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Chapter

Outdoor Performance and Stability Assessment of Dye-Sensitized Solar Cells (DSSCs)

Reema Agarwal, Yogeshwari Vyas, Priyanka Chundawat, Dharmendra and Chetna Ameta

Abstract

In this era the requirement for energy is enhancing, therefore, many energy resources are developed among them the emerging third-generation dye-sensitized solar cell is one of the environment-friendly solar cell-based technology. Generally, dye-sensitized solar cells consist of a nanomaterial-based photoanode, dye molecules as an absorber, electrolyte, and counter electrode. In the case of indoor application, this solar cell works easily so this is the characteristics of a dye-sensitized solar cell. Moreover, the outdoor performance of DSSC degrades on exposure to sunlight. Exposure to sunlight increases the temperature of the internal component of DSSC and consequently degradation in device performance. Long-term stability is obtained by the choice of such material where degradation takes place slowly and plastic covers are also coated over DSSC to prevent degradation. The solar response of DSSC towards dye was also mentioned, the higher the percentage of EQE higher the efficiency of the device. In this chapter, the authors discuss the introduction of a solar cell, the working principle of DSSC, and the available research background for outdoor performance and long-term stability with a solar response of device i.e. EQE or IPCE.

Keywords: DSSC, Solar energy, Outdoor, Stability, IPCE

1. Introduction

Climate change in the 21st century influences the water resources and food which pattern disease and impact greatly the mankind livelihood. Thus, an efficient mechanism is mandatory to control the emission of hazardous gases. The reduction in carbon emission will also help greatly for the environment, most of the nations are seriously working to mitigate this problem. The utilization of available low Carbon energy resources such as solar and wind will be a milestone to cater to the energy necessities of the globe without harming the environment. After the oil crisis in the year 1973, the alternative sources for energy harvesting are derived by many scientists and still, research is going on [1]. The rising population and higher living standards are influencing climate change significantly. Industrialization, the technologically driven changing landscape of cities have increased the energy demand hugely. The resources of energy are commercial and non-commercial where the commercial resources

mainly include fossil fuels like coal or natural gas whereas the non-commercial resources include wood and animal and agriculture wastes as well. Fossil fuel resources are non-renewable, limited in stocks, and creates pollution in the environment, as well as these, are fastly depleting. Therefore, research on the development of new energy resources is extremely needed to cater to the energy demand of the revolutionized world. Renewable energy resources are eco-friendly, abundant, and practically inexhaustible. Sun is one of the renewable resources for green and free energy which provides a tremendous amount of energy without any expenditure. The sun irradiates more energy per hour vis-à-vis the total energy consumed globally during one year. Solar energy is non-depletable, pollution-free, and available in abundance on the surface of Earth planet throughout the year. The Bloomberg New Energy Finance (BNEF) research organization made research on the current scenario of energy consumption and production and concluded that 50 percent of the world's energy would come from solar cells and wind by the end of 2050 [2]. Therefore, the use of solar energy could increase the economic growth of any country without affecting the environment.

The solar cell is a device that transforms solar or light into electrical energy, it is just a p-n junction or a diode. The Silicon-based solar cells were firstly used to convert sunlight into electricity, therefore, these solar cells are also recognized as traditional or conventional solar cells. The solar cells are classified into three generations. The first generation or crystalline Silicon solar cells are widely used as these have been shown higher power conversion efficiency (η) about 26% [3, 4] and dominated the solar cell market ever since its invention, but fabrication of crystalline Silicon solar cells suffers from high module cost and a significant amount of by-products. The second generation comprises thin-film-based solar cells which reduced materials consumption and consequently cost of the device. This generation includes amorphous silicon solar cells, cadmium telluride (CdTe) thin-film solar cells, and copper indium gallium diselenide (CIGS) thin-film solar cells [5–7]. The materials to the second generation solar cells are rare elements (e.g. Tellurium) and hazardous (e.g. Cadmium). Due to the high cost of first-generation solar cells, and toxicity, and limited availability of materials for second-generation solar cells, a new generation of solar cells emerges as third generation [8]. The third-generation solar cells comprise a variety of new materials besides the evergreen and champion Silicon which include nanomaterials and Silicon wires. The third-generation solar cells are designed to trim down the cost and are based on the simple, cheap, and easy fabrication process. This generation includes dye-sensitized, polymer, quantum dot, perovskite solar cells. Given cost-effectiveness, efficiency, and easy fabrication process, the dye-sensitized solar cells (DSSC) could be one of the best promising alternatives to the Silicon solar cells [9].

The configuration of dye-sensitized solar cells (DSSCs) comprises a glass substrate (conductive substrate), nanostructure semiconductor (photo-anode), sensitizer (dye), electrolyte, and catalyst counter electrode [10]. Nowadays, the DSSC devices are developed to have such a photo-anode that could efficiently harvest the energy, increase the dye pickup, light scattering ability, reduce recombination reaction and improve charge transferability [11]. The prototype DSSC was reported by Michael Gratzel in 1991. The DSSCs are one of the most efficient photo-to-electron conversion devices under indoor and low-level outdoor lighting for integrating green buildings. For a DSSC device, the highest achieved efficiency is 14.30% (practically) to the date where the Co (II/III) based electrolyte was used with the co-sensitization of organic dyes [12]. The theoretically predicted maximum efficiency for DSSC is 32% which is estimated and limited by the Shockley-Queisser limit based upon the principle of detailed balance [13]. In the architecture of dye-sensitized solar cells, usually, TiO_2 (titanium dioxide) is preferred because of its photoactive, low cost, and abundant availability [14]. The most used dye for DSSC is N719 (Cis-Di-(thiocyanato) bis (2,2′-bipyridyl)-4,4′-dicarboxylate)

ruthenium (II)) owing to its good light absorber and charge transfer properties vis-à-vis to any other dyes [15]. A volatile electrolyte such as iodide/triiodide is commonly used which has a highly corrosive nature and good reaction with Platinum (Pt) based counter electrode [16, 17]. The photo-anode of DSSC is usually coated employing chemical route-based techniques like doctor blade and spin coating followed by high-temperature heat treatment [18–20].

DSSC can be useful for portable electronic devices, iPods, and solar lamps that work on the outdoor light source. The outdoor performance of the DSSC device was observed by many scientists in terms of the commercialization of DSSC. But the main factor that affects solar efficiency is a temperature that decreases the long-term stability of the device. To increases the stability of DSSC it was covered by plastic but appropriate results are not obtained. DSSC can easily work in a low-light condition or cloudy condition so these cells are a good option for building integrated photovoltaic cells (BIPV). However, DSSC also exhibits photoresponse/EQE concerning dye and electrolyte. Higher the EQE/IPCE means the photon absorbed by dye molecule is high therefore regeneration of electrolyte takes place and high efficiency of the respected device is observed. This chapter comprises a basic introduction to solar cells viz. principle of solar cells, and description of dye-sensitized solar cells as well the outdoor performance and stability along with photoresponse external quantum efficiency of the solar cell (EQE).

A solar cell directly converts solar energy into electrical energy by a physical process termed as "photovoltaic effect". The conversion of energy occurs without any intermediate process in certain semiconductor materials. In the photovoltaic effect, a semiconducting material generates charge carriers (electrons in conduction band and corresponding holes in valence band) when it is exposed by light where the light or solar energy and optical energy band gap of the exposed material are the important parameters. In the photoelectric effect, charge carriers are electrons while in the photovoltaic effect, charge carriers are both the electrons and holes. The photovoltaic effect was firstly discovered in 1839 by French Physicist Edmond Becquerel. During experimentation with wet cells, Becquerel noted that the voltage of the cell increased when its silver plates were exposed to the sunlight [21]. The solar cells are composed of different types of semiconductors where p-type and n-type layers are joined together to form a p-n junction (**Figure 1**). The junction between two types of semiconductors promotes an electrical field which is formed in the region of the junction as electrons move towards the positive p-side and holes towards the negative n-side. This generated field causes negatively charged carriers to move in one direction and positively charged carriers in opposite direction. On connecting it with the load, an electric current is produced in the circuit.

The sunlight is composed of photons which are the smallest energy bundles of electromagnetic radiation or energy. These photons can be absorbed by the absorber layer of the photovoltaic cell if the photons have energy ($h\upsilon$) equal or greater than E_g and less than 2 E_g where E_g is the band gap of the layer concerned. When the light of a suitable wavelength is incident on these cells, energy from the photon is transferred to an atom of the semiconducting material in the p-n junction. Specifically, energy is transferred to the electrons in the material. This causes the electrons to jump to a higher energy level which is known as the conduction band. This leaves behind a "hole" in the valance band from which an electron is jumped up. This movement of the electron as a result of added energy creates two charge carriers viz. electrons in the conduction band and holes in the valence band. The asymmetric junction of different natures of semiconducting materials in the solar cell leads to the separation of these charge carriers (electron and holes) and establishes the built-in potential which impels these charge carriers towards the respective electrodes to contribute to electric current in the circuit.

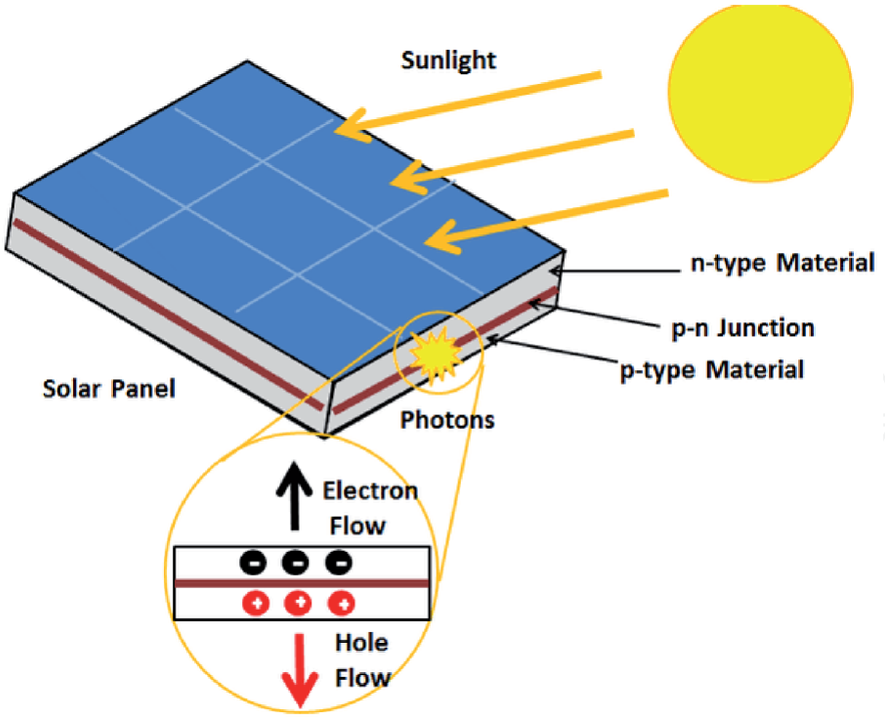


Figure 1.
A systematic presentation of the photovoltaic effect [22].

2. Dye-sensitized solar cells

As stated in the introduction part that the energy demand has increased the depletion of fossil fuels, therefore, the development of new skills which are based on renewable energy resources are spurred by world-leading scientists so that the upcoming new generation does not face any crisis related to the energy. Photovoltaic technology is eco-friendly and attractive among all renewable energy technologies. It directly converts sunlight into electrical energy, thus, it is broadly used for harvesting solar energy. The conventional Silicon-based solar cells are quite restricted because of their high cost, hence inexpensive, environmentally friendly, and simple fabrication process-based solar cells such as dye-sensitized solar cells (DSSCs) are used [23]. The dye-sensitized solar cells are comprised of a semiconducting material photo-anode, a counter electrode, an electrolyte, and a sensitizer (dye). DSSC can work in dark and cloudy conditions so it is an excellent candidate for indoor applications. O'Regan and Gratzel developed the first dye-sensitized solar in 1991 by colloidal nanoparticles of TiO_2 thin films which had an efficiency of 7.1%. The main aim of the present chapter is to introduce DSSC therefore, it is discussed in detail.

2.1 Device structure and working principle of dye-sensitized solar cell

A typical dye-sensitized solar cell is assembled in a sandwich-type structure. Generally, transparent conductive glass is used as a substrate for the deposition of nanocrystalline thin films of metal oxide. The metal oxide films are sensitized by absorbing dye molecules where dye is covalently attached to the surface of the photo-anode for generating the photoelectrons. An organic electrolyte solution that contains redox couple is used for collecting electrons at the surface of the counter electrode and regenerating dye molecules. A catalyst deposited on a conductive substrate is used as a counter electrode for the development of dye-sensitized solar cells [24]. The schematic representation of the device structure to a typical DSSC is shown in **Figure 2**.

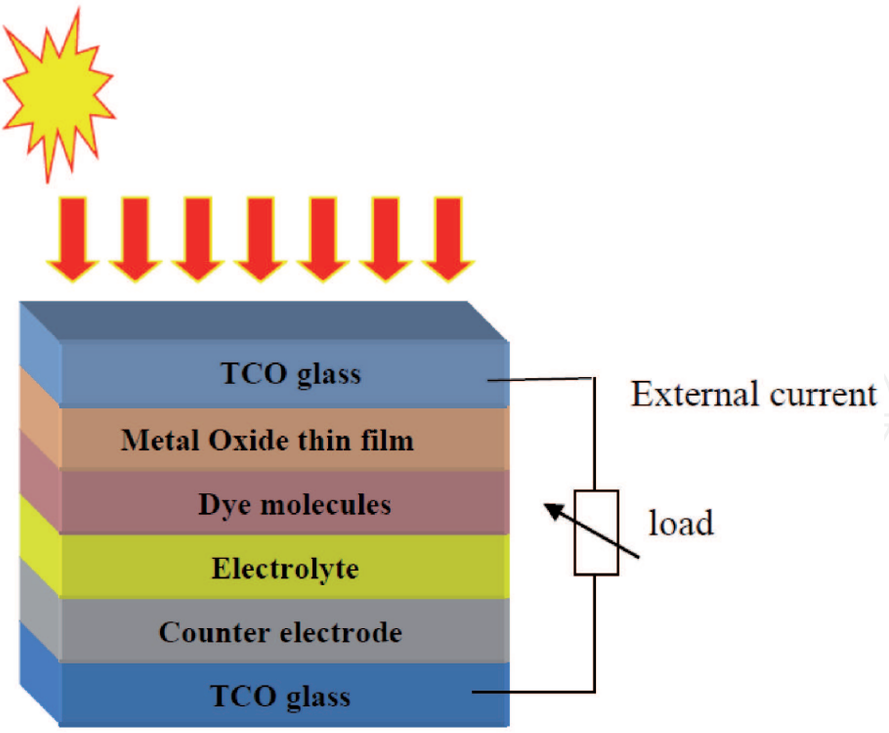


Figure 2.
Schematic device structure of a typical dye-sensitized solar cell (DSSC).

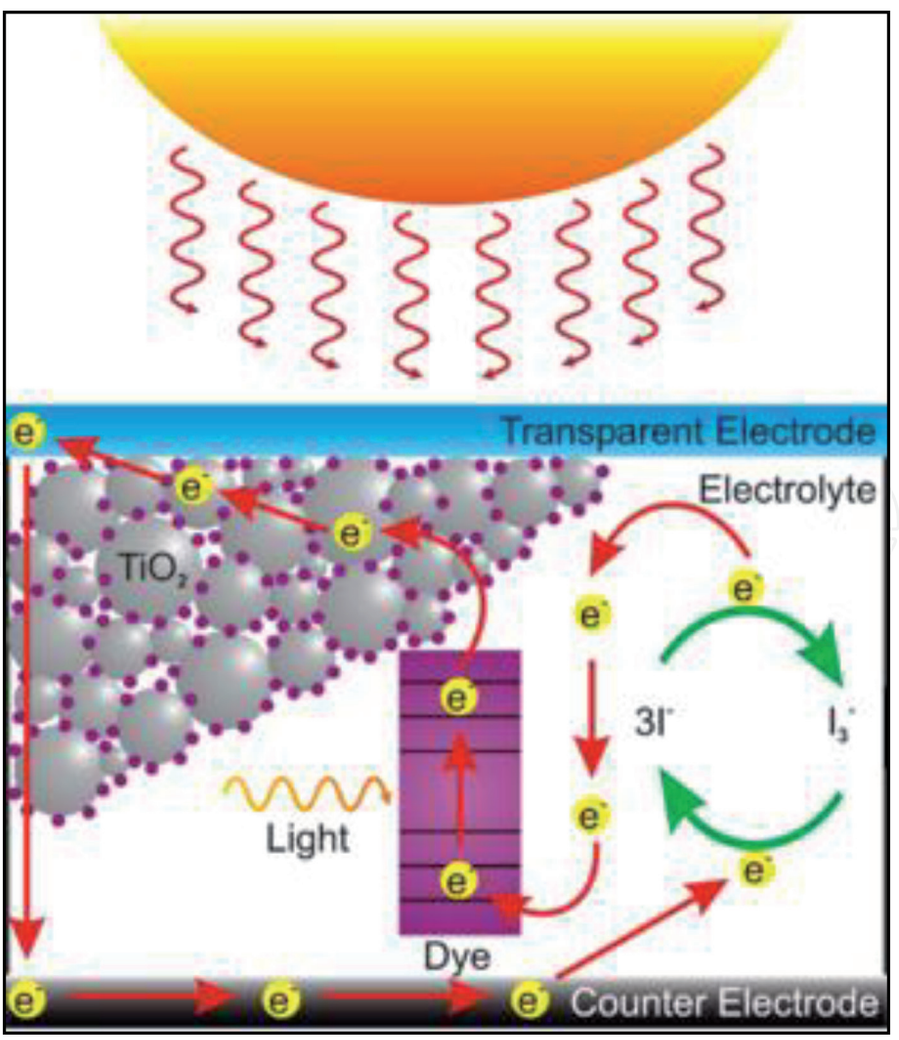


Figure 3.
A pictorial view of the operational principle of a typical dye-sensitized solar cell [26].

The absorption of irradiance and charge separation is quite different in the dye-sensitized solar cell as compared to the classical p-n junction solar cell [25]. An electron transfer process of sandwich-type dye-sensitized solar cells is systematically represented in **Figure 3**. The whole working process of the dye-sensitized solar cell is explained in three steps (1) Photo-excitation, (2) Transportation, and (3) Regeneration.

When the sunlight falls on a dye-sensitized solar cell device, then the present dye molecules on the surface of the TiO_2 layer (behaves like electron transport layer) absorb the incident photons and consequently excite the electrons. The excited electrons of dye which present above the conduction band of TiO_2 are immediately injected into the conduction band of TiO_2 and dye molecules get oxidized. At this stage, an electrochemical potential difference is generated between semiconductor oxide and electrolyte, and the electron density of TiO_2 also is increased due to charge carrier transfer from dye molecules to metal oxide.

Now, these electrons transfer from metal oxide to counter electrode through the external load where these electrons further transfer to the electrolyte. Herein, reduction of the electrolyte takes place by converting tri-iodide (I_3^-) into iodide (I^-). Regeneration of dye molecules is occurred by receiving electrons from iodide and simultaneous oxidation of iodide to tri-iodide happens. Regeneration of I^- is taken place by counter electrode so the whole cycle is regenerated. The flow of electrons through the external circuit generates electrical energy [27–29].

The chemical reactions that took place in the mechanism are given as below [30–33]:

2.1.1 The chemical reaction of dye-sensitized solar cell

$$\mathrm{Dye} + \mathrm{hv} \rightarrow \mathrm{Dye}*\left(\mathrm{Photoexcitation}\right) \tag{1}$$

$$\mathrm{Dye}* + \mathrm{TiO_2} \rightarrow \mathrm{Dye}^+ + \mathrm{e_{CB}}^- \left(\mathrm{TiO_2}\right)\left(\mathrm{Electron\ injection}\right) \tag{2}$$

$$2\mathrm{Dye}^+ + 3\mathrm{I}^- \rightarrow 2\mathrm{Dye} + \mathrm{I_3}^- \left(\mathrm{Dye\ regeneration}\right) \tag{3}$$

$$\mathrm{I_3}^- + 2\mathrm{e}^-_{\mathrm{catalyst}} \rightarrow 3\mathrm{I}^- \left(\mathrm{Electrolyte\ regeneration}\right) \tag{4}$$

$$\mathrm{Dye}^+ + \mathrm{e_{CB}}^- \left(\mathrm{TiO_2}\right) \rightarrow \mathrm{Dye} + \mathrm{TiO_2}\left(\mathrm{Recombination}\right) \tag{5}$$

$$\mathrm{I_3}^- + 2\mathrm{e}^-_{\mathrm{CB}} \left(\mathrm{TiO_2}\right) \rightarrow 3\mathrm{I}^- + \mathrm{TiO_2}\left(\mathrm{Back\ reaction}\right) \tag{6}$$

$$\mathrm{Dye}* \rightarrow \mathrm{Dye} \tag{7}$$

2.2 Components of dye-sensitized solar cell

a. **Substrate:** Generally, a transparent conductive glass substrate is used for the fabrication of thin-film layers which could be employed as transparent conducting oxide substrates to develop a device. The transparent conducting oxide can be either Fluorine doped Tin oxide (FTO) or Indium doped Tin oxide (ITO) [34]. FTO substrate is usually applied for DSSC owing to good conduction property, stability, durability, and low toxicity. Besides the conductive

glass substrates, the plastic materials, metal sheets, Ti foils are also useful substrates for DSSCs and according to the device, architecture may be designed.

b. **Photo-anode:** In DSSC, the photo-anode is a wide bandgap semiconducting material e.g. TiO_2, ZnO, SnO_2, ZrO_2, Nb_2O_5, Al_2O_3 are used as photo-anode for device development [35–41]. The main goal of these semiconductor materials is to absorb dye molecules and collection of the photo-excited electrons. Photo-anode materials should have a high surface area so absorption of dye molecules could be increased which eventually enhanced the power conversion efficiency of the solar cell device concerned. The crystallite size, porosity, microstructure, etc. play an important role to develop an efficient device for maximum harvesting of the incident irradiance. Typically, the DSSC photo-anode is prepared by conventional technique i.e. doctor blade but nowadays, many techniques are available which could be applied as per need and device architecture [42–46]. Doping of semiconductor material with suitable cation or anion also alters its optical energy bandgap, and post-deposition treatments like annealing affect the electrical, structural, and other relevant properties [47–49].

c. **Counter electrode:** The counter electrode (cathode) plays an important role in the regeneration of electrolytes by transporting electrons to the electrolyte which arrived externally from the circuit. Thus, the counter electrode should have good conductivity and catalytic activity. Platinum (Pt) is normally preferred to choose as a counter electrode for dye-sensitized solar cells [50]. The high cost and corrosion of Platinum limit its use and therefore, alternative options could be undertaken for counter electrodes. Carbon and conducting polymers (PEDOT) are also suitable materials due to their low cost, abundance, and adequate conductivity but their catalytic activity is lower as compared to the Platinum [51, 52]. Besides these, NiS/rGO, polypyrrole (PPy), $Co_{0.5}Ni_{0.5}Se$/GN, and WO_2 are utilized as counter electrodes for dye-sensitized solar cells [53–56].

d. **Electrolyte:** The function of electrolyte is to regenerate dye molecules and to work as conducting medium. Electrolyte plays important role in achieving higher efficiency of a solar cell. Based on the physical state, the electrolytes are classified into three main categories as a liquid electrolyte, quasi-solid electrolyte, and solid electrolyte [57]. As a liquid, triiodide/iodide (I_3^-/I^-) is mostly used as a redox couple because of the fast regeneration of the dye and slow recombination process in the dye-sensitized solar cell. Other electrolytes are also available like Br^-/Br_3^-, $SeCN^-/(SeCN)_2$, $SCN^-/(SCN)_2$, Co (II)/(III), Cu (I/II) etc. [58–60]. To overcome the problem of volatilization and leakage of liquid electrolytes, the quasi-solid and solid electrolytes are explored. Quasi solid electrolytes are organic liquid polymers that are converted into gel form by chemical and physical reactions that have cohesive nature and diffusive transport properties [61]. As solid electrolytes, mainly hole-transporting materials (HTM) are used viz. spiro-OMeTAD, CuSCN, CuI, P3HT, PEDOT, $CsSnI_3$ which can overcome the issue of leakage, corrosion, and salvation for DSSCs [62]. In HTM or semiconductors, charge transportation takes place via electrons or holes while in electrolytes, it takes place through ions.

e. **Sensitizer:** Dyes play the important role of photo-sensitizer in DSSCs where a self-assembled layer of dye is anchored on the surface of the photo-anode. When sunlight strikes on dye molecules then these dye molecules absorb photons and consequently, the photoexcitation of electrons occurs which injects electrons into the conduction band of the photo-anode. Based on the composition used

in dye, it is classified into three main categories viz. metal complex, metal-free organic complex, and natural sensitizer [63]. Ruthenium-based sensitizers are remarkable for achieving higher efficiency in dye-sensitized solar cells [64, 65].

3. Outdoor performance and stability of dye-sensitized solar cell

In outdoor conditions the main factor that affects efficiency is temperature. In this section different solar radiation illumination was discussed. The stability of dye-sensitized solar cell is mainly influenced by electrolyte, liquid electrolyte exhibit higher efficiency but the volatile nature of liquid electrolyte degrades solar cell and therefore stability of the cell reduces.

Yuan et al. [66] tested outdoor application of DSSC for Building Integrated Photovoltaics (BIPV) application where a time duration of four years was taken into consideration. Here dye Z991 and Z907 were used for cell fabrication where the first one harnesses 15% more electricity over the later one for two years. Given the stability of the device, the efficiency of dye Z991 based solar cell decreases to 17% for the initial two years thereafter efficiency remains stable for the remaining two years. Moreover, the Z907 based DSSC device is out of the use or degrade after four years in outdoor application. The stability of Z991 over Z907 is due to the presence of thiophene moieties in Z991 i.e. responsible for better energy harvesting and thermal stability. When the solar irradiance increase there is no linearly incremented in electricity generation for irradiance of lower than 20 Wh.

Kato et al. [67] synthesized dye-sensitized solar cells with N719 dye, TiO_2, and carbon counter electrode and tested durability test in the outdoor working condition for a time duration of 2.5 years. The DSSC modules were developed monolithically series interconnected on the TCO substrate and covered by a waterproof cover. Before the exposure to sunlight, the device reveals 0.32 and 0.71 suns from the current–voltage curve and power-voltage curve. During the stability test voltage was approximately kept around 1.6 V. The solar parameters such as JSC fall for 5 months thereafter it remains constant for left years and efficiency decreases/degrades subsequently decrement in VOC and FF. Additionally, EIS reveals exposure of cell in outdoor increases the Nernst impedance of triiodide and Raman spectra also reveals increment in luminescent ingredients of electrolyte, therefore, V_{OC} and FF decreases in outdoor condition. Berginc et al. [68] outdoor exposed ionic liquid-based dye-sensitized solar cell for 7 months in solar radiation of 906kWh/m^2. In the summers maximum V_{OC} is obtained in the early morning and on an autumn day when days are shorter and temperature is lower that time J_{SC} of cell increases. Park et al. [69] observed the change in film thickness effects J-V curve (**Figure 4**) of TiO_2 based solar cell under 1 sunlight intensity. On increasing the thickness, the J^{SC} of the cell increases from 6.6 to 10.7 mA/cm^2 i.e. about 62% whereas the fall down in V_{OC} is 759 to 727 mV due to increases in surface area that accounts for more dye molecule absorbing.

Asghar et al. [70] developed dye-sensitized solar cell and tested in outdoor condition as well comparison with silicon cell was carried out. Here the lower irradiance and higher temperature are suitable for DSSC, at these parameter DSSC harvest more energy instead of silicon solar cell. The efficiency of DSSC decreases as time duration increases. Moreover, the device that was fabricated by employing MPN as an electrolyte degrades fast whereas ionic liquid-based devices are more stable and constant efficiency was observed for two months then degradation initiates. The thermal influence of dye-sensitized solar cells was studied by Matsui et al. [71] where the current collecting study was done. When the temperature was maintained at around 85° C leakage of ionic liquid does not occur but the long-term stability of the device is strongly affected by moisture. Therefore double-sealed

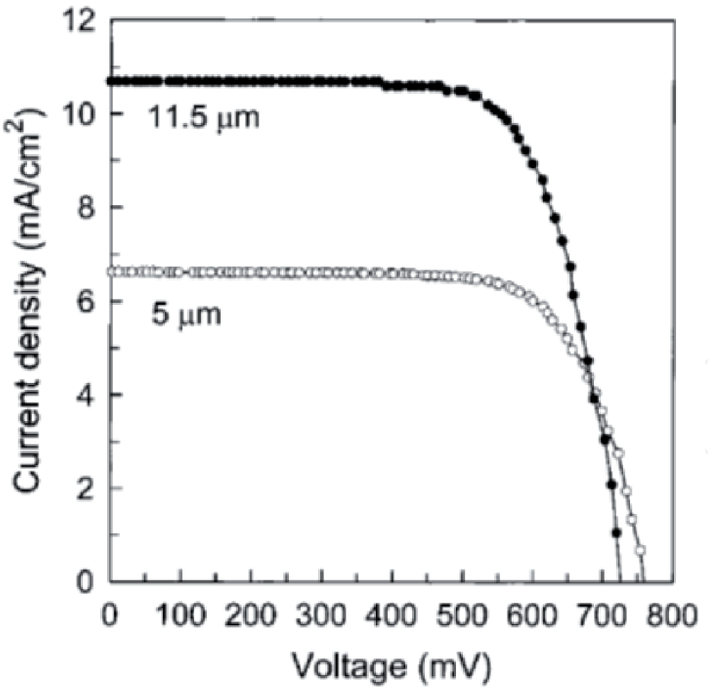


Figure 4.
The effect of film thickness on the J-V curve of DSSC. Reprinted with permission from ref. [69] copyright (2000) American Chemical Society.

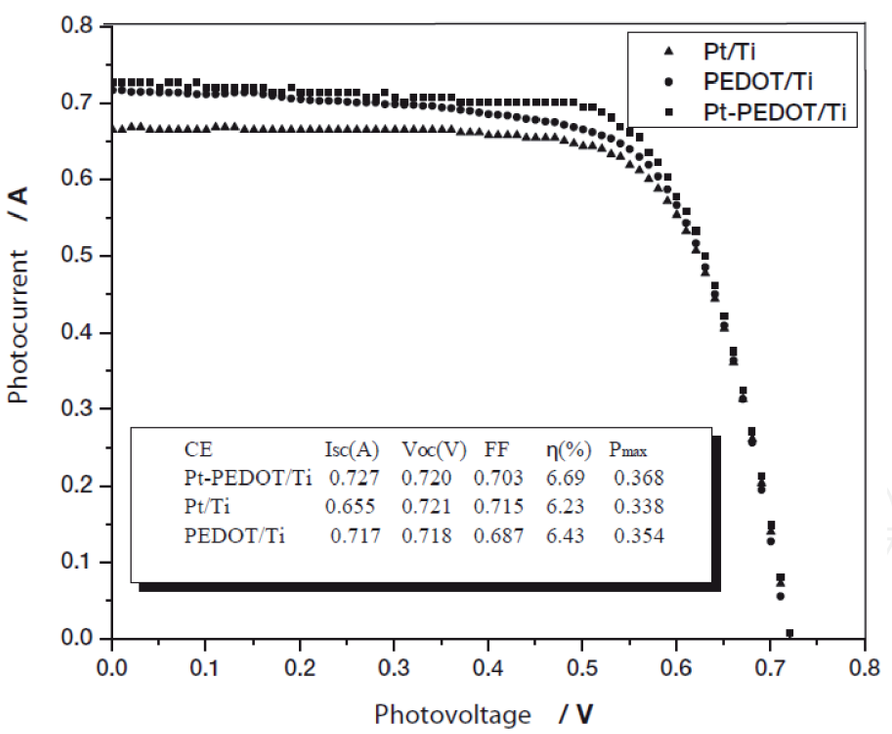


Figure 5.
The J-V curve for DSSC with the different counter electrodes. Reprinted with permission from ref. [73] copyright (2012) John Wiley and Sons.

package for the device was invented and a test on substrate size of 50 mm × 50 mm was used where 85° C temperature was maintained for 1000 hours and stability was observed. Bella et al. [72] designed fluoropolymer and rare elements-free light shifting coating systems for dye-sensitized solar cell devices. The introduction of fluorescent species in DSSC downshifts UV photons into visible light that significantly improves PV efficiency by 60%. The improvement in efficiency is

accountable for improvement in photon flux i.e. caused by the introduction of luminescent agent that results from nanometric light shifting in organic dyes. Now the outdoor long-term stability was measured for 3 months where the introduction of a light shifting agent preserves the power conversion efficiency of the solar cell.

Freitag et al. [74] demonstrated dye-sensitized solar cells with dye D35 and XY1 were copper-based redox electrolyte is used. At the AM of 1.5 G, the observed PCE is 11.3% and under 1000 lux indoor condition it achieves 28.9%. The obtained results point out DSSC are suitable for ambient light condition. Mehmood et al. [75] constructed DSSC with an organic photosensitizer. The PCE of the cell was 2.58% at 25°C in air mass of 1.5 G and illumination of 100 mW/cm^2. The increment in temperature falls down the efficiency of this solar cell it is stable up to 35°C. Wu et al. [73] demonstrated dye-sensitized solar cells with an area of 100 cm^2 and lightweight based on Ti substrates. Here PEDOT counter electrode is used which is having good transparency and electrocatalytic activity. The J-V curve (**Figure 5**) reveals the current density (I_{SC}) of PEDOT-Pt/Ti is higher. The photoconversion efficiency was achieved about 6.69% and in an outdoor condition of solar radiation of 55 mW cm^{-2} 0.368 W power output was observed.

4. Spectral response/external quantum efficiency (EQE) response/ incident photon-to-current conversion efficiency (IPCE)

Generally, dye-sensitized solar cell photoresponse for a given incident wavelength of light and the result is depicted in form of varying wavelength and percentage of IPCE. When the current is generated through the response of photon that time characteristics peak appears at a particular wavelength. It is the ratio of generated electrons to the incident photons. Moreover, IPCE depends upon the yield of electron transfer and light-harvesting efficiency that causes quantum charge injection and electron quantum efficiency in the present external circuit of the device. In the case of DSSC, the measurement of IPCE clears that dye is well linked to photoanode and electrolyte. When incident photons are exposed on DSSC that time dye uptake electrons from photoanode and create electron–hole pair and holes are transmitted to the electrolyte.

The generation of photocurrent i.e. dependent on wavelength is known as external quantum efficiency (EQE) where AC and DC mode is used for the generation of the beam. In the case of DC mode irradiation of monochromatic beam on a sample is continuously carried out for 3 sec so electrons reach to steady-state. In AC mode monochromatic light is chopped by shutter and illumination of bias light on a sample is carried out. Jeong et al. [76] measured EQE of DSSC and tandem cell (DSSC/CIGS) in DC mode. The EQE spectra reveal in the wavelength range of 300–800 nm EQE of DSSC was observed and for tandem cells, EQE spectra are almost similar to DSSC. When Berginc et al. [68] DSSC was exposed to outdoor conditions for seven months, the EQE of the solar cell was measured. The peak at 360 nm is accountable for absorption in the TiO_2 layer, 380 nm for change in I3- and at 450 nm for dye molecules degradation.

Kubo et al. [77] developed a tandem structure-based solar cell that improves the photocurrent of dye-sensitized solar cells. The IPCE of tandem solar cells is relatively outstanding to single cells. Tandem solar cell has elevated solar response (good external quantum efficiency), photocurrent and conversion efficiency from single-cell as well lower VOC and higher FF was also observed. Park et al. [69] prepared homogeneous, crack-free, and rod-shaped rutile TiO2 thin films with having a thickness of 12 μm. The measurement of IPCE (incident photon-to-current

efficiency) till 600 nm wavelength indicated that a significant amount of light was absorbed very fast in few microns but at higher wavelength, the increment in IPCE was directly proportional to the film thickness see **Figure 6**. Rutile and anatase films were compared having similar thickness where photocurrent of rutile based solar cell was 30% lower vis-a-vis to the anatase phase owing to the less amount of absorbed dye, small surface area, and transportation of electrons was also slow for rutile thin film-based solar cells. Lepikko et al. [78] tested outdoor performance of DSSC for 1000 h in 1 sun. The efficiency and fill factor of cell rise in outdoor condition i.e. just double of indoor condition well-remaining of solar irradiance. The IPCE decreases about 30% during testing of the cell this is due to photodegradation of electrolyte see **Figure** 7.

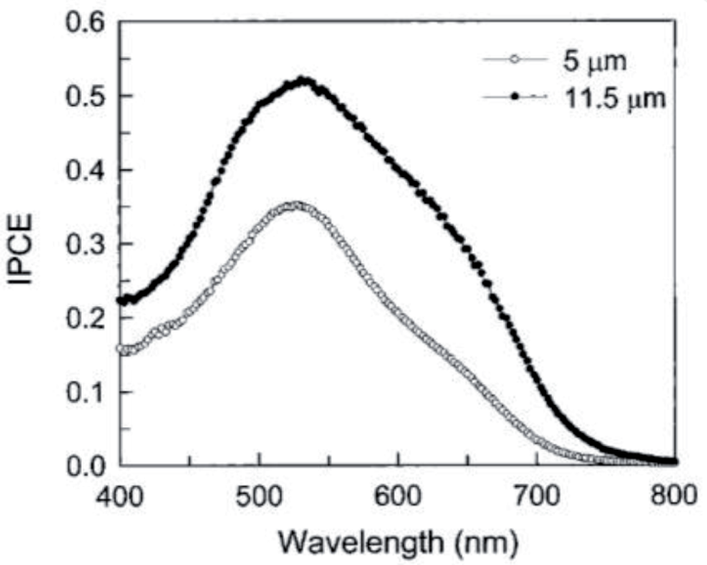


Figure 6.
The effect of a film thickness of TiO_2 on IPCE value of a solar cell. Reprinted with permission from ref. [69] copyright (2000) American Chemical Society.

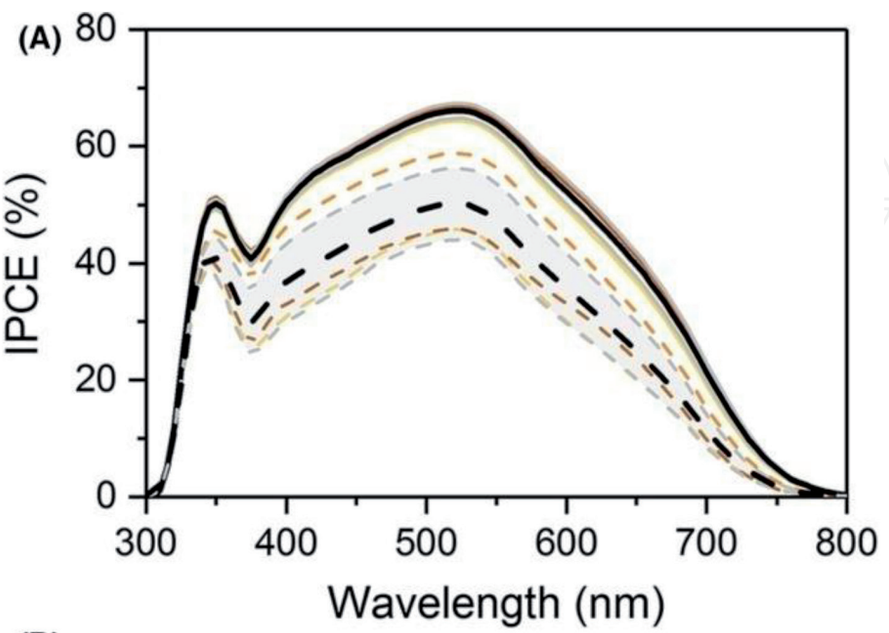


Figure 7.
The IPCE curve of DSSC in harsh northern outdoor conditions. Reprinted with permission from ref. [78] copyright (2018) John Wiley and Sons.

Roy et al. [79] studied the annealing of TiO2 nanotubes at 450°C for 30 minutes where the amorphous phase was converted into anatase. Post annealing and the TiCl4 treatments were carried in a closed vessel at 70°C for 30 min. SEM image of TiO2 nanotubes treated with TiCl4 confirmed uniform decoration with TiO2 nanoparticles and IPCE of the decorated samples was found 66% with a conversion efficiency of 3.8%. The ultrathin nanosheets of SnO2 were introduced as photo-anode in dye-sensitized solar cells for improvement in photoconversion efficiency by Xing et al. [80]. The nanosheets were developed by hydrothermal method and screen printed over FTO substrates, then a coating of TiO2 on SnO2 was performed to solve the problem of lower open-circuit voltage. The diffraction peak in XRD patterns revealed to the tetragonal rutile like SnO2 and FESEM images displayed a 3D flowerlike structure. HRTEM images of nanosheets showed lattice fringes over the entire surface. The efficiency of the devices using SnO2 NSs-TiO2 was 1.79% and IPCE was 35% which was much higher vis-a-vis the devices made up of SnO2 nanoparticles i.e. revealed by **Figure 8**.

Kumara et al. [81] employed natural dyes obtained from Ixora sp. (IX) and Canarium odontophyllum (CMB) which mainly contained anthocyanin that was used to improve the performance of DSSCs. The layered co-sensitization of dyes was carried out by firstly immersing TiO2 electrode in CMB extract followed by de-adsorption and then again immersed in second sensitizer IX for adsorption. The absorption spectrum of the co-sensitized electrode was increased as compared to the individual and mixture sensitized and similar results were obtained in IPCE measurement. The photovoltaic properties of the co-sensitized electrode were obtained under irradiance of 1000 W/m2 with a short circuit current density of 9.80 mA/cm2, VOC of 343 mV, fill factor of 0.46, and photoconversion efficiency of 1.55%. Gupta et al. [82] developed Cu/S co-doped TiO_2 as a photoanode for dye-sensitized solar cells. Here undoped TiO_2 exhibits about 70.02% of IPCE whereas it increases further on codoping with Cu/S. 0.1% Cu/S exhibits 73.65% of IPCE and on increment, the 0.3% Cu/S exhibits 82.98% of IPCE at a wavelength of 530 nm.

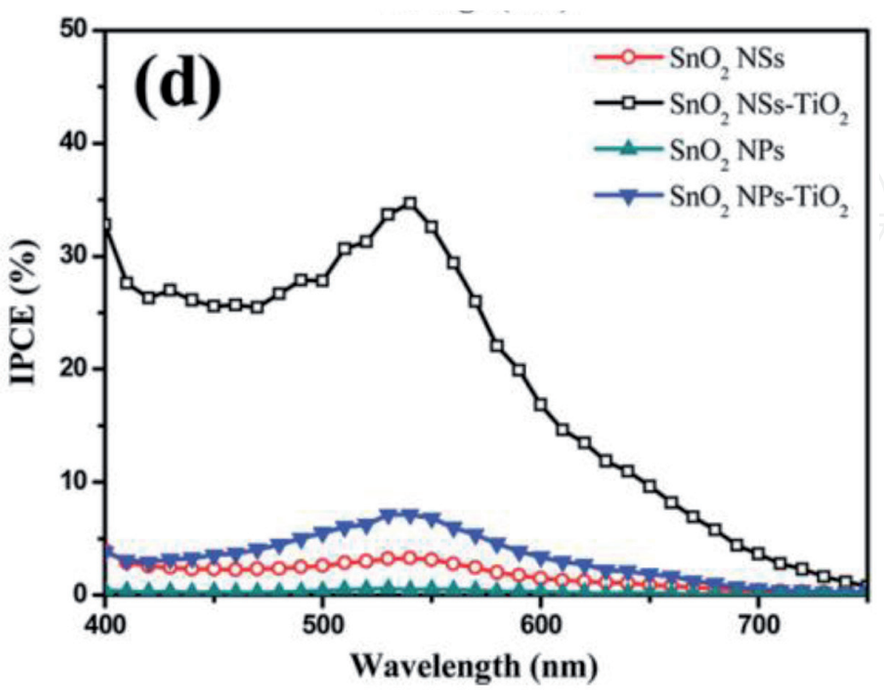


Figure 8.
IPCE curve of DSSC with different photoelectrode. Reprinted with permission from ref. [80] copyright (2012) American Chemical Society.

The improvement in IPCE is accountable due to the small size of particles and enhancement in short circuit current density (J_{SC}).

Patni et al. [83] fabricated dye-sensitized solar cells with natural dyes. The natural dyes were used are anthocyanin, betalain, and chlorophyll obtained from the extracts of Roselle spinach beetroot respectively. At the wavelength of 430 nm 6.21% IPCE was observed for anthocyanin dye and at 530 nm 9.9% of IPCE was measured for betalain and 6.1% IPCE was observed for chlorophyll-based dye at a wavelength of 660 nm. The blending or mixing of dye improves the IPCE. Wood et al. [84] reported the IPCE for different dye i.e. The cationic 1-hexyl-2,3,3-3H indolium acceptor dye (CAD3) dye exhibit IPCE of 50% and bodipy dye, it is 53% and for P1 54% was observed where the p-type dye-sensitized solar cell was fabricated. This chapter comprised literature on the solar response of DSSC on exposure of induced photons. Different dyes exhibit a variation in photon-to-current conversion efficiency. The higher the IPCE means the efficiency of the cell is a good and better amount of energy can be harvested by solar cell.

5. Conclusion

The dye-sensitized solar cell technology has an impact on the PV market owing to easy fabrication, cost, chemical stability, availability of chemicals, and good power conversion efficiency. In this chapter, we discussed the introduction of solar cells with working principles, complete elaboration of dye-sensitized solar cells, and outdoor performance and stability in different solar irradiations. Outdoor performance is affected by the temperature because on exposure to sunlight the temperature raise degrades the electrolyte and therefore stability and performance of the device decreases. Moreover, on rainy days the chances of degradation are increasing due to water or moisture, therefore, coating/layer of a suitable material is carried out over the solar cell this also increases the long-term stability of the device. The IPCE of solar cells initially is higher but with time duration it falls due to cell degradation or leaking and for a long time it stabilizes without so many changes. This chapter emphasizes the efficiency of DSSC when it exposes the outdoor and solar response of DSSC.

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Conflict of interest

The authors declare no conflict of interest.

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