International Journal of Advanced Research and Review

www.ijarr.in

A COMPREHENSIVE STUDY OF DIFFERENT GENERATION OF SOLAR CELLS: BENEFITS AND POTENTIAL CHALLENGES.

M S Sadek[1]

[1]Dept. of Electrical and Electronics Engineering, School of Science and Engineering, Southeast University, Dhaka, Bangladesh. E-mail: sami.seu@gmail.com

ABSTRACT

Solar cells are used to convert light energy into electrical energy directly with an appeal that it does not generate any harmful bi-products, like greenhouse gasses. All commercial solar cells use the same basic construction of using a semiconductor material to conduct electricity under certain conditions. So from the very beginning of the solar cell invention and its route towards the modernization, efficiency, durability and most importantly prices are always the prime research issues. The manufacturing of solar cells is actually based on the types of semiconducting or non-semiconducting materials used and commercial maturity. In this paper, different generation of solar cells technologies are elaborately discussed with a view to have some comprehensive ideas about different kinds of semiconductor materials used, advantages and disadvantages of different generations of cells in terms of efficiency, lifetime and costs. This paper has also highlighted the potential research areas of different generation of Solar Cells which are yet to be explored more.

Keywords: Solar Cells, Silicon, Thin film, Efficiency, Costs, Materials, DSSC, CZTS.

1. INTRODUCTION

Based on different technologies and materials, the solar cells can also be grouped into three different generations. First generation solar cells are mainly base on crystalline silicon wafers and typically demonstrate a performance about 15-20%. These types of cells are most widely used in commercial applications due to their good performance and also for their high stability. However, they are rigid and require a lot of energy in production.

The second generation solar cells are based on amorphous silicon, CIGS and CdTe, where the typical efficiency is 10-15%. But these kinds of solar cells avoid the use of silicon wafers and have a lower material consumption. So it is cost effective than the first generation solar cell.
The third generation solar cells use most advanced techniques. They employ not only inorganic materials like Si, but also organic materials such as small molecules or polymers and even Hybrid technologies. This type of solar cells has only to some extent a commercial

application due to their huge production costs. Polymer solar cell or plastic solar cells shows a lot of promises on small area applications due to its simple, quick and large scale production.

1. FIRST GENERATION SOLAR CELLS

2.1 Monocrystalline Silicon Solar Cells

Monocrystalline silicon (or single-crystal silicon) is the base material for silicon chips used in virtually all electronic equipment today. Mono-Si also serves as photovoltaic, light-absorbing material in the manufacture of solar cells.In 2013, monocrystalline solar cells had a market-share of 36 percent, that translated into the production of 12,600 megawatts of photovoltaic capacity,[1] and ranked second behind the somewhat cheaper sister-technology of polycrystalline silicon.[2]. Currently, SunPower(USA) manufactures the world's most efficient monocrystalline solar panels (Model – SunPowerX21) having an efficiency of 22.5% though maximum lab efficiency is 25%, which are the highest.

Mono-Si based solar cells have some very distinguishable and prominent features which makes it unparalleled basically in terms of longevity and efficiency. According to solar engineers, there will be a slight drop off in efficiency of around 0.5% on average per year. Most performance warranties go for 25 years, which proves its longevity, but as long as the PV panel is kept clean it will continue to produce electricity. Another feature is greater Heat resistance – An efficiency reduction of 12% to 15% can be expected when sunlight reaches around 50^0C in case of monocrystalline silicon cells which is lower than polycrystalline silicon cells. Moreover, it is environment friendly.

Although C-Si is dominant technologies in current PV market, cost still remains the main concern of such type of cells. PV panels madefrom single cell silicon crystals is one of the most complex and costliest than any other competing technologies. Moreover, monocrystalline silicon cells are very fragile, so a safety glass is used at the top which eventually adds more costs.

2.2 Polycrystalline Solar Cell

Polycrystalline or multi crystalline (mc-Si) solar panels are the most common because they are less expensive although lower efficiency than the Mono-Si Solar cell but better efficiency than the thin film based cells. It can be recognized by visible grain, generally square in shape and looks like a mosaic.

Polycrystalline Solar Cells provide approximately same amount longevity and durability like c-Si solar cells with lower per Panel Costs. For smaller area, like roof tops, the cost per panel is cheaper than the cost of monocrystalline silicon cell.

Besides producing the electrical output energy from the sun, the mc-Si sola cell reduces the greenhouse gases and related environmental problems of extracting fossil fuels. Moreover, it has lower temperature coefficient than monocrystalline silicon solar cells.

The mC-Si cell suffers more or less same problems as in c-Si, but due to the cost effective features makes it distinguished from other competitors. Extensive efforts are given to improve the overall efficiency.

2.3 Amorphous Silicon Cells

It is the non–crystalline version of silicon based Solar cells. Simplified and low cost deposition techniques make ita prominent PV material for devices which require very little power, such as pocket calculators. It is deposited in thin films onto a variety of flexible substrates, such as glass, metal and plastic. So it can be placed also in second generation of solar cells which is called thin film solar cells. Amorphous silicon cells generally feature low efficiency, but are one of the most environmentally friendly photovoltaic technologies, since they do not use any toxic heavy metals such as cadmium or lead.

More recently, efficiency improvements in a-Si is done by stacking several thin film cells with the envision to use it for large-area as well. Each cell is tuned to work well at a specific frequency of light. Moreover, such type of stacking also helps to reduce Staebler-Wronski Effect.

The most important feature of a-Si is their low manufacturing costs. Uses of thin layer allows uniform deposition of silicon over a flexible substrate over large areas. The electrochemical properties of a-Si do not hamper too much due to the outside defects as a-Si is inherently full of defects. a-Si can be produced in a variety of shapes and sizes, which makes it ideal for a variety of applications such as powering of calculators, solar wristwatches, garden lights and o power car accessories.According to NREL, a-Si, gives better result against temperature increase.

By using different advanced techniques like light trapping, high rate deposition, Hybrid Nano technology etc., Unisolar (USA based Solar Cell Company) expects 12% efficiency of such cells, but still it is much less efficient per unit area, so not suitable for roof installations, which restricts the applicable areas for such type of cells small area applications.
Another aspect to give emphasis is the expected lifetime of a-Si which is shorter than the lifetime of the c-Si.

2. SECOND GENERATION SOLAR CELLS

This generation is so called thin film solar cells due to the fact that, when compared to crystalline silicon based cells they are made from layers of semiconducting materials only a few microns thick. The combination of using less amount of materials and lower cost manufacturing processes eventually helps the manufacturer to produce and sell solar panels at much lower costs. Such solar cells are light-weight and easier to integrate. Most of the thin film cell technology has an efficiency of 12-20%.However, the second generation solar cells use some toxic materials and vital raw materials that are in great demand in other applications.

Basically three types of thin film solar cells are considered in this category, a-Si (amorphous Si), CIGS (Copper Indium Gallium Diselenide) and Cadmium Telluride (CdTe). Together,CdTe and CIGS accounted for around 16.8% of the panes sold in 2009.

3.1 CIGS Solar Cell

Copper Indium Diselenide consist of $CuInSe_2$. This material is one of the best light absorber known, and about 99% of the light is absorbed before reaching 1 µm into the material. There have been made homo-junctions of CIS, but a heterojunction with cadmium sulfide (CdS) has been found to be more stable and efficient. CIGS technology has achieved efficiency levels of 20% in the laboratory, much higher than Cadmium Telluride. As CIGS are devoid of toxic Cadmium (Cd), it showed great promises, but its' manufacture and behavior has not yet been mastered. Furthermore, true large-scale production at promised costs and efficiencies is not yet proven. Currently most manufacturers are producing relatively small amounts in the 1–30 megawatts per year range.

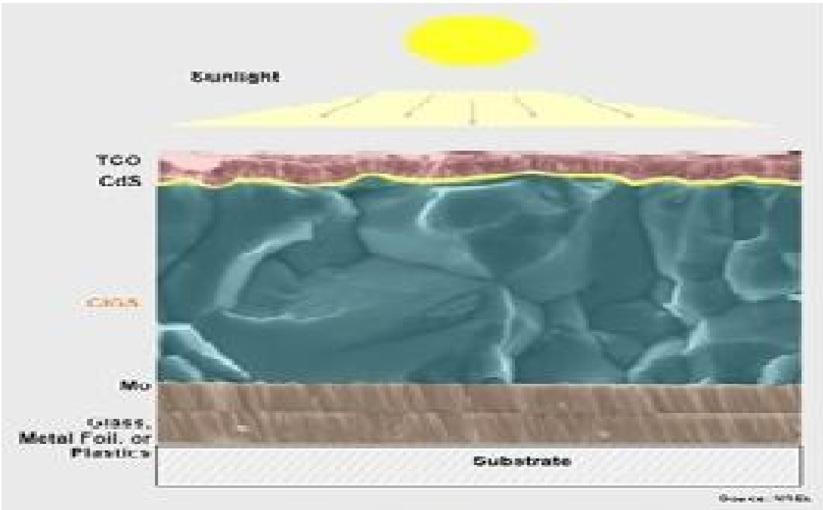


Figure-1 Typical Design of a CIGS based Solar Cell

Cells made from CIGS are usually heterojunction structures— the most common material for the top or window layer in CIS devices is cadmium sulfide (CdS), although zinc is sometimes added to improve transparency. Adding small amounts of gallium to the lower absorbing CIS layer boosts its bandgap from its normal 1.0 electron-volts (eV), which improves the voltage and therefore the efficiency of the device. This particular variation is commonly called a copper indium gallium di-selenide or "CIGS" solar cell.

The most common technique adopted by most of the manufacturing companies is vacuum based process, which co-evaporates or co-sputters copper, gallium and indium, and then anneals the resulting film with a selenide vapor to form the final CIGS structure. There is an alternative to directly co-evaporate copper, gallium, indium and selenium onto a heated substrate. But both the processes are costly and time-consuming.

The active layer (CIGS) is deposited in apolycrystalline form directly onto flexible molybdenum coated glass sheets which reduces both the energy as well as the precious Si as the substrate materials. Cd is basically used in CIGS, although in a very limited amount, but now recently Zn is used as the replacement of toxic Cd, provides environmental advantages. CIGS solar cell panels show a better resistance to heat than silicon based solar panels.
Main challenges are obviously to increase efficiency as well as reducing the cost. Like all thin film solar panels, CIGS panels are not as efficient as crystalline silicon solar cells. Furthermore, the cost of fabricating the product makes this type of Solar cells difficult to be competitive with its concurrent technologies.

3.2 CdTe Solar cell

Solar panels based on CdTe are the first and only thin film photovoltaic technology to surpass crystalline silicon PV in cheapness for a significant portion of the PV market, namely in multi-kilowatt systems. Best cell efficiency has been plateaued at 16.5% byNREL in 2001. Improved doping of CdTe and efficient processing techniques (Cadmium Chloride recrystallization and contracting) are key to improving cell efficiency.

The most prominent features of CdTe is the lower cost of CdTe based solar panel. First solar, a USA based company has produced solar cells for less than $1.00 per watt. Experts believe it will be possible to get the solar cell costs down to around $0.5 per watt by using CdTe.Another important aspect of CdTe based solar cell is the manufacturing ease. The required electrical properties can be established by simply mixing two types of cadmium molecules – cadmium sulfide and cadmium telluride, which eliminate complex multi-step process of joining two different types of doped silicon in a silicon solar panel.Cadmium telluride absorbs sunlight at close to the ideal wavelength about ~ 860 nm (Bandgap of CdTe is 1.44 eV), capturing photons at shorter wavelengths, which is not possible for Si.

While price is a major advantage, there are some drawbacks to this type of solar panels, namely:
Lower efficiency levels: Cadmium telluride solar panels currently achieve an efficiency of 10.6%, which is significantly lower than the typical efficiencies of silicon solar cells.
Tellurium supply: While Cadmium is relatively abundant, Tellurium is not. Tellurium (Te) is an extremely rare element (1-5 parts per billion in the Earth's crust. According to USGS, global tellurium production in 2007 was 135 metric tons.
Toxicity of Cadmium: Cadmium is one of the top 6 deadliest and toxic materials known. However, CdTe appears to be less toxic than elemental cadmium, at least in terms of acute exposure.The disposal and long term safety of cadmium telluride is a known issue in the large-scale commercialization of cadmium telluride solar panels.

Research on CdTe research focuses on several of today's challenges:

1. Boosting efficiencies by, among other things, exploring innovative transparent conducting oxides that allow more light into the cell to be absorbed and that collect more efficiently the

electrical current generated by the cell.
2. Studying mechanisms such as grain boundaries that can limit the voltage of the cell.
3. Understanding the degradation that some CdTe devices exhibit at contacts and then redesigning devices to minimize this phenomenon.
4. Designing module packages that minimize any outdoor exposure to moisture.

3. THIRD GENERATION SOLAR CELLS

Third-generation photovoltaic cells are solar cells that are beginning to emerge in the marketplace after 20 years of research and potentially able to overcome the Shockley–Queisser limit of 31–41% power efficiency for single bandgap solar cells. 3G approaches to PVs aim to decrease costs to $0.50/W by significantly increasing efficiencies but maintaining the economic and environmental cost advantages such as thin film solar cells.

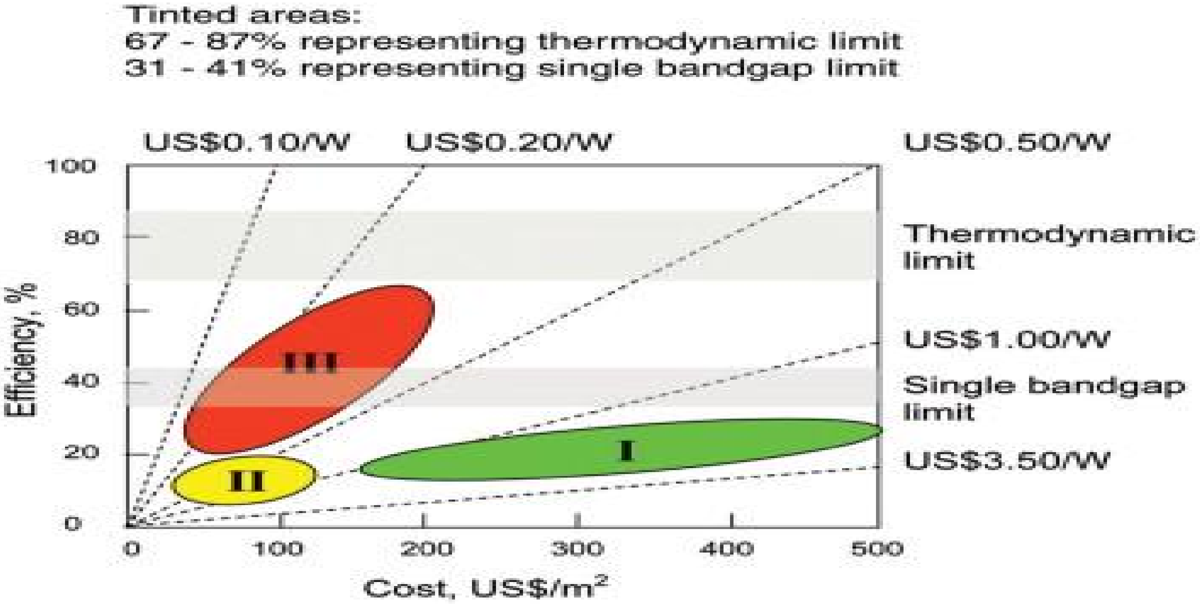


Figure – 2Efficiency and cost projections for first- (I), second- (II), and third-generation (III) PV technologies (wafer-based, thin films, and advanced cell technology, respectively).

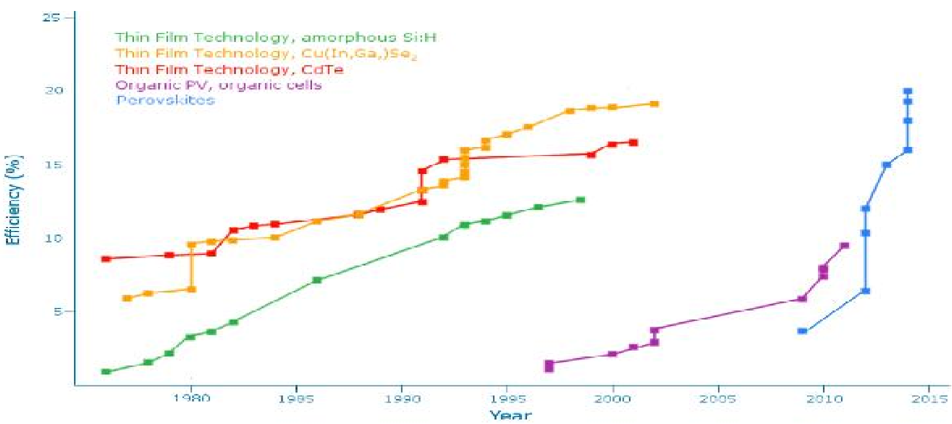
Third generation PVs are showing their potentials due to the insight of leading material developers such as Konarka and Plextronics in the organic photovoltaics (OPV) domain, and Dyesol, EPFL, G24i, Mitsubishi and Peccell on the dye-sensitized cells (DSC) front. Both DSC and OPV technologies lag far behind on the efficiency curve when compared to conventional solar (i.e., >20 percent efficiency), so they will likely succeed in markets where their low cost, substrateflexibility, and ability to perform in dim or variable lighting conditions provide them with a significant competitive advantage. DSC will target larger area BIPV applications while OPV will find its application in lower power consumer applications.

4.1 Techniques employed in 3G Solar Cell Design

The most important loss mechanisms in single-bandgap cells namely non absorption and

thermalization loss are somewhat mitigated by using multiple energy bandgap solar cell systems.
Three families of approaches have been proposed for applying multiple energy levels: (a) increasing the number of energy levels; (b) multiple carrier pair generation per high energy photon or single carrier pair generation with multiple low energy photons; and (c) Hot carrier cells (capturing carriers before thermalization). Of these, tandem cells, an implementation of strategy (a), are the only ones that have, as yet, been realized with efficiencies exceeding the Shockley-Queisser limit.
Common third-generation systems include multi-layer ("tandem") cells made of amorphous silicon or gallium arsenide, while more theoretical developments include frequency conversion, hot-carrier effects and other multiple-carrier ejection techniques.[3][4][5][6]

4.2 Perovskite Solar Cell



A perovskite solar cell is a type of solar cell which includes a perovskite structured compound, most commonly a hybrid organic-inorganic lead or tin halide-based material, as the light-harvesting active layer. [7] The efficiency has significantly rises from 3/8% in 2009 to 21.0% in 2015 by using methyl-ammonium lead halides ($CH_3NH_3PbX_3$) materials as absorber layer which are cheap andsimple to manufacture.

Figure-3Perovskite solar cells have increased in power conversion efficiency at a phenomenal rate [NREL Efficiency Chart].

Traditional silicon cells require expensive, multistep processes, conducted at high temperatures (>1000 °C) in a high vacuum in special clean room facilities. [8]Meanwhile the organic-inorganic perovskite material can be manufactured with simpler wet chemistry techniques in a traditional lab environment. Most notably, methylammonium and formamidinium lead trihalides have been created using a variety of solvent techniques and vapor deposition techniques, both of which have the potential to be scaled up with relative feasibility.

Currently, there is not known to be a significant negative aspect of perovskite based solar cells. Although there are some factors which are yet to be proven.Firstly, there is no evidence to suggest their lifetime is any less than that of pure organic devices.Secondly, the use of lead (although in small amount) in perovskite compounds is not ideal, but there is potential for a lead alternative to be used.Finally, thicker light harvesting layers are required as the optical density is still lower than other active materials. As a result, the perovskite devices may cause some fabrication limitations; particularly for solution processed devices where creating such thick layers with high uniformity can be difficult.

4.3 CZTS (Copper Zinc Tin Sulfide) Solar Cell

Copper-zinc-tin-sulfur CZTS-based technology uses materials that avoid heavy metals, earth abundant and also at a lower cost. he constituents of this semiconductor, copper, zinc, tin and sulfur, have the advantages of being both abundant in the earth's crust and non-toxic. CZTS also has near ideal properties for solar photovoltaics, as it is a very strong absorber and has a band gap of around 1.4eV. IBM has an active research department in this area and recently announced a CZTS based solar cell that had a conversion efficiency of 11.1% and could potentially be printed. [9] This efficiency is lower than the equivalent laboratory records of 19.6% for CIGS and 17.3% for CdTe, however CZTS is at a much earlier stage of development.[10]

Some key factors make the IBM solar cells become a viable alternative to existing "thin film" solar cells. These includes –
Firstly – It uses rather earth abundant, Nontoxic elements as the constituents. It is well known that in case of CdTe based cell, Tellurium are extremely rare, and Cd is toxic. And in case of CIGS, Indium and Gallium are rare and most widely used in displays.

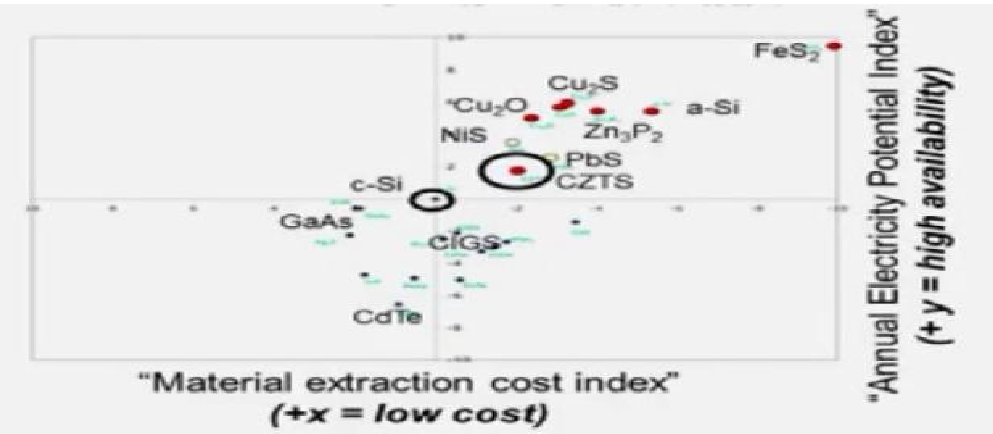


Figure-4 Cost Vs Availability curve of the most used solar cell manufacturing materials along with CZTS.

Secondly- An inexpensive ink-based manufacturing process. According to a study done by IBM, thin film solar cells will likely be limited to producing about 0.3 terawatts, but the new cells from IBM could produce an order of magnitude more power.[11]

4.4 Dye Sensitized Solar Cell

Dye Sensitized solar cells (DSSC), is a third generation thin film grouped photovoltaic (solar) cell that converts any visible light into electrical energy. It is based on a semiconductor formed between a photo-sensitized anode and an electrolyte, a photo electro chemical system. A modern DSSC is composed of a porous layer of titanium dioxide nano particles, covered with a molecular dye that absorbs sunlight. The titanium dioxide which acts like an anode is immersed under an electrolyte solution, above which is aplatinum-based catalyst which acts like a cathode.

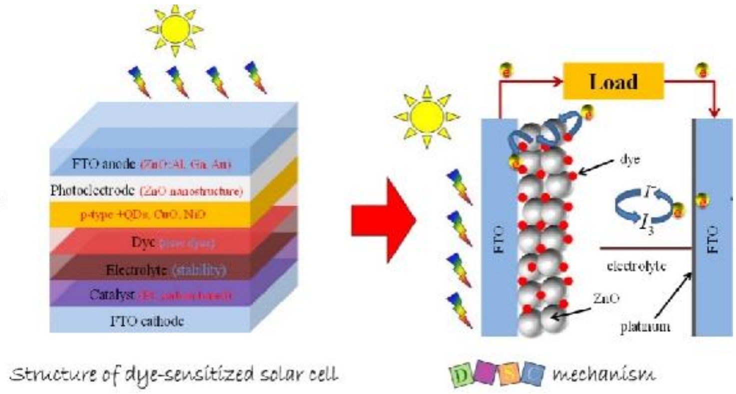


Figure-5DSSC sample structures and working mechanisms

Sunlight passes through the transparent electrode into the dye layer where it can excite electrons that then flow into the titanium dioxide. The electrons flow toward the transparent electrode where they are collected for powering a load. After flowing through the external circuit, they are re-introduced into the cell on a metal electrode on the back, flowing into the electrolyte. The electrolyte then transports the electrons back to the dye molecules.

In quantum efficiency terms, DSSCs are extremely efficient. Due to their "depth" in the nanostructure there is a very high chance that a photon will be absorbed, and the dyes are very effective at converting them to electrons. The rate of photon absorption depends upon the absorption spectrum of the sensitized TiO2 layer and upon the solar flux spectrum.

DSSCs are currently the most efficient third-generationsolar technology available according to U.S. Department of Energy Office. Overall peak power conversion efficiency for current DSSCs is about 11% [12]. Other thin-film technologies are typically between 5% and 13%, and traditional low-cost commercial silicon panels operate between 14% and 17%.

Differential kinetics of electron transfer from the Dye to TiO_2 provides an extra advantage in case of DSSC. The rate of electron generation from the Dye is very fast and the recombination of the generated electron back to dye is rather very slow process. So as a consequence of this, DSSCs work even in low-light conditions. DSSCs are therefore able to work under cloudy skies and non-direct sunlight, whereas traditional designs would suffer a "cutout" at some lower limit of illumination, when charge carrier mobility is low and recombination becomes a major issue. The cutoff is so low they are even being proposed for indoor use, collecting energy for small devices from the lights in the house. [13]

A practical advantage, one DSSCs share with most thin-film technologies, is that the cell's mechanical robustness indirectly leads to higher efficiencies in higher temperatures. DSSCs are normally built with only a thin layer of conductive plastic on the front layer, allowing them to radiate away heat much easier, and therefore operate at lower internal temperatures.

The instability of the dye solar cell was identified as a main challenge. Its efficiency however, improved during the course of the time by optimizing the porosity, but the instability remained a problem. [14]
The major research issue of DSSC design is the use of the liquid electrolyte. This liquid has temperature stability problems. At low temperatures the electrolyte can freeze, ending power production and potentially leading to physical damage. Higher temperatures cause the liquid to expand, making sealing the panels a serious problem. Another disadvantage is that costly ruthenium (dye), platinum (catalyst) and conducting glass or plastic (contact) are needed to produce a DSSC.

A third major drawback is that the electrolyte solution contains volatile organic compounds (or VOC's), solvents which must be carefully sealed as they are hazardous to human health and the environment. This, along with the fact that the solvents permeate plastics, has precluded large-scale outdoor application and integration into flexible structure. [15]
Replacing the liquid electrolyte with a solid has been a major ongoing field of research. Recent experiments using solidified melted salts have shown some promise, but currently suffer from higher degradation during continued operation, and are not flexible. [16]
Most of the small losses that do exist in DSSC's are due to conduction losses in the TiO2 and the clear electrode, or optical losses in the front electrode.

4. CONCLUSION

The attributes discussed are actually the inherentproperties of the particular solar cell technology. These attributes are very handy for proper selection of the correct solar cell required for any particular application. Some cells are suitable for large area applications and some are very efficient in small area applications. As cost and efficiency are the two prime factors in choosing a cell, so demand base choice is essential. As generation of solar cell design moves forward, the ultimate purpose is to reduce the cost and increase overall conversion efficiency. Some solar cells are yet totally explored, many facts, loss terms are yet toimprove.Therefore, the choice of a particular typeof Solar cell will depend on the attributes discussed in thispaper, the application and applying suitable decisionmaking technique.

The understanding of attributes will encourageexperimental study to establish the relative advantages anddisadvantages. It will also facilitate the investors to makechoice on which technology to invest.

REFERENCES

[1] Photovoltaics Report, Fraunhofer ISE, July 28, 2014, pages 18,19

[2] S.R.Wenham et al, Applied Photovoltaics, Earthscan, 2007, Chap. 2.
[3] Shockley, W., Queisser, H. J. (1961). "Detailed Balance Limit of Efficiency of p-n Junction Solar Cells". Journal of Applied Physics 32 (3): 510.
[4] Green, M. A. (2001). "Third generation photovoltaics: Ultra-high conversion efficiency at low cost". Progress in Photovoltaics: Research and Applications 9 (2): 123.
[5] Martí, A., Luque, A. (1 September 2003). Next Generation Photovoltaics: High Efficiency through Full Spectrum Utilization. CRC Press.
[6] Conibeer, G. (2007). "Third-generation photovoltaics". Materials Today 10 (11): 42.
[7]Collavini, S., Völker, S. F. and Delgado, J. L. (2015). "Understanding the Outstanding Power Conversion Efficiency of Perovskite-Based Solar Cells". Angewandte Chemie International Edition 54 (34): 9757–9759.
[8] Is Perovskite the Future of Solar Cells? engineering.com. December 6, 2013.
[9] M. LaMonica, "IBM Breaks Efficiency Mark with Novel Solar Material," Technology Review, 20 Aug 12.
[10] M. A. Green et al., "Solar Cell Efficiency Tables (Version 40)," Prog. Photo-volt. Res. Appl. 20, 606 (2012).
[11] http://www.solar-facts-and advice.com/CZTS.html.
[12] Gao, F et all, "A new heteroleptic ruthenium sensitizer enhances the absorptivity of mesoporous titania film for a high efficiency dye-sensitized solar cell".Chemical communications (23): 2635–7. (2008).
[13] Kimberly Patch, "Solar cell doubles as battery", Technology Research News, 2006.
[14]Matsumura, M. et all, "Dye Sensitization and Surface Structures of Semiconductor Electrodes". Ind. Eng. Chem. Prod. Res. Dev. 19 (3): 415–421(1980).
[15] Ecole Polytechnique Fédérale de Lausanne, "New Efficiency Benchmark For Dye-sensitized Solar Cells", ScienceDaily, 3 November 2008.
[16] Nathalie Rossier-Iten, "Solid hybrid dye-sensitized solar cells: new organic materials, charge recombination and stability", École Polytechnique Fédérale de Lausanne, 2006.