The Scope of Dye-Sensitized Solar Cells for Future Applications

Vijay Pratap Singh[1], Rohit Rawat[2]

[1,2]Student, VidyaGyan School, Bulandshahr

Abstract
This paper delves into the renewable energy sector, specifically focusing on the role of solar power. The main focus is on dye-sensitized solar cells (DSSCs), third-generation solar cells known for their cost-effectiveness and adaptability to low-light conditions. In this context, the paper explores DSSCs' attributes and challenges, emphasizing their potential to advance renewable energy solutions. It concludes by emphasizing the need for further research to enhance DSSCs' commercial viability. This paper serves as a comprehensive exploration of DSSCs and their significance in shaping the future of renewable energy.

Keywords: Solar energy, Dye-Sensitized Solar Cell, Renewable energy, Photovoltaic

1. Introduction

The sun, a reliable fusion reactor active for over 4 billion years, supplies Earth with an immense amount of solar energy. Solar energy is an abundant, renewable resource, but its utilization is relatively recent, with practical solar cells emerging less than 30 years ago. Photovoltaic solar power, which harnesses this energy, has several advantages. It is environmentally friendly, has no moving parts, requires minimal upkeep, and boasts a lifespan of 20-30 years with low operating costs. What sets it apart is its decentralized nature; it can be deployed in both small and large systems, offering self-sustaining electricity generation even in remote areas. This modularity makes it ideal for developing countries, where extending power grids is costly and impractical. However, solar power's efficiency depends on sunlight availability and initial equipment costs. Despite these limitations, solar energy holds immense promise, especially in regions lacking conventional power infrastructure. Its ongoing evolution and adaptation are vital in addressing the world's energy needs and transitioning towards a more sustainable future[1].
Solar energy could be the best option for the future world because of several reasons [2,3]:

- First, the Sun emits solar energy at a rate of $3.8*10^{23}$ kW, of which the planet receives about $1.8*10^{14}$kW. This makes solar energy the most plentiful energy source. In addition, it is a cost-free energy source as opposed to other sources, which are quite expensive. The quantity of solar energy that reaches the planet is 4200 times more than what the whole human population would need in 2035, according to theory.
- Second, it offers stable and rising production efficiency compared to other sources of energy, making it a potential source of energy around the globe because it is not exhaustible.
- Third, since solar energy does not emit any other dangerous gases that might affect the environment; using and tracking it has no negative effects on the ecosystem where natural balance is maintained for the benefit of living organisms.

- Fourth, since solar energy is readily available, inexpensive, and practical, it may be utilized to power homes, businesses, and villages.
- Last but not least, purchasing a solar system first sounds pricey. The cost of operation is quite minimal after the solar system is built. Therefore, using solar energy would be more cost-effective in the long term than using other sources of energy.

It is significant because, to satisfy rising demand, renewable energy sources are required, and solar energy can do it without harming the environment. Avoiding unintended repercussions of the energy crisis is crucial. Furthermore, it has been reported that due to rising energy consumption, fossil fuel supplies would run out even before 2300[4]. Therefore, a reliable and safe substitute is immediately required.

In order to harness solar energy, we need semiconductor devices that can capture the sunlight and convert it into electricity through the photovoltaic effect; these devices are called solar cells. This process dates back to 1839 when Edmond Becquerel accidentally discovered the photovoltaic effect while conducting experiments involving an electrolytic cell containing two metallic electrodes. His findings revealed that certain materials, particularly platinum, generated small electric currents when exposed to sunlight. In 1883, Charles Fritts invented the first solar cell utilizing selenium, but it was impractical to use because its power efficiency was just 1%[5].

One significant departure from conventional solid-state junction devices involves replacing the semiconductor's contact phase (the portion of the semiconductor that comes in direct contact with other electrodes) with an electrolyte, whether in liquid, gel, or solid form, resulting in photo-electrochemical cells. Recent advancements in nanocrystalline materials have opened up exciting opportunities for these systems. Surprisingly, devices built on networks of mesoscopic semiconductors (semiconductors that exhibit properties from an intermediate scale between the macroscopic and microscopic) have demonstrated impressive conversion efficiencies, competing with traditional counterparts. The prototype for this new generation is the dye-sensitized solar cell (DSSC), combining a sensitizer for light absorption with a wide-bandgap semiconductor (semiconductor materials which have energy difference between highest energy electron and lowest energy electron as 2 - 4 eV) featuring nanocrystalline morphology. This evolution promises more affordable and efficient solar energy solutions[6].

The modern Dye-Sensitized Solar cells (DSSCs) were invented by Professor Michael Graetzel and Dr Brian O'Regan at Ecole Polytechnique Federale de Lausanne (EPFL), Switzerland in 1991. These are also known as Graetzel cells [7].

2. Types of Solar Cells

Since the 1800s, there has been a lot of research and development in the area of solar cells to make them more efficient, scalable and commercially viable [8]. Figure 1 presents a quick summary of the types of solar cells.

2.1 First Generation Cells

These are based on crystalline silicon wafers. The components (thick layers of silicon) cost more than those used in other solar cells. They are now in use on a global scale. Additionally, they have an absorption efficiency of around 11%. Some examples of first-generation cells include:

- Monocrystalline Solar Cell: Highly efficient photovoltaic devices made from single-crystal silicon.
- Polycrystalline Solar Cell: Photovoltaic devices made from multiple small silicon crystals.

2.2 Second Generation cells

Thin film solar cell technology is the foundation of these cells. These are created by placing thin layers of silicon (1µm thick) on glass rather than silicon wafers. Compared to the first-generation, they are cheaper. They also have a 20% absorption efficiency. Some examples of second-generation cells include:

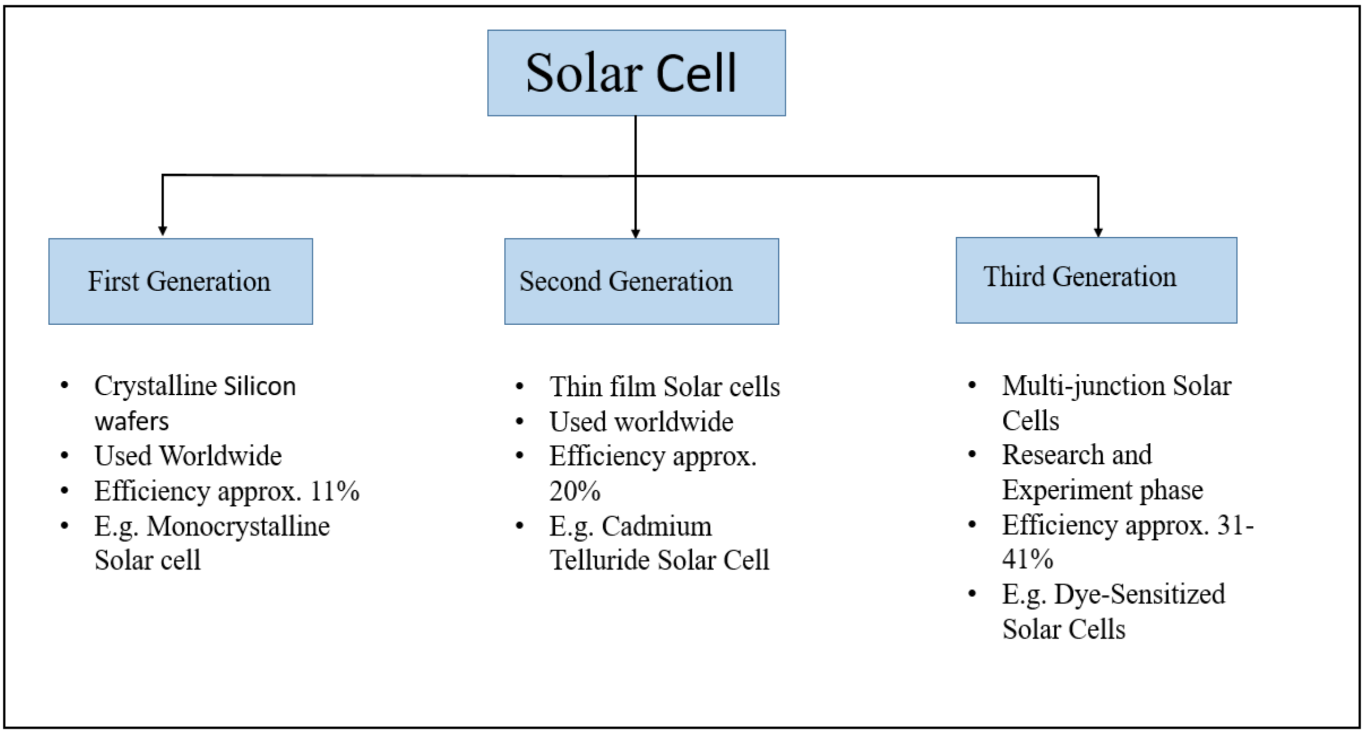
- Copper Indium Gallium Di-Selenide [CIGS]: Thin layer of Copper, Indium, Gallium and Selenium are deposited on glass. It has high absorption efficiency.
- Cadmium Telluride Solar Cell (CdTe): Cadmium telluride is a photovoltaic cell that is based on the use of cadmium telluride, a thin semiconductor layer.

2.3 Third Generation cells

These are based on multi-junction solar cells (cells with multiple p–n junctions made of different semiconductor materials) technology with 31-41% power efficiency. These are the most cost-efficient solar cells and are currently under research and experiment. Some examples of third-generation cells include:

- Dye-Sensitized Solar Cells (DSSCs): These are photovoltaic cells that use dye to convert sunlight into electric current.
- Quantum Dot Solar Cells: Solar cells that use quantum dots instead of heavy materials i.e. Silicon, Cadmium, copper indium, etc. as a photovoltaic material.

Figure 1. Types of Solar Cell



3. Advantages and Disadvantages of DSSCs

3.1 Advantages

- Its strategic design allows it to draw more protons from the sun's beams.
- Due to the absence of expensive metals or minerals, it has a cheaper production cost.
- It can properly function in overcast weather and absorb fluorescent light and diffused sunshine.

- It has a long shelf life and doesn't break down in the sun.
- It is made of materials that are both lightweight and durable and has a high mechanical strength [9].

3.2 Disadvantages

- These have not been made commercially viable and are still in the research and development stage.
- Its makeup includes liquid electrolytes, making it sensitive to both high and low temperatures. Thus, it can only withstand a certain working temperature.
- Volatile organic solvents make up the electrolyte. Therefore, it has to be sealed carefully. The dye-sensitised solar cell needs to be fitted carefully because of its flammable nature [9].

4. Making of DSSCs

This section outlines the materials used and the fabrication process involved in (DSSCs), providing a comprehensive overview of the intricate procedures employed in the manufacturing process of DSSCs [7,10].

4.1 Materials used in DSSCs

Transparent and conductive substrate: DSSCs usually consist of two transparent and conductive sheets that serve as both current collectors and substrates for the deposition of the catalyst and semiconductor. A good substrate should have minimal energy losses, an effective charge transfer, and transparency of at least 80%. Fluorine-doped tin oxide (FTO, SnO_2:F) and indium-doped tin oxide (ITO, In_2O_3:Sn) are two of the most used substrates.

Working electrode: The working electrode (WE) is made by coating a thin layer of a semiconductor oxide, such as titanium dioxide (TiO2), zinc oxide (ZnO), lead dioxide (SnO2), niobium (v) oxide (Nb2O5), and nickel oxide (NiO), to the mentioned above substrates. The energy band gap in these oxides is rather large. TiO2 is the most often used oxide since it is non-toxic, inexpensive, and readily available.

Sensitizer (Dye): The incident light that strikes the cell is absorbed by the dye. To emit the light that was previously absorbed, it should be luminous. To absorb as much light as feasible, the dye's absorption spectrum must include both near-infrared (NIR) and ultraviolet-visible (UV-Vis). Examples of dyes that can be used are Ruthenium-complex dyes, metal-free organic dyes, QD sensitizers, perovskite-based sensitizers, mordant dyes, and natural dyes.

Electrolyte: The primary components of the electrolyte are a redox couple (oxidation and reduction simultaneously), an ionic liquid or solvent, additives, and cations. The redox couple must be able to regenerate the oxidized dye. It must have strong chemical, thermal, and electrochemical stability. The electrolytes I^-/I_3^-, Br^-/Br_2, SNC^-/SCN_2, and CO(II)/Co(III) are a few of the more popular ones.

Counter Electrode (CE): Typically, carbon (C) or platinum (Pt) are used for manufacturing counter electrodes. The function of the CE is to act as a catalyst in the reduction of the redox couple.

4.2 Fabrication Process

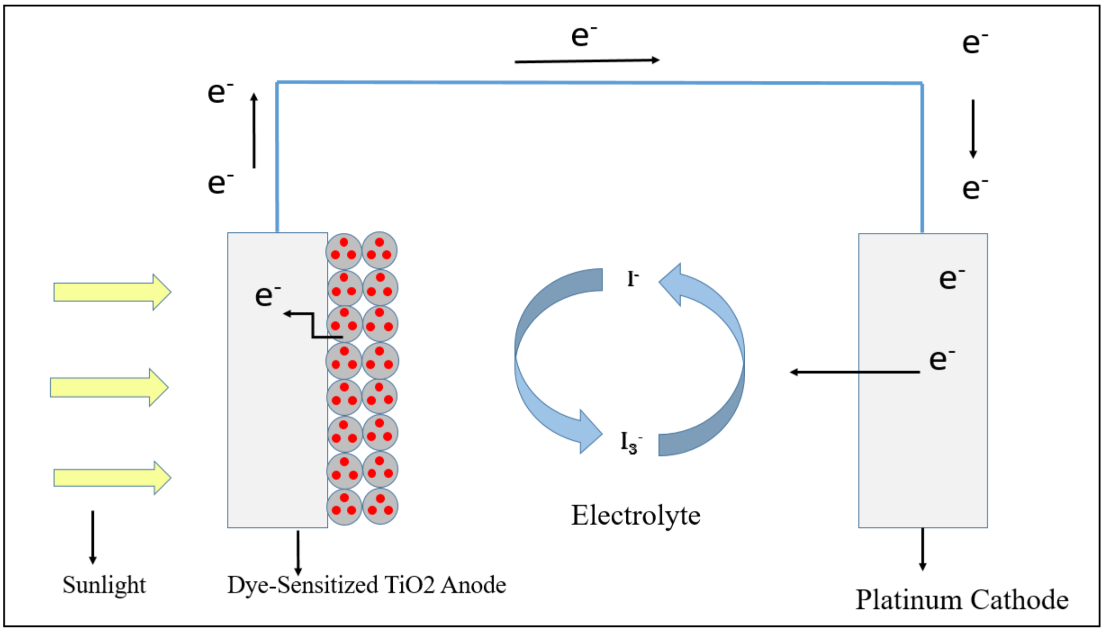
The fabrication process requires the following components: indium-doped Tin Oxide (ITO) glass, TiO2 paste, Ethanol, Dye, Pure iodine, Potassium Iodide, Ethylene glycol, Scotch tape, Hot plate and Binder clips. The process starts by masking the conductive side of the ITO glass using scotch tape, leaving a precisely squared-shaped opening for the subsequent application of a specialized TiO2 paste. The preparation of the TiO2 paste entails the gradual addition of ionized water to TiO2 powder, with continuous stirring until the desired consistency is achieved. Following this, the TiO2 paste is applied evenly onto the ITO glass surface, aided by the use of a rollerblade for uniform distribution. Upon the complete drying of the TiO2 paste, the scotch tape covering the glass is meticulously removed, and the glass is subjected to a sintering process on a hot plate, maintaining a temperature of 100 degrees Celsius for 15 minutes. In the assembly of the light sensitizer electrode, ethanol-based dye droplets are carefully introduced onto the TiO2-coated surface of the glass. This step marks the final stage in the creation of the light-sensitive electrode.

In the preparation of the counter electrode, a layer of graphite is applied to the conductive side of the Fluorine-doped tin oxide glass. Regarding the electrolyte solution, it is formulated by combining pure iodine and potassium iodide within Ethylene glycol. A small volume of this solution is delicately inserted between the two electrodes. To complete the assembly, the two electrodes are securely fastened together using binder clips, and subsequently, the output voltage is assessed for its performance.

5. Working Principle of Dye-Sensitized Solar Cells

The working principle of DSSCs is based on four steps: light absorption, electron injection, carrier movement, and current collection. When sunlight strikes the DSSC, the dye molecules absorb photons, become excited and release electrons into the TiO2 semiconductor material. The injected electrons move through the semiconductor, constituting an electric current. Simultaneously, the dye is left in an oxidized state, requiring the transfer of electrons to maintain its functionality. The electrons from the platinum cathode are transferred to the electrolyte. Here, the electrolyte solution plays a crucial role. It typically contains an iodide/triiodide redox couple. It reduces iodide ions to form triiodide ions. The triiodide ions then migrate to the platinum electrode. The platinum electrode facilitates the reduction of triiodide ions back to iodide ions while simultaneously allowing the electrons to flow through an external circuit. This regeneration of iodide ions enables the dye to continue absorbing sunlight and injecting electrons into the semiconductor, thus sustaining the electric current [11, 12]. Figure 2 presents a schematic diagram for the working principle of DSSCs.

Figure 2. Working Principle of Dye-Sensitized Solar Cell



6. Real Life Installations

6.1 Building-Integrated Photovoltaic Applications (BIPV)

BIPVs are photovoltaic (PV) technologies that may replace traditional building structures as components of the fenestrations, such as roof tiles, wall cladding or skylights. In addition to producing electricity, PV facades are easier to create than traditional building facades and have a more contemporary appearance.
Several commercial organisations, including Dyesol, Dyepower, and the Commonwealth Scientific and Industrial Research Organisation (CSIRO), have created the DSSC module prototypes used in BIPV applications. In comparison to standard PV cells, DSSC is also less sensitive to temperature and angle of incidence, and it can even operate at greater temperatures while still achieving higher power conversion efficiency (PCE). Lee and Yoon showed that the installation angle has a major impact on the power output of the DSSC windows by demonstrating that the sloping DSSC windows can create a 43.38% larger amount of power yield when compared to the vertical DSSC windows. Because it had a greater sky view factor and more diffuse radiation than the vertical plane, the sloping plane had a higher power yield [13,14].

6.2 Smart Farming

In recent years, the issues of food security and agricultural productivity have been further complicated by climate change and human-induced environmental destruction, such as urbanization, deforestation, desertification, and salinization. One of the solutions lies in the emerging greenhouse cultivation that allows optimal growth for crops even in harsh circumstances. Typically, the greenhouse environmental control elements involve light, humidity, temperature, nutrients, and carbon dioxide [15].
The semitransparent and colour-tunable DSSCs are ideal for greenhouse applications. The colours of DSSCs are tunable by the types of dyes used, and hence, the DSSCs can serve as photoselective coverings or plant growth regulators by manipulating the light spectrum that can enter the greenhouse, which allows optimized plant growth. The adjustable transparency of DSSCs can also minimize the negative impacts on crop growth compared with the opaque silicon-based PV.
Apart from greenhouses, the electricity generated from the DSSC modules can be utilized to energize various sensors (soil moisture sensor, temperature sensor, humidity sensor, etc.) as well as IoT setup (Wi-Fi modules and long-range devices), which require a low-power consumption [15].

6.3 Indoor Energy Harvesting Applications

The performance of DSSCs under ambient or low-light conditions has been investigated by several research groups [16]. Interestingly, most of the DSSCs can achieve higher Power Consumption Efficiency under low-light conditions compared with the standard AM 1.5G illumination. In 2009, G24 Innovations created the world's first commercial products based on the DSSC technology, which were backpacks and bags integrated with DSSC modules. The integrated DSSC modules can harvest energy even under indoor low-light conditions to recharge mobile electronic devices [17].

7. Conclusion

Dye-sensitized solar cells (DSSCs) are a promising new type of solar cell with the potential to be more efficient and cost-effective than traditional silicon solar cells. However, DSSCs are still in the early stages of development, and some challenges need to be addressed before they can be commercialized. Researchers are working on developing new electrolytes and dyes that are more stable and efficient and improving the fabrication process of DSSCs. They are also exploring new ways to use DSSCs, such as in tandem with other types of solar cells to improve overall efficiency. By conducting further research in these areas, we can make DSSCs more viable for commercialization and help to meet the world's growing energy needs. Overall, this paper provides a comprehensive and informative overview of the potential of DSSCs to revolutionize the solar energy industry. It is a valuable resource for anyone interested in learning more about this promising new technology.

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