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A Review on Current State, Recent Developments and Future Prospects of Dye Sensitized Solar Cells

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ABSTRACT

The sun is a primary abundant renewable source of energy for most of the life forms in our planet. By fully grasping the power of the sun, we can improve our way of life, reduce our dependence on fossil fuels or other types of energy sources and stimulate economy by bringing new jobs to all our planet industry. Among sustainable and renewable energy sources, solar cell, also known as photovoltaic cell, is one of the promising options of renewable energy and the most efficient. For the past several years, different photovoltaic devices like inorganic, organic and hybrid solar cells are invented for different application purposes. Regardless of its high conversion rate of silicon-based solar cells, the high module cost and complicated production process restricted their application. Research has been focused on alternative organic solar cells for their inherent low module cost and easy fabrication processes. Dye sensitized solar cell (DSSC) is considered to be one of the most promising, efficient, low-cost organic solar cells in recent years. DSSC, being transparent to some extent and comparatively cheaper than conventional solar photo-voltaic, can be a potential energy source for the future. This review paper focuses on the working of DSSC, its current state and recent developments in the various components of DSSC. The perspectives for the future development of the technology have also been discussed.

Keywords: Renewable energy, Photovoltaic devices, Organic Solar cells, Dye sensitized solar cell.

1. Introduction

A dye-sensitized solar cell (DSSC) is a low-cost, efficient solar cell belonging to the group of thin film solar cell (Zulkifili A N B et al, 2015, Mane R S et al, 2008, Suhaimi S et al, 2015, Yoon S et al, 2011). DSSC is a most promising, inexpensive route towards sunlight harvesting (Grätzel M, 2003, Karuppuchamy S et al, 2001). The good light-harvesting efficiency of the best desensitized solar cells (DSSCs) is the product of a dye with moderate extinction and a photo anode of high surface area (approximately 1200 times the area of a flat electrode). This combination allows for ample absorbance over the majority of the visible spectrum with room for improvement in the red wavelengths (Martinson A B F et al, 2007, Bessho T et al., 2010, Huang Z et al, 2007). Applications of nano-sized TiO_2 porous film electrodes were first reported by O'Regan and Gratzel (O'Regan B &Grätzel M, 1991). An overall efficiency up to 10% had been achieved with Ruthenium-based dyes (Hironori Arakawa, 2007). In general, highly efficient photovoltaic conversions, combined with ease of manufacturing and low production costs (Seigo Ito et al, 2008) make the DSSC technology an attractive approach for large-scale solar energy conversion comparing to other forms of solar cells. The basic components of DSSC include photoanode, sensitizer, electrolyte and counter electrode.

2. Materials and Methods

2.1 Working of Dye-Sensitized Solar Cells

A schematic diagram and working of a DSSC is shown in Fig. 1.

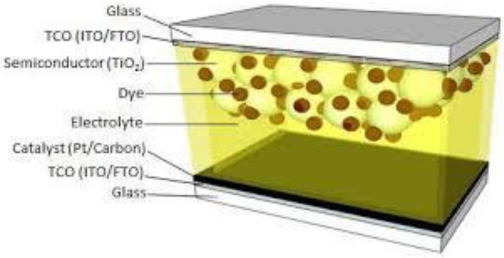

Fig. 1 –DSSC Schematic Band Diagram.

When the photon energy from the sun falls on the dye, the dye is excited and its molecules inject electrons into the TiO_2 conduction band and hole is injected in the electrolyte as well. These electrons diffuse through the TiO_2 particles and flow through an external circuit through the load. High performance in DSSC can be achieved by high electron injection from the dye and rapid electron transport. An efficiency of about 12% has been achieved in DSSCs (Yella A et al, 2011). The photon incident on the dye excites the dye. Electrons from excited state of the dye enters the conduction band of TiO_2 (or any semiconductor material used) (Franco G et al, 1999, Cherepy N J et al, 1997). The electrons then flow through the porous TiO_2 thin film to the transparent conducting oxide (TCO). This electron flow depends on the incident intensity and trapping-de-trapping effect (Peter L M et al, 1999, Peter L M et al, 2000, Fredin K et al, 2005). The oxidized dye molecules are regenerated, when the dye receives electrons from a redox mediator (I^- / I^{3-}). The mediators are oxidized in the process. Further, these oxidized redox mediators (I^{3-}) are diffused to the counter electrode where they are regenerated by reduction due to the electrons reaching the counter electrode, through an external circuit, for a complete operation cycle (Papageorgiou N et al, 1996). The working can be understood better from the Schematic band diagram shown in Fig. 1 (Brijesh T et al, 2014). The dye molecule is excited by the incident photon. The excited dye (Dye*) is at a higher energy level and releases an electron into the conduction band of the TiO_2 (or other nano material like ZnO, CuO, etc.) nano particle, creating a potential difference. This electron is free to move through an external circuit and reach the counter electrode. At the counter electrode and electrolyte interface, the electron takes part in the redox reactions and then supplied back to the dye molecules.

3. Results and Discussion

3.1 The Current state and recent developments in the various components of DSSC

3.1.1 Review of improvements in photoanode

The fundamental component of the DSSC is a photoanode consisting of a monolayer of sensitizer (dye) adsorbed onto a mesoporous semiconductor oxide (typically TiO_2). In contrast to conventional solar cell systems, where the semiconductor assumes both the task of light absorption and charge carrier, in dye sensitized solar cells light is absorbed by the anchored dye and charge separation takes place at the interface via photo induced electron injection from the dye into the conduction band of the solid (Wang Q et al, 2006, Oluwaseun A et al, 2016). Various nano structures such as nano-rods, nanotubes, nanowires, nano-cones, nano-leaves or their mixture has been fabricated on transparent conductive glass (Mir N &Salavati-Niasari M, 2012). For many years, TiO_2 nanostructured materials and the ruthenium-bipyridyl dye families such as N719, N3 and C101 are the most efficient materials for the photoanode and have subjugated the highly efficient solar cells (Ito S et al, 2006, Nazeeruddin M K et al, 2011). ZnO nanostructures for DSSC (Zhang Q et al, 2009) are some of the works involving applications of ZnO in DSSC. Many recent studies show the application of ZnO nanostructures for photo-electrodes with enhanced photovoltaic performance of dye sensitized solar cells. DSSC developed using network structure of electron-spun ZnOnano fiber mats (Il-Doo K et al, 2007), ZnO nanosheets derived from growth mechanisms directed by surfactants (Hui L et al, 2012), effects of morphology of nanostructures of ZnO films on efficiency on DSSC (Giannouli M &Spiliopoulou F, 2012), effects of annealing on the performance of DSSC using ZnO (Lu L et al, 2010).

Semiconductor oxides used in dye-sensitized solar cell include SnO_2, Nb_2O_5, TiO_2, ZnO and so forth, which serve as the carrier for the monolayers of the sensitizer using their high surface and the medium of electron transfer to the conducting substrate. Due to low-cost price, abundance in the market, non-toxicity and biocompatibility, and as it is also used widely in health care products as well as in paints, TiO_2 becomes the best choice in semiconductor till now (Fan-Tai K et al, 2007). Titanium Dioxide (TiO_2) films are covered on the conducting substrate such as metal foil, flexible polymer film and conducting glass. Recently, researches have been done on 3D electrode fabrication to improve electron collection, hence enhancing cell performance. Moreover, electrodes derived from sol-gel synthesized nanoparticles of TiO_2 showed higher photoelectric conversion efficiency (Masood H et al, 2012, Cheol C S & Ho S S, 2012). A TiO_2 double layer composite film on sponge like TiO_2 as over layer and commercial grade nanoparticles P25 as under layer showed overall efficiency of 5.48%, which is 51.4% greater than that of P25 nanoparticles film (Guotian D et al, 2012). Mixed nanostructure with different phase composition of TiO_2 reported for the improvement of electron transport rate by TiO_2 electrode. New chemical techniques for screen printing paste of P25 TiO_2 done to form mesoporous TiO_2 film showed efficiency of 8.07%. The effect of hydroxyl group attachment on the nanocrystalline TiO_2 photoelectrodes was investigated and the result showed enhanced performance due to dye absorbed on OH group of the electrode (Alagesan S & Hong-Wen W, 2012). Besides TiO_2, dye sensitized ZnO solar cells also showed improved performance up to 4.38% after surface treatment through the incorporation of Zn_2SnO_4 quantum dots on ZnO nanoparticles (Yafeng L et al, 2012). Doping of TiO_2 photo anode by 1 mol% 'Sb' showed a better photoelectric conversion efficiency of DSSCs and is achieved up to 8.13%, which is noticeably higher than that of the undoped DSSCs (Min W et al, 2012). Increased performance of photoelectrode by 3% N-doping resulted in 23.03% higher than that of pure TiO_2. Incorporation of carbon nanotubes and graphene sheets into semiconductor electrodes improved performance of DSSC, with 44% increase in short circuit photocurrent and 18.7% overall energy conversion have been achieved (Jiazang C et al, 2012). Carbon material-based counter electrode in DSSCs using multiwall carbon nanotubes (MWNTS)/graphene nanotubes (GNS) showed a maximum power conversion efficiency of 4% with 60% MWNTS and 40% GNS (Battumur T et al, 2012). Graphene aerogels as counter electrode worked efficient and showed efficiency close to that of platinum electrode achieved. With the introduction of titania aerogels, a class of mesoporous 3D structure, a power conversion efficiency improvement of 16% (7.22 vs 8.36%) is achieved as compared with P25%-TiO_2 based cells (Yi-Chun C et al, 2012).

An efficiency of 34.4% has been reported by Xu et al (Jinlei X et al, 2014). Using a double light-scattering layer ZnO film consisting of ZnO monodisperse aggregates as underlayer and sub-micro meter sized plate-like ZnO as overlayer used as photoanode, DSSC was fabricated. The fabricated ZnO micro-flowers/nano particles bilayer fil-based solar cell had much higher light harvesting efficiency, lower resistance and longer electron lifetime as compared with the ZnO nanoparticles film-based one, which gave an improved conversion efficiency of around 47% greater than monodispersed aggregates ZnO layer alone. Zi et al. grew zinc oxide (ZnO) samples with different morphologies, e.g., film, nano-wire and nano-sheet, with electrochemical deposition (ECD) by controlling the precursor concentration (Min Z et al, 2014). The photovoltaic conversion efficiency of the dye-sensitized solar cells (DSSC) assembled with different ZnO photoanodes was inspected. It was observed that the DSSC constructed with ZnO nanowire array as photoanode can absorb more dye, improve the photon utilization rate and provide rapid collection channels for the photo-excited carriers, thus improving the corresponding efficiency. Bokhari et al. worked on the elimination of heterogeneous interface between FTO and nano-rods cooperatively with the growth of composite ZnO/ZnPnano-rods on the top of ZnO film (Bokhari M et al, 2013). Three different methods were followed for the same. In the first method, ZnOnano-rod film was grown on the FTO by the process of Chemical Bath Deposition method. The second method employed composite nano-rods ZnO/ZnP grown on ZnO film. And the third one was fabrication of DSSC using composite ZnOnano-rods on FTO. The results showed that the composite nanostructure increases the surface to volume ratio for anchoring dye molecule. The optical/photon absorption and conversion capability of the DSSC increased. Zhu et al. synthesized ZnO nanorods-nanosheets (NR-NS) hierarchical architecture (Shibu Z et al, 2014). Long nano-rods act as the backbone and thin nano-sheets as branches on zinc foil substrate developed by a two-step hydrothermal growth process for dye-sensitized solar cells application. This helped in giving flexibility to the photoanode for DSSC. Song et al (Kyungho S et al, 2014) reported the synthesis of echinoid like particles which contributed in two major factors. It provided larger surface areas for the dyes and also produced a light scattering effect leading to enhanced light harvesting ability, for the DSSC. The reported analysis shows faster recombination of electrons in the echinoid-like particles. The VOC decreased and dye loading increased and hence there was an increase in the JSC.

Mohammad Reza Golobostanfard and Hossein Abdizadeh, in their work, have successfully assimilated carbon nanotubes (CNT) in Titania photoanode of DSSC, with hierarchical porous structure synthesized by controlled phase separation (Mohammad R G & Hossein A, 2014). The results showed lower resistance, lower charge injection resistance, and higher electron lifetime. The charge transport and separation properties are desirable for efficient DSSCs. Moreover, addition of CNTs in Titania matrix increased the critical thickness with which the maximum efficiency of the cell could be achieved. In another innovative approach, Satapathi et al. fabricated DSSC using photoanodes made from Graphene-TiO_2 nanocomposites (Soumitra S et al, 2014). The relation between the size of graphene sheets and the cell performance was explored. It was concluded that cells loaded with the smaller graphene sheets yielded larger enhancement. The smaller graphene sheets improved the dye adsorption, leading to higher conversion efficiency. Fan et al. fabricated DSSC using double layers of nano-structured TiO_2 films as photoanodes (Fan J et al, 2014). The performances of DSSCs based on composite photoanodes in the forms of TiO_2 nanoparticles/nanoparticles (TiO_2 P-P), TiO_2 nanoparticles/nano-belts (TiO_2 P-B), TiO_2nano-belts/nano-belts (TiO_2 B-B) double layered electrodes with the same film thicknesses were studied in detail and the corresponding efficiencies were 4.81%, 3.55% and 0.36% respectively. The optical scattering effect provided by TiO_2nano-belts and high dye absorbing capacity of the TiO_2nano-particles helped to improve the overall efficiency. Xu et al. synthesized rutile nano-rod array, nano-flower and microspheres by changing the ratios of HCl and CH_3COOH in solvent keeping all other conditions constant (Fang X et al, 2012). Keeping the VHCl/VCH_3COOH concentration ratio as 10:2, 8:6 and 4:4, TiO_2nano-rod arrays, nano-flowers film and microspheres film are obtained respectively. The microsphere derived photoanode showed higher conversion efficiency than that of nano-rod arrays and nano-flowers film. The reason for this being the large surface curvatures of microspheres, which facilitates better dye absorption, less electron transfer interface resistance. Priyadharsini et al. used nanoparticles as light harvesting agents to improve efficiency of the solar cell (Priyadharsini K &Vasanthan T, 2013). In this study, a thin layer of titanium dioxide nano-particles has been used to create the active layer (anode) which is infused with natural dye molecule namely anthocyanin (from pomegranate and hibiscus) and chlorophyll.

Shanmugam et al. worked to replace sol-gel TiO_2 with an RF-sputtered one to achieve higher VOC and RSH (Shanmugham M et al, 2009). In 2012, in a work done by Hu et al. an improvement in the conversion efficiency was reported, when different quantities with the same area and a parallel interconnected type of TiO_2, working electrode was designed on a flexible substrate (Jui-En H et al, 2012). The cell size, fill factor, conductivity and conversion efficiency of substrates were all affected by the internal resistance of the DSSC. Saurdi et al. compared two monolayers of photoanodes with ultrasonic and without ultrasonic TiO_2 for different parameters (Saurdi I et al, 2013). Kim et al. fabricated DSSC with graphene-titania films by supersonic kinetic spray known as aerosol deposition (Do-Yeon K et al, 2014). Graphene concentration was varied to fabricate 0.1, 0.3, 0.5, 0.7 and 1.0 wt% G-TiO_2 films for dye-sensitized solar cell (DSSC) application and to investigate the effect of graphene concentration on their energy conversion efficiency. The investigation showed that the 0.3 wt% case showed the highest conversion efficiency of 5.02%. Sangiorgi et al. developed an optimized spin coating process using an alcoholic $TiCl_4$ solution and correlated to the final properties of the layer (Alex S et al, 2014). Fang et al. reported that the density of the nano-rod arrays depends on the thickness of the seed layer (Xiang F et al, 2014). It increases as the seed layer thickness is increased, resulting in greater surface area for adsorption of dyes. The results showed that there was a significant enhancement in the photocurrent densities and conversion efficiencies of ZnOnano-rod array-based DSSCs. Han et al. experimented with nano crystalline TiO_2 developed through hydrothermal synthesis (Qiaolin H et al, 2013). GhanbariNiaki et al. came up with a new strategy for improving the efficiency of TiO_2 dye sensitized solar cells by design of a new double layer film doped with Zn ions, with various morphologies and phase arrangements (Naki A H G et al, 2014). Chou et al. proposed a simple hydrolysis method for the fabrication of quasi core-shell TiO_2 (hydrolysis)/PbS composites for working electrodes (Chuen-Shi C et al, 2014). Metal chalcogenide semiconductors such as cadmium sulfide (CdS) (Lin S C et al, 2007, Prabakar K et al, 2009, Zhu G et al, 2011), cadmium selenide (CdSe) (Shen Q et al, 2008, Fan S Q et al, 2009), lead sulfide (PbS) (Liu Y & Wang J, 2010, Luther J M et al, 2010), and CdS/CdSe (Lee Y L & Lo Y S, 2009) have been used to fabricate quantum dot-sensitized solar cells.

3.1.2 Review of improvements in sensitizers

Dye sensitizer serve as the solar energy absorber in DSC, whose properties will have much effect on the light harvesting efficiency and the overall photoelectric conversion efficiency. The ideal sensitizer for dye-sensitized solar cells should absorb all light just below a threshold wavelength of 920 nm and firmly grafted to the semiconductor oxide surface and inject electrons to the conduction band with a quantum yield of unity (Fan-Tai K et al, 2007, Sokolsky M &Girak J, 2010). Secondly, the lowest unoccupied molecular orbital (LUMO) of the dye must be sufficiently higher than the conduction band of TiO_2 for efficient charge injection, and the highest occupied molecular orbital (HOMO) of the dye must be lower than the hole transport material for efficient regeneration of the oxidized dye. Finally, the light harvesting ability of the dye in both the visible and/or near IR regions should be considerable to enhance the efficacy of the absorption process (Tachibana Y et al, 2000). Sufficient amount of work has been done over the years to make all possible improvements in the dye (Jasim K E, 2011, Mehmood U et al, 2014, Mehmood U et al, 2014). Liu et al. reported preparation of four artificial chlorin-type sensitizers in their work (Xiujun L et al, 2013). Wang et al. synthesized two new D-A-pi-A indoline dyes (XS45 and XS46) with different additional donors, to investigate the influence of donor and bridge structure in indoline dyes on the photovoltaic properties of dye-sensitized solar cells employing iodine/cobalt electrolyte (Lina W et al, 2014). Design of three dyes 1e3 with different electron donors, i.e., carbazole, indoline and coumarin has been reported by Zhang et al (Ji Z et al, 2013).

Mao et al. derived three organic dyes from C219 and with just different electron donors were designed to further improve the VOC of the cell (Mao M et al, 2014). Wu et al. proposed development of two novel organic dyes containing julolidine as the electron donor and cyanoacetic acid or rhodamine-3-acetic acid as the electron acceptor bridged by bithiophene unit, and named them as J5 and J6 (Guohua W et al, 2013). Li et al. reported two new cyclometalated ruthenium sensitizers (Yen L C et al, 2014). Four new organic dyes, coded as CSORG6, CSORG7, CSORG8 and CSORG9, were synthesized by Reddy et al (Anil R M, 2014). Zhu et al. reported two new sensitizers based on triphenylamine-dicyanovinylene and used for p-type dye sensitized solar cells (Linna Z et al, 2014). Lee et al., cyan acrylic acid as an additional anchoring group was introduced to the phenoxazine for efficient electron extraction from the donor part and an N-substituent was added to suppress dye aggregation (Woosung L et al, 2014). The most important sensitizer showing highest conversion efficiency and long-term stability are that of Ruthenium and Osmium (Sapp S A et al, 2002). Ruthenium based complexes have fairly broad absorption spectra (delta lambda = 350 nm) but possesses low molar extension coefficients (10,000-20,000 M^-) (diss.fuberlin website, Gao F, 2008) as compared to number of organic dyes (50,000-2,00,000 M^- cm^-) (Nazeeruddin M K, 1993). Thus, organic dyes provide a better alternative to thin film solar cells with higher light harvesting properties. Some organic dyes like indole derivatives are also showing much progress in the last few years (Horiuchi T et al, 2004). Derivatives of indole dyes and coumarin dyes have been synthesized which showed better efficiencies. Perylenes (Keerthi A et al, 2012) and Xanthene based DSSCs have been employed. A carbazole dye presented by AIST senior research Hara et al. provides an improved cell conversion efficiency and longer life (AIST Website). Efforts have also been done on natural dye based DSSCs. Natural dyes extracted from heena, pomegranate, cherries, bauraini raspberries (Ebrahim J K, 2012) are also exclusively been researched for DSSCs to produce low cost and environmentally friendly alternative to conventional Ru-complexes. Among natural dyes, anthocyanines has shown best results so far. Further research is also been done on natural Betalain dyes (Corneliu I O et al, 2012). Improvements in designing dyes which cannot only give high power conversion efficiency but also greater potential to scale beyond 19 GW per year, which is the limit set by the availability of Ruthenium (USGS Website). Research have proved that a best dye contain electron rich (donor) and electron poor (acceptor) sections connected through a conjugated pi-bridge. Introduction of two 4-tert-butyl benzene moieties in the donor part of tri phenyl amine group developed an efficient D-π-A organic sensitizer (LI-17) shows conversion efficiency of 5.35% under standard global AM 1.5 solar light (Jei S et al, 2012).

Series of high-performance organic dyes with D-π-A structure used in DSSC to establish the structure-performance relationship and its influence on the performance of the dye (Wei-Lu D et al, 2013). A novel indoline donor-based dye Ba-03 has been synthesized which showed the efficiency of 6.38% which was greater than carbazole donor-based dye of Ba-01 (Akhtaruzzaman M et al, 2013). All organic (Zhang Z et al, 2008) electrolytes have resulted in more promising power-conversion efficiencies. Earlier CoII/CoIII suffered slow recombination rate due to bulky groups on these ligands functioning as insulating spacers (Gregg B A et al, 2001). Development of new electrolytes with high oxidation potential seems to increase cell potential (Yella A, 2011). A quasi-solid electrolyte made by the combination of a non-volatile ionic liquid and a gel with a conversion efficiency of above 7% was reported by professor Hayase et al (Hayase S et al, 2001). Fully solid electrolytes are under research using inorganic compounds and polypyrroles etc. Solid state inorganic (Tennakone K et al, 1995) and organic (Bach U et al, 1998) whole conductors have been developed and tested for solid state DSSC. Recently, an impressive 6% efficiency were achieved with in situ polymerized poly (3,4-ethylenedioxythiophene) (PEDOT) as a hole conducting material (Liu X et al, 2010).

3.1.3 Review of improvements in electrolytes

Many types of redox couples such as Br^-/Br^3, $SCN^-/(SCN)^2$, $SeCN^-/(SeCN)^2$ (Mehmood U et al, 2014) and substituted bipyridyl cobalt (III/II) have been investigated. Solid state electrolytes replace the liquid electrolyte with a p-type semiconductor (Mehmood U et al, 2014). Arof et al. suggests that a mixed iodide salt system with two dissimilar cations is used to increase the efficiency of dye-sensitized solar cells made with polyvinylidene fluoride (PVdF) based gel (Arof A K et al, 2014). Research by Amalina et al. demonstrated the effect of solution concentration of copper (I) iodide (CuI) to the thin film's properties and photovoltaic performance (Amalina M N &Rusop M, 2013). The surface morphology and electrical properties of CuI thin films which was deposited on the glass substrates were studied. The results showed that the CuI thin film properties sturdily hinge on its forerunner concentration. This validates the possibility for mist atomization technique to substitute the existing technology of current deposition of hole transport material, which can be used in the future commercial production of solid-state dye sensitized solar cells. Akhtar et al. developed effective composite electrolytes of different inorganic nanofiller (TiO_2, SiO_2, Al_2O_3) and polyethylene glycol (PEG) (Akhtar M S et al, 2013). Counter electrodes developed using graphene nano particles (GNP) or multi-wall carbon nanotubes (MWCNT) were proposed by Ahmed et al (Iftikhar A et al, 2014). The life and efficiency of the counter electrode have improved. Bu proposed the development of carbon nano-onions as carbon electrodes in his work (Bu Ian Y Y, 2014). The deposition was done by carbon flame synthesis on Cu-coated substrate. The work reported better efficiency of CE. A method for fabrication of highly transparent platinum counter electrodes has been developed based on spray coating of Pt nano-particles on hot substrates, as reported by Iefanova et al (Anastasiia I et al, 2014). There was 86% reduction in the consumption of platinum, hence the fabrication cost reduced. Composite photo electrode with Pt nano-particles deposited on three-dimensional (3D) fluorine-doped tin oxide (FTO) conductive grid was fabricated as the counter electrode (CE) of dye sensitized solar cell, by Wang et al (Min W et al, 2014). In another attempt by Dong et al. to improve the efficiency of the DSSC a nanostructure-based Pt counter electrode was fabricated by assembly of silver nanoparticles on glass substrate and thin layer of Pt was deposited (Hua D et al, 2014).

3.1.4 Scope for further research

All the above works have shown some significant improvement in the working of the DSSC. There is still scope for further improvement in the DSSC with respect to each of its components. The DSSC if developed can be used as a flexible, low cost and environment friendly solution for energy generation from solar power. With improvements, the DSSC can serve as a better commercial product in the future. It has a fairly good potential to be used in building integrated photovoltaic, due to the transparent nature.

4. Conclusion

In conclusion, the world's non-renewable energy degrades time by time and the consumption rate increases inversely. To weaken these two controversies, new environmental friend green renewable energy resources are highly needed to our planet. Among different types of renewable green energy sources, solar energy is regarded as one of the perfect energy resources. There has been a continuous effort in searching for affordable organic solar energies among which dye sensitized solar cells (DSSCs) thus far demonstrate the highest energy conversion efficiency, and have been regarded as the most prospective technology in the near future. Dye sensitized solar cells have gained widespread attention in recent years because of their low production costs, easy fabrication, its lighter weight property, environmentally friendly and recyclable advantages and tuneable optical properties such as colour and transparency, regardless of its low efficiency output comparing with silicon solar cell. This review summarizes all attempts and work done to improve the performance of the DSSC recently. The review suggested that if proper consideration is given to each of the four components of the DSSC by using highly efficient materials and techniques for the development, a highly efficient cell can be fabricated which could be of high value on a commercial scale. The recent developments put together can help enhance the overall power conversion efficiency of the DSSC.

References

Zulkifili, A.N.B., Kento, T., Daiki, M. &Fujiki, A. (2015). The Basic Research on the Dye-Sensitized Solar Cells (DSSC). *J Clean Ener Technol*, *3*, 382.

Mane R S, Lee W J, Pathan H M & Nan S H (2008). *Phy Chem*, *109*, 24254.

Suhaimi, S., Shahimin, M.M., Alahmed, Z.A., Chysky, J. &Reshak, A.H. (2015). *Int J Electrochem Sci*, *10,* 2859.

Yoon S, Tak S, Kim J, Jun Y, Kang K & Park J. (2011) *Build Environ, 46*, 1899.

Grätzel, M. (2003) *Elsevier J PhotochemPhotobiol*, *4*, 145.

Karuppuchamy, S., Nonomura, K., Yoshida, T., Sugiura, T. & Minoura, H. (2001) *Solid State Ion*, *151,* 19.

Martinson, A.B.F., Elam, J.W., Hupp, J.T. &Pellin, M.J. (2007) *Nano Lett*, *7,* 2183.

Bessho, T., Zakeeruddin, S.M., Yeh, C.Y., Diau, E.W.G. &Grätzel, M. (2010) *Communications*, *49*, 6646

Huang, Z., Liu, X., Li, K., Li, D., Luo, Y., Li, H., Song, W., Chen, L. & Meng, Q. (2007) *ElectrochemCommun*, *9,* 596.

O'Regan, B. &Gratzel, M. (1991) *Nature*, *353*, 737.

Hironori Arakawa, Recent Advances in Research and development for Dye-sensitized solar Cells II (CMC Publishing, Tennessee), 2007, p. 9.

Seigo Ito, Murakami, T.N., Comte, P., Liska, P., Grätzel, C., Nazeeruddin, M.K. &Grätzel, M. (2008) *Thin Solid Films*, *516,* 4613.

Yella, A., Lee, H.W., Tsao, H.N., Yi, C., Chandiran, A.K., Nazeeruddin, M.K., Diau, E.W.G., Yeh, C.Y., Zakeeruddin, S.M. &Grätzel, M. (2011) *Science*, *334*, 629.

Franco, G., Gehring, J., Peter, L.M., Ponomarev, E.A. &Uhlendorf, I. (1999) *J Phys Chem B*, *103*, 692.

Cherepy, N.J., Smestad, G.P., Gratzel, M. & Zhang, J.Z. (1997) *J Phys Chem B*, *101*, 9342.

Peter, L.M. &Wijayantha, K.G.U. (1999) *ElectrochemCommun*, *1,* 576.

Peter, L.M. &Wijayantha, K.G.U. (2000) *Electrochim Acta*, *45*, 4543.

Fredin, K., Nissfolk, J. &Hagfeldt, A. (2005) *Sol Energy Mater Sol Cells*, *86*, 283.

Papageorgiou, N., Gratzel, M. &Infelta, P.P. (1996) *Sol Energy Mater Sol Cells*, *44*, 405.

Brijesh, T., Pankaj, Y. & Manoj, K. (2014) *Sol energy*, *108*, 107.

Wang, Q., Ito, S., Grätzel, M., Santiago, F.F., Sero, I.M., Bisquert, J., Bessho, T. & Imai, H. (2006) *J Phys Chem B*, *110*, 25210.

Oluwaseun, A., Kamil, T. &Oladiran, A.A. (2016) *Int J Eng Tech*, *2*, 34.

Mir, N. &Salavati-Niasari, M. (2012) *Sol Energy*, *86,* 3397.

Ito, S., Nazeeruddin, M.K., Liska, P., Comte, P., Charvet, R., Pechy, P., Jirousek, M., Kay, A., Zakeeruddin, S.M. &Grätzel, M. (2006) *Prog Photovolt*, *14*, 589.

Nazeeruddin, M.K., Baranoff, E. &Gratzel, M. (2011) *Sol Energy*, *85*, 1172.

Zhang, Q., Dandeneau, C.S., Zhou, X. & Cao, G. (2009) *Adv Mater*, *21*, 4087.

Il-Doo, K., Jae-Min, H., Byong, L., Hong, Kim & Dong, Y. (2007) *Appl Phys Lett*, *91*, 163109.

Hui, L., Zhang, Y. & John, W. (2012) *J Am Ceram Soc*, *95*, 1241.

Giannouli, M. &Spiliopoulou, F. (2012) *Renew Energy*, *41*, 115.

Lu, L., Renjie, L., Ke, F. &Tianyou, P. (2010) *Sol Energy*, *84*, 844.

Fan-Tai, K., Song-Yuan, D. & Kong-Jia, W. (2007) *Adv Optoelectron*, *2007*, 1.

Masood, H., Vahid, J. &Afsahar, G. (2012) *Mater Sci Semicond Process*, *15*, 371.

Cheol, C.S. & Ho, S.S. (2012) *Power Technol*, *226*, 157.

Guotian, D., Li, Z. &Shimin, W. (2012) *J Alloys Compd*, *539*, 264.

Alagesan, S. & Hong-Wen, W. (2012) *Appl Surf Sci*, *258*, 7833.

Yafeng, L., Ya, W., Caiyum, C., Aiying, P. &Mingdeng, W. (2012) *Chem Eur J*, *18*, 11716.

Min, W., Shouli, B. &Aifan, C. (2012) *Electrochim Acta*, *77*, 54.

Jiazang, C., Bo, L., Jianfeng, Z., Jianghong, Z. &Zhenping, Z. (2012) *J Phy Chem C*, *116*, 14848.

Battumur, T., Mujawar, H.S. & Truong, T.Q. (2012) *CurrApplPhy*, *12*, E49.

Yi-Chun, C., Wei-Yun, C. & Shih-Yuan, L. (2012) *Int J Electrochem Sci*, *7*, 6910.

Jinlei, X., Ke, F., Wenye, S., Kan, L. &Tianyou, P. (2014) *Sol Energy*, *101*, 150.

Min, Z., Min, Z., Ling, C., Haoming, W., Xiaopeng, Y. &Bingqiang, C. (2014) *Ceram Int*, *40*, 7965.

Bokhari, M, Kasi, A.K., Kasi, J.K., Gujela, O.P. &Afzalpurkar, N, Improving photoelectric conversion efficiency of DSSC using ZnO/ ZnP composite nanorods, In: Proceedings of the International Conference on Manipulation, Manufacturing and Measurement on the Nanoscale (IEEE, Suzhou), 2013, p. 243

Shibu, Z., Liming, S., Xin, T., Xinyu, Z., Ding, S., Xingbo, L., Li, W. &Zuowan, Z. (2014) *Ceram Int*, *40*, 11663.

Kyungho, S., Inseok, J., Donghoon, S., Yong, S.K. &Seong-Geun, O. (2014) *Sol Energy*, *105*, 218.

Mohammad, R.G. & Hossein, A. (2014) *Sol Energy Mater Sol Cells*, *120*, 295.

Soumitra, S., Hardeep, S.G., Sriya, D., Lian, L., Lynne, S., Micah, J.G. & Jayant, K. (2014) *Appl Surf Sci*, *314*, 638.

Fan, J., Li, Z., Zhou, W., Miao, Y., Zhang, Y. & Hu, J. & Shao, G. (2014) *Appl Surf Sci*, *319*, 75.

Fang, X., Yao, W., Xuyan, Z., Zhiyong, G. & Kai, J. (2012) *Micro Nano Lett*, *7*, 826.

Priyadharsini, K. &Vasanthan, T., Natural Dye-Sensitized Solar Cells with Titania Nanoparticles (IEEE, Chennai), 2013.

Shanmugam, M., Baroughi, M.F. &Galipeau, D. (2009) *Electron Lett*, *45*, 12.

Jui-En, H., Shu-Ying, Y., Jung-Chuan, C. & Po-Hao, S. (2012) *Micro Nano Lett*, *7*, 1162.

Saurdi, I., Mamat, M.H., Musa, M.Z., Amalina, M.N., Abdullah, M.H. &Rusop, M., Photoanode of nanostructured TiO2 prepared by ultrasonic irradiation assisted sol-gel with P-25 for dye-sensitized solar cells (IEEE, Daerah Langkawi), 2013, p. 258.

Do-Yeon, K., Bhavana, N.J., Jung-Jae, P., Jong-Gun, L., You-Hong, C., Tae-Yeon, S., In, N.S., Hyo-Jin, A., Al-Deyabe, S.S. & Sam, S.Y. (2014) *Ceram Int*, *40*, 1089.

Alex, S., Riccardo, B., Nicola, S., Alessandra, S. & Bal-larin, B. (2014) *Ceram Int*, *40*, 10727.

Xiang, F., Yan, L., Shuai, Z., Li, B., Ningyi, Y. &Jianning, D. (2014) *Sol Energy*, *105*, 14.

Qiaolin, H., Min, Y. & Jiang, L. (2013) *Micro Nano Lett*, *8*, 238.

Naki, A.H.G., Bakhshayesh, A.M. &Mohammadi, M.R. (2014) *Sol Energy*, *103*, 210.

Chuen-Shi, C., Feng-Cheng, C., Feng-Cheng, S. & Ping, W. (2014) *Adv Powder Technol*, *25*, 1679.

Lin, S.C., Lee, Y.L., Chang, C.H., Shen, Y.J. & Yang, Y.M. (2007) *Appl Phys Lett*, *90*, 143517.

Prabakar, K., Seo, H., Son, M. & Kim, H. (2009) *Mater Chem Phys*, *117*, 26.

Zhu, G., Pan, L., Xu, T. & Sun, Z. (2011) *J Electroanal Chem*, *659*, 205.

Shen, Q., Kobayashi, J., Diguna, L.J. & Toyoda, T. (2008) *J Appl Phys*, *103*, 084304.

Fan, S.Q., Kim, D., Kim, J.J., Jung, D., Kang, S.O. & Ko, J. (2009) *ElectrochemCommun*, *11*, 1337.

Liu, Y. & Wang, J. (2010) *Thin Solid Films*, *518*, e54.

Luther, J.M., Gao, J., Lloyd, M.T., Semonin, O.E., Beard, M.C. &Nozik, A.J. (2010) *Adv Mater*, *22*, 3704.

Lee, Y.L. & Lo, Y.S. (2009) *Adv Funct Mater*, *19*, 604.

Sokolsky, M. &Cirak, J. (2010) *Act Elec Tech Info*, *10*, 78.

Tachibana, Y., Haque, S.A., Mercer, I.P., Durrant, J.R. & Klug, D.R. (2000) *J Phys Chem B*, *104*, 1198.

Jasim, K.E., Dye Sensitized Solar Cells-Working Principles, Challenges and Opportunities, (Intechopen, London) 2011, p. 171.

Mehmood, U., Rahman, S., Harrabi, K., Ibnewaleed, A., Hussein & B.V.S. Reddy (2014) *Adv Mater Sci Eng*, *2014*.

Mehmood, U., Rahman, S., Harrabi. K., Ibnelwaleed, A., Hussein & Reddy, B.V.S. (2014) *Adv Mater Sci Eng*, *18*, 155.

Xiujun, L., Chengjie, L., Xiao, P., Yongzhu, Z., Zhe, Z., Yuanchao, L., Tianyi, Z., Bao, Z., Yi, D., Dongming, S., Ping, C. &Yaqing, F. (2013) *Dyes Pigm*, *98*, 181.

Lina, W., Mao, L., Yue, Z., Fangyi, C., Xuda, W. &Zhe, S. (2014) *Dyes Pigm*, *101*, 270.

Ji, Z., Hai-Bin, L., Yun, G., Shi-Zheng, W., Rong-Lin, Z., Yong, W., Qiang, F. & Zhong-Min, S. (2013) *Dyes Pigm*, *99*, 127.

Mao, M., Xiao-Lin, Z., Xia-Qin, F., Go-Hua, W., Song-Yuan, D., Qin-Hua, S. & Xian-Xi, Z. (2014) *J Power Sour*, *268*, 965.

Guohua, W., Fantai, K., Jingzhe, L., Wangchao, C., Xiaqin, F., Changneng, Z., Qianqian, C., Xianxi, Z. &Songyuan, D. (2013) *Dyes Pigm*, *99*, 653.

Yen, L.C., Chaochin, S., Hsiou-Hsuan, W., Prabakaran, K., Chia-Hsuan, H., I-Ting, L., Wei-Chun, C., Yogesh, S.T., Ting-Yu, L., Chia-Feng, L. & Wen-Ren, L. (2014) *Dyes Pigm*, *100*, 57.

Anil, R.M., Botla, V., Suresh, T., Niveditha, S., Bhanuprakash, K., Prakash, S.S., Ashraful, I., Liyuan, H. &Malapaka, C. (2014) *Synth Met*, *195*, 208.

Linna, Z., Hong, B.Y., Cheng, Z. & Ming, L.C. (2014) *Dyes Pigm*, *105*, 97.

Woosung, L., Sim, B.Y., Jun, C., Hae, J.K., Hyun, W.K., Se, H.K., Boeun, K., Jae, K.M. &Pil, K.J. (2014) *Dyes Pigm*, *102*, 13.

Sapp, S.A., Elliott, C.M., Contado, C., Caramori, S. &Bignozzi, C.A. (2002) *J Am Chem Soc*, *124*, 11215.

http_www.diss.fuberlin.de_diss_servlets_MCRFileNodeServlet_FUDISS_derivate_000000002568_02_2 (21 March 2021)

Gao, F. (2008) *J Am Chem Soc*, *130*, 10720.

Nazeeruddin, M.K. (1993) *J Am Chem Soc*, *115*, 6382.

Horiuchi, T., Miura, H., Sumioka, K. & Uchida, S. (2004) *J Am Chem Soc*, *126*, 12218.

Keerthi, A., Liu, Y. & Wang, Q. (2012) *Chem Eur J*, *18*, 11669.

http://www.aist.go.jp/aost_j/press_release/pr2008/pr20081119/pr20081119.html (21 March 2021)

Ebrahim, J.K. (2012) *Sains Malays*, *41*, 1011.

Corneliu, I.O., Anca, D. & Irina, E. (2012) *J PhotochemPhotobiol*, *240*, 5.

http://minerals.usgs.gov/minerals/pubs/commodity/platinum/myb1-2010-plati.pdf (21 March 2021)

Jei, S., Zhaofei, C. & Cheng, Z. (2012) *Dyes Pigm*, *95*, 244.

Wei-Lu, D., Dong-Mei, W., Geng, Z.Y., Xiao-Ling, Z. & Wei-Bing, X. (2013) *Dyes Pigm*, *98*, 125.

Akhtaruzzaman, M., Menggenbateer, C., Islam, A., El-Shafei, A., Asao, N., Jin, T., Han, L., Khalid, A., Alamry, Samia, A., Kosa, Asiri, A.M. & Yamamoto, Y. (2013) *Tetrahedron*, *69*, 3444.

Zhang, Z., Chen, P., Murakami, T.N., Zakeeruddin, S.M. & Gratzel, M. (2008) *Adv Funct Mater*, *18*, 341.

Gregg, B.A., Pichot, F., Ferrere, S. & Fields, C.L. (2001) *J Phys Chem B*, *105*, 1422.

Yella, A. (2011) *Science*,*334*, 629.

Hayase. S., Sumino, H., Murai, S. &Mikoshiba, T. (2001) *IEICE Tech Rep*, *101*, 27.

Tennakone, K., Kumara, G., Kumarasinghe, A., Wijayantha, K. &Srimanne, P. (1995) *Semicond Sci Technol*, *10*, 1689.

Bach, U., Lupo, D., Comte, P., Moser, J.E., Weissortel, F., Salbeck, J., Spreitzer, H. &Gratzel, M. (1998) *Nature*, *395*, 583.

Liu, X., Zhang, W., Uchida, S., Cai, L., Liu, B. & Ramakrishna, S. (2010) *Adv Mater*, *22*, E150.

Arof, A.K., Aziz, M.F., Noor, M.M., Careem, M.A., Bandara, L.R.A.K., Thotawatthage, C.A., Rupasinghe, W.N.S. & Dissanayake, M.A.K.L. (2014) *Int J Hydrog Energy*, *39*, 2929.

Amalina, M.N. &Rusop, M., The Properties of P-type Copper (I) Iodide (CuI) as a Hole Conductor for Solid-State Dye Sensitized Solar Cells (IEEE, Daerah Langkawi), 2013, p. 300.

Akhtar, M.S., Zhen, Y.L., Wojin, L. & O-Bong, Y., Effective inorganic-organic composite electrolytes for efficient solid-state dye sensitized solar cells (IEEE, Florida) 2013, p. 2414.

Iftikhar, A., Joseph, E.M., Mazhar, B. &Gunko, Y.K. (2014) *Sol Energy*, *102*, 152.

Bu Ian, Y.Y. (2014) *Sol Energy*, *105*, 236.

Anastasiia, I., Jeevan, N., Prashant, P., Daren, D., Umesh, G., Venkataiah, M., Qiquan, Q., Brian, L. & Farrokh, B.M. (2014) *Thin Solid Films*, *562*, 578.

Min, W., Yin, Z., Shuai, Y., Zhuyi, W., Xin, R., Meihong, Z., Liyi, S. &Dongdong, L. (2014) *Chem Eng J*, *255*, 424.

Hua, D., Zhaoxin, W., Yucui, G., El-Shafei, A., Bo, J., Yang, D. &Xun, H. (2014) *Org Electron*, *15*, 1641.