
3) Li-Iron & Li-polymer
4) Zn-Al air batteries

Harvard University researchers have created Quinone, a new type of battery based on organic molecules. Quinone is found in plants and is useful in that way, it can store solar energy for a few days. This device, which rely heavily on a new aqueous, rechargeable lithium-oxygen battery used in sunlight, can not only store energy but also reduce the costs of renewable energy by 25% [12]. The current solar cell developments, running the gamut from Si solar cells to TFSC, DSSC and perovskite type solar cells, as well as energy storage devices. The influence of texturing, anti-reflective coating and surface passivation on the performance of silicon solar cells, in addition to progress in a-Si material development [13].

A fundamental understanding of each constituent layer's performance on TFSCs, a combinatorial approach to TFSCs and key achievements in photo conversion efficiency of CIGSe, CZTSe, TFSCs, earth-abundant light absorbers and their device performance evaluation as well as an overview of DSSC progress has also been achieved [14]. Investigation of impact of different counter electrode (CE) material parameters on electrochemical catalytic activity and PCE values, as well as transparent CEs for semi-transparent DSSCs and large area DSSC modules were performed [15]. The progression of Pb-based and Pb-free absorbers, the electron/hole transport layer [16] and CEs for perovskite solar cells, energy storage devices and bi-functional devices as well as the prospects and upside potential of energy conversion and storage systems [17].

Recent advances have put solar energy as an economical option to be used for RO (Reverse Osmosis) desalination that is independent of RO plant capacity and proposed an equation to estimate the unit production costs of RO desalination plants [18] that can be used to calculate unit production costs for desalinated water using photovoltaic solar energy based on current and future PV module prices [19] and in an experimental plant for seawater reverse osmosis (SWRO) desalination powered from renewable energy sources (RES) at Libya's coast of the Mediterranean sea with both wind energy conversion (WEC) [20] and photovoltaic power generation being integrated into a grid connected power supply for a reverse osmosis desalination plant with power recovery [21].

In addition to this, Building-integrated photovoltaic (BIPV) systems incorporating photovoltaic properties into building materials such as roofing, siding and glass are emerging and they offer advantages in cost and appearance as they are substituted for conventional materials in new construction [22]. Building design to have the PV modules shade the building in summer, to reduce cooling loads, while at the same time allowing solar energy to enter the building during the heating season to provide daylight and conducted an analysis of the system performance, evaluation of system efficiency and power output [23][24].

Experimental study of a centralized photovoltaic and hot water collector wall system that can serve as a water pre-heating system using collectors mounted at vertical facades preferring natural water circulation over 6 forced circulation and thermal efficiency was found to 38.9% at zero reduced temperature [25] and the corresponding electricity conversion efficiency was 8.56% [26] have also been incorporated with the use of hybrid photovoltaic and thermal (PVT) collector technology using water as coolant as a solution for improving the energy performance. PVs are also now studied for developing photovoltaic–thermal system for domestic heating and cooling concluding that the system can meet a remarkable percentage of the domestic heating and cooling demands [27].

Energy storage is a potent problem faced by PV technology that can be remarkably solved by the use of energy storage devices like batteries, superconductors and hybrid devices. Supercapacitors are electrochemical energy storage devices that are classified into three types based on their charge storage mechanism: non-Faradic electrochemical double-layer capacitors (EDLCs), Faradic pseudo-capacitors and hybrid capacitors that use both. Bifacial solar cells can generate electricity not only from incident sunlight on the front surface of a solar cell but also from reflected sunlight at the back also [28]. Large bodies of water can be used to erect PV cells in order to obtain a solution for large landscape waste [29].

The floating PV technology would be developed and furthered. PV panels integrated into building architecture would provide a solution to bulky solar panel arrays installation and maintenance issues. Solar trees, like natural trees, could be established, capable of transforming nearly all incident sunlight and producing electricity. The same agricultural land can be used for both crop cultivation and solar panel installation [30].

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