# Improving Efficiency of PV Module

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1. Mathematical Modeling of Solar PV Module

A solar cell is the building block of a solar panel. A photovoltaic module is formed by connecting many solar cells in series and parallel. Considering only a single solar cell; it can be modelled by utilizing a current source, a diode and two resistors. This model is known as a single diode model of solar cell. The equivalent electric circuit diagram of PV cell consists of a photocurrent source, a diode, a parallel resistor also called shunt resistor (Rsh) expressing a leakage current and a series resistor (Rs) describing internal resistance to the current flow
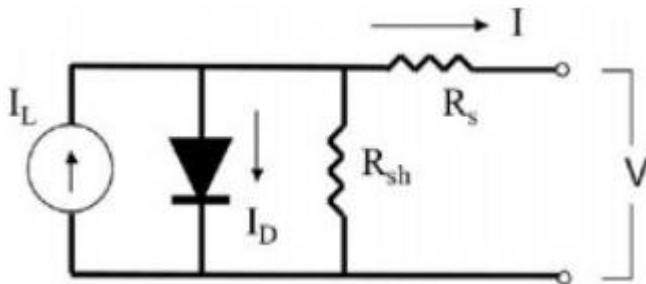
The PV cell's electrical characteristic under solar irradiance (S) is given in terms of PV cell output current(I) and PV cell voltage (V). PV cells are made of semiconductor materials, such as silicon. For solar cells, a thin semiconductor wafer is specially treated to form an electric field, positive on one side and negative on the other. When light energy strikes the solar cell, electrons are knocked loose from the atoms in the semiconductor material. If electrical conductors are attached to the positive and negative sides, forming an electrical circuit, the electrons can be captured in the form of an electric current-that is, electricity. This electricity can then be used to power a load. The power produced by a single PV cell is not enough for general use. So by connecting many single PV cell in series (for high voltage requirement) and in parallel (for high current requirement) can get us the desired power. Generally a series connection is chosen this set of arrangement is known as a module. Generally commercial modules consist of 36 or 72 cells.

The p-n junctions of mono-crystalline silicon cells may have adequate reverse current characteristics and these are not necessary. Reverse currents waste power and can also lead to overheating of shaded cells. Solar cells become less efficient at higher temperatures and installers try to provide good ventilation behind solar panels.

1.1 I-V Equation of PV cell

The PV cell is usually represented by the single diode model. The I-V characteristics equation of solar cell is given as

$$I = I_L - I_O \left\{ exp^{\left[\frac{q(V+I_{RS})}{AkTc} \right]} - 1 \right\} - \frac{(V+I_{RS})}{R_{Sh}}$$

IL is a light generated current or photo current (representing the current source), IO is the saturation current (representing the diode), Rs series resistance, A is diode ideality factor, k(=$1.38 \times 10{-23}$W/m2K) is Boltzmann's constant, q (=$1.6 \times 10{-19}$C) is the magnitude of charge on an electron and TC is working cell temperature. Photo current or light generated current, mainly depends on the solar insolation and cell working temperature, which is described as:

$$I_L = G \left[I_{SC} + K_I (T_C - T_{ref}) \right]$$

Where Isc is the short circuit current at 25°C and 1KW/m2, KI is the short circuit current temperature coefficient, T ref is the reference temperature and G is the solar insolation KW/m2,on the other hand, the cells diode current or saturation current varies with the cell temperature which is described as:

$$I_O = I_{RS} \left(\frac{T_C}{T_{ref}} \right)^3 exp \left[\frac{qEG \left(\frac{1}{T_{ref}} - \frac{1}{T_C} \right)}{KA} \right]$$

Where IRS is the cells reveres saturation current at reference temperature and a solar radiation, EG is the band-gap energy of the semi conductor used in cell

1.2 I-V Equation for PV Module

I-V equation of a PV module is similar to that of solar cell, except that the module I-V curve is the combination of I-V curves of all solar cells connected in a module. Equation 1 can be written in terms of voltage of a single solar cell as well

$$V = - IR_S + K \log \left[\frac{I_L - I + I_O}{I_o} \right]$$
$$\text{Where, K is a constant} \left(= \frac{AkT}{q} \right)$$

If Imo and Vmo are the current and voltage of solar PV module, respectively than relationship between Imo and Vmo will be similar to that of a solar cells I-V relationship, i.e

$$V_{mo} = - I_{mo} R_{Smo} + K_{mo} \log \left(\frac{I_{Lmo} - I_{mo} + I_{Omo}}{I_{Omo}} \right)$$

Where ILmo light generated current of module, IOmo is reverse saturation current of the module, Rsmo is the series resistance of the module and Kmois the constant for the module. If there are NS cells connected in series in a module, than its series resistance will be the sum of each cells series resistance Rsmo=NS×RS. Similarly, the module constant will be written as Kmo=NS×K. But since same

current flows in series connected cells, the current terms in equation 5 will be the same as that of individual cell i.e Iomo=Io and ILmo=IL. Thus, the module Imo-Vmo equation of NS series connected cells will be written as:

$$V_{mo} = - I_{mo} N_S R_S + N_S Klog(\frac{I_L - I_{mo} + I_o}{I_o})$$

In the similar fashion, the current–voltage equation can be written for the parallel connected cells. If there are NP cells connected parallel in a module, than relationship between the current and voltage of the module will be given as:

$$V_{mo} = - I_{mo} \frac{R_S}{N_p} + K \ log(\frac{N_{sh} I_L - I_{mo} + N_p I_o}{N_p I_o})$$

In the case of parallel connection the series resistance is divided by the number of cells in parallel(Np) and light generated current and reverse saturation current get multiplied by the NP. In this case the module factor K remain sun affected and is same as that of K of a single cell

(a) General model

(b) Generalized model

(c) Appropriate model
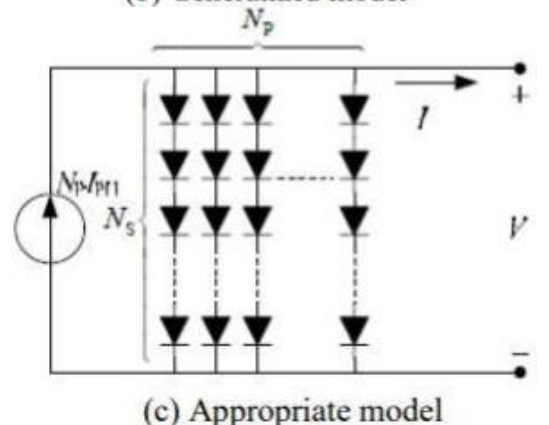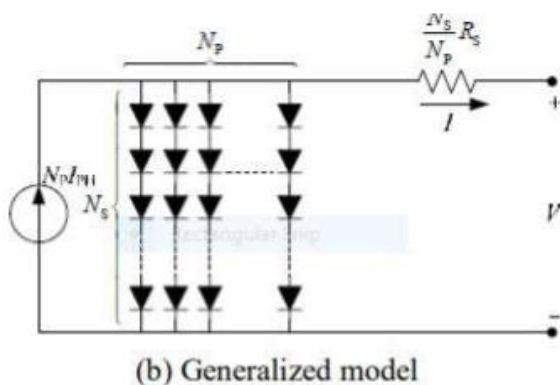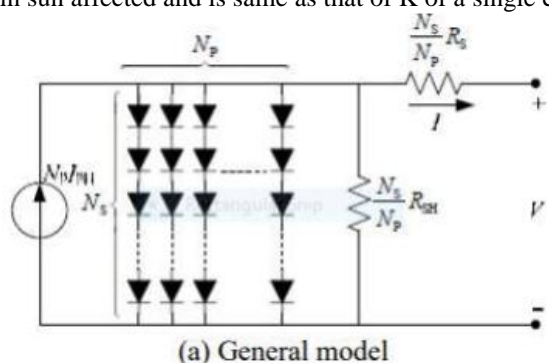
1.3 Programming Based Simulation on Matlab for Solar PV Model

Simulation program is developed with considering single-diode PV cell mathematical model with neglecting series

and shunt resistances. Specific values of the input and climatic parameters are taken into account. Simulation program tested on matlab for **36WTataBP184459** solar PV module at two conditions:

1) Constant solar radiation intensity and varying module temperature.
2) Constant temperature and varying solar radiation intensity. Simulation parameters for above two conditions are listedinTable1andTable2

Table 1: Simulation parameters for constant solar radiation intensity and varying module temperature

Simulation Parameters	Values
Solar radiation intensity (S)	800W/m² (constant)
Temperature of cell (T_{mod})	25ºC,35 ºC,40 ºC,45 ºC
Reference temperature (T_{ref})	40ºC
Short Circuit Temperature Coffecent (K_i)	0.00023mA/ºC
Reverse Saturation Current (I_{rr})	21×10⁻¹⁰ A
Boltzman's constant (k)	1.38×10⁻²³W/m²-K
Charge of electron (q)	1.602×10⁻¹⁹C
Cell Saturation Current (I_{scr})	0.75Ma
Fil Factor (FF)	0.85
Area of the Module (A_r)	0.40 m²
Ideality Factor (A)	4
The Curent Temperature Cofficient(α)	0.473mA/ºC
The Voltage Temperature Cofficient (β)	636 V/ºC
Band Gap Energy (E_{go})	6.5eV
Number of Cells connected in parallel (N_p)	4
Number of Cells connected in series (N_s)	9

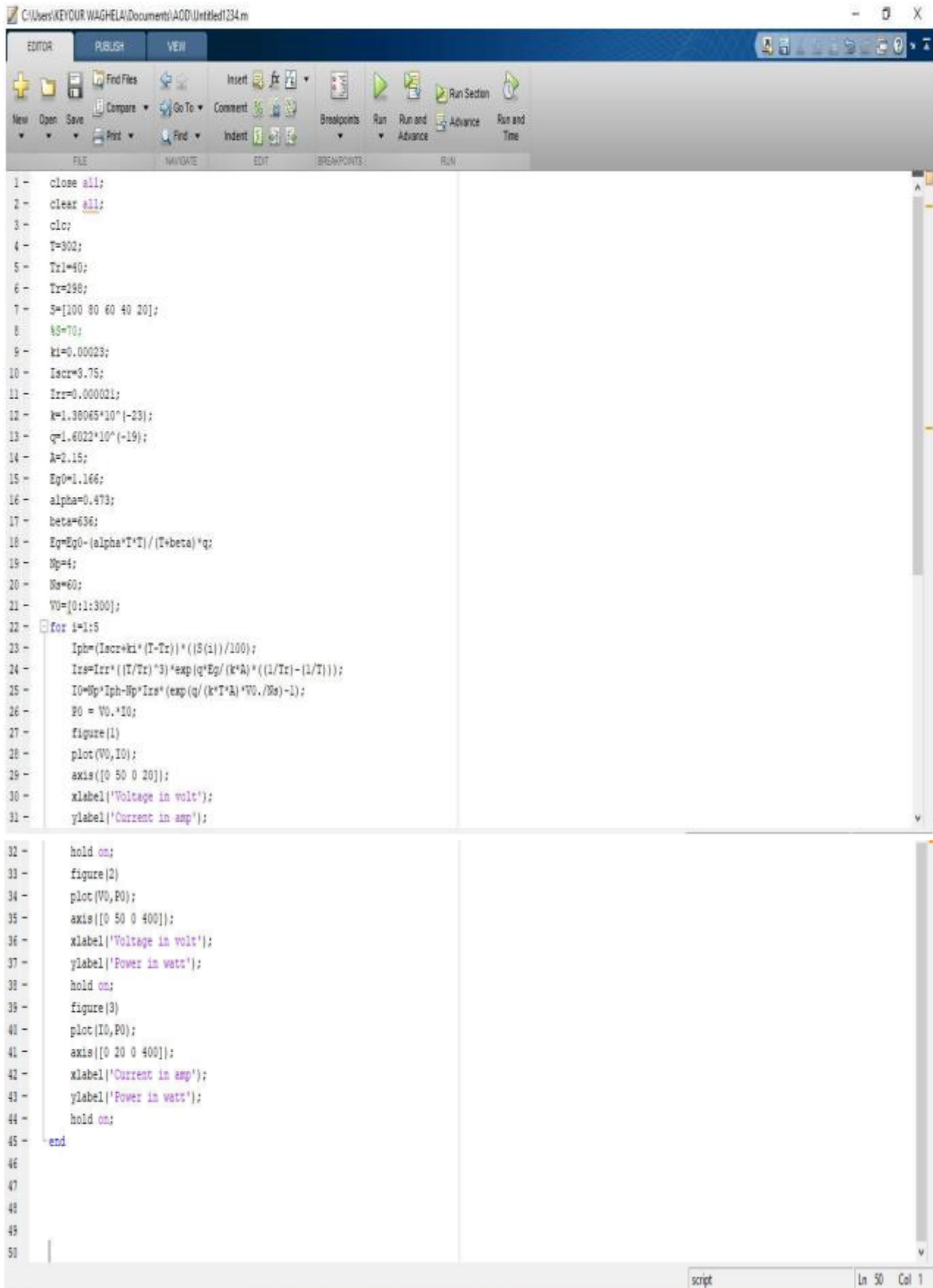**Table 2:** Simulation parameters for constant temperature and varying solar radiation intensity

Simulation Parameters	Values
Varying Solar radiation intensities (S)	200W/m² ,400W/m² , 600W/m² , 800W/m² , 1000W/m²
Temperature of cell (T_{mod})	25 +273 (Constant)
Reference temperature (T_{ref})	40+273
Short Circuit Temperature Coffecent (K_i)	0.00023mA/ºC
Reverse Saturation Current (I_{rr})	21×10⁻¹⁰ A
Boltzman's constant (k)	1.38×10⁻²³W/m²-K
Charge of electron (q)	1.602×10⁻¹⁹C
Cell Saturation Current (I_{scr})	0.75mA
Fil Factor (FF)	0.85
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Band Gap Energy (E_{go})	6.5eV
Number of Cells connected in parallel (N_p)	4
Number of Cells connected in series (N_s)	9

Manufacturing data specifications of 36W solar PV module (TataBP184459) are shown in Table3

Table 3: Specification of the PV module

Model	Tata BP 184459
Maximum power	36W
Open circuit voltage	18V
Short circuit current	2A
Number of cells	36
Dimensions	950×425×35 mm
Weight	6 kg
Fill factor	0.85

2. MATLAB Code with Graphs

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EDITOR    PUBLISH    VIEW

1 -    close all;
2 -    clear all;
3 -    clc;
4 -    T=302;
5 -    Tr1=40;
6 -    Tr=298;
7 -    S=[100 80 60 40 20];
8      %S=70;
9 -    ki=0.00023;
10 -   Iscr=3.75;
11 -   Irr=0.000021;
12 -   k=1.38065*10^(-23);
13 -   q=1.6022*10^(-19);
14 -   A=2.15;
15 -   Eg0=1.166;
16 -   alpha=0.473;
17 -   beta=636;
18 -   Eg=Eg0-(alpha*T*T)/(T+beta)*q;
19 -   Np=4;
20 -   Ns=60;
21 -   V0=[0:1:300];
22 - ☐ for i=1:5
23 -       Iph=(Iscr+ki*(T-Tr))*((S(i))/100);
24 -       Irs=Irr*((T/Tr)^3)*exp(q*Eg/(k*A)*((1/Tr)-(1/T)));
25 -       I0=Np*Iph-Np*Irs*(exp(q/(k*T*A)*V0./Ns)-1);
26 -       P0 = V0.*I0;
27 -       figure(1)
28 -       plot(V0,I0);
29 -       axis([0 50 0 20]);
30 -       xlabel('Voltage in volt');
31 -       ylabel('Current in amp');
32 -       hold on;
33 -       figure(2)
34 -       plot(V0,P0);
35 -       axis([0 50 0 400]);
36 -       xlabel('Voltage in volt');
37 -       ylabel('Power in watt');
38 -       hold on;
39 -       figure(3)
40 -       plot(I0,P0);
41 -       axis([0 20 0 400]);
42 -       xlabel('Current in amp');
43 -       ylabel('Power in watt');
44 -       hold on;
45 -   end
46
47
48
49
50

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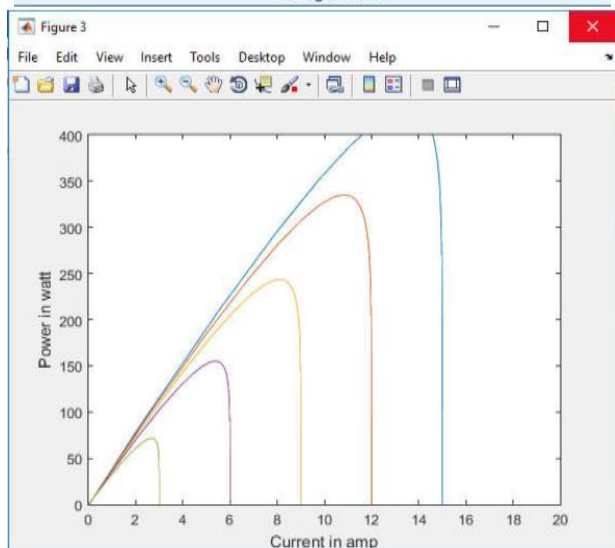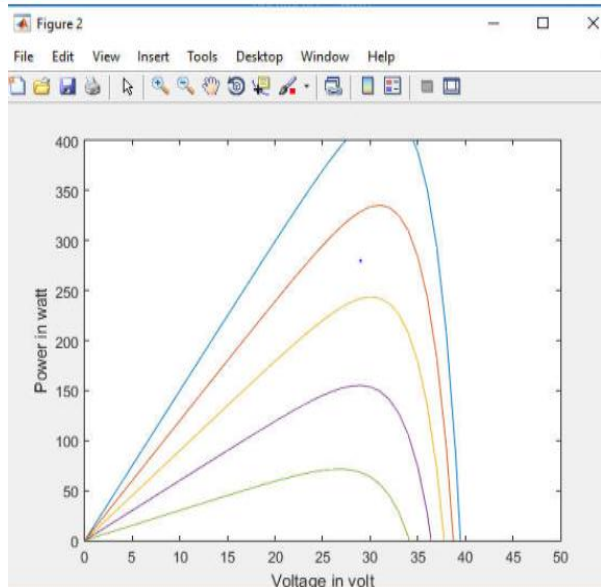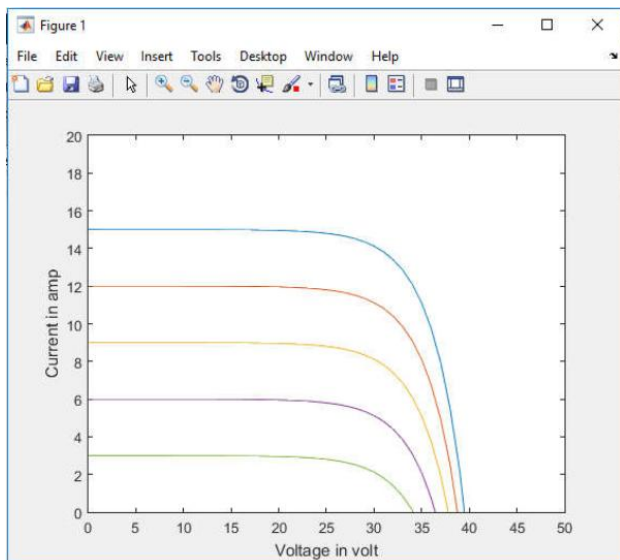
2.1 Perovskite Solar Cells

The manufacture cost of silicon-based solar cells has been significantly reduced in the recent few decades. Inorder to make solar cell widely adopted, the price has to be decreased even further. However, currently, there is not too much room for price reduction for silicon solar cells. A new generation of photovoltaics is expected to replace the old types of solar cells. Perovskite solar cell is the one we are looking for, which offers both lower price and high energy conversion efficiency.

Perovskite or more specifically, lead-halide perovskite, is a semiconductor follows ABX3 structure. In this structure, A and B are cations while X is halide. In order to form a perovskite structure, the ionic radii of A,B, and X have to follow the octahedral and tolerance factor rules

$$\text{Tolerance factor: } 0.81 < t = \frac{R_A + R_X}{\sqrt{2(R_B + R_X)}} < 1.11$$

$$\text{Octahedral factor: } 0.44 < \mu = \frac{R_B}{R_X} < 0.9$$

The A cation in the structure could also be formamidinium (FA, NH2CH=NH2+) and Cesium (Cs). The B cation could either be Lead (Pb) or T in (Sn). Xanionishalide (I, Cl, and Br). This great amount of combination offers perovskite excellent flexibility inmaterial properties.
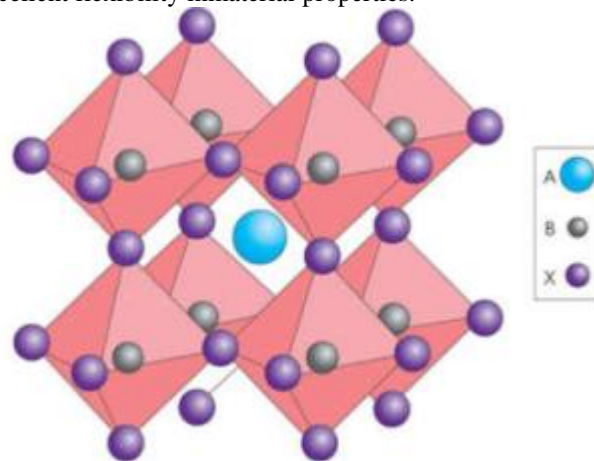
2.2 Basic working of perovskite solar cells

During exposure to sunlight, the perovskite layer firstly absorbs photons to produce excitons (electron-hole pairs). Due to the difference in the exciton binding energy of the perovskite materials, these excitons can form free carriers (free electrons and holes) to generate a current or can recombine into excitons. Due to the low carrier recombination probabilities of CH3NH3PbI3(MAPbI3) and other perovskite materials and the higher carrier mobility, the diffusion distance and life time of the carrier are long. The longer diffusion distance and lifetime of carriers are the source of the superior performance of perovskite solar cells. Then, these free electrons and holes are collected by an electron transport material (ETM) and a hole transport material (HTM). Electrons are transferred from the perovskite material to TiO2, which is used for the ETM layers and finally collected by FTO. At the same time, the holes are transferred to the HTM layer and collected by the metal electrode. Finally, the FTO and metal electrode are connected and the photo current is generated in the outer circuit.
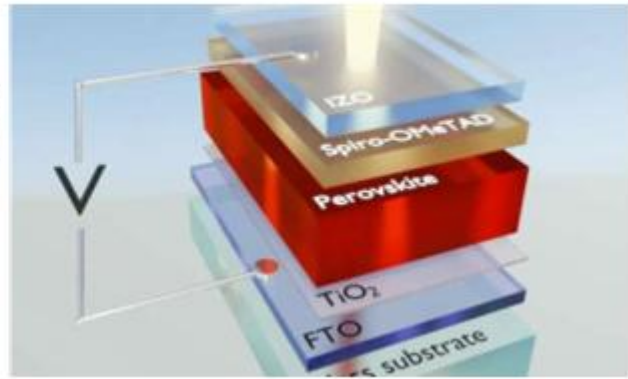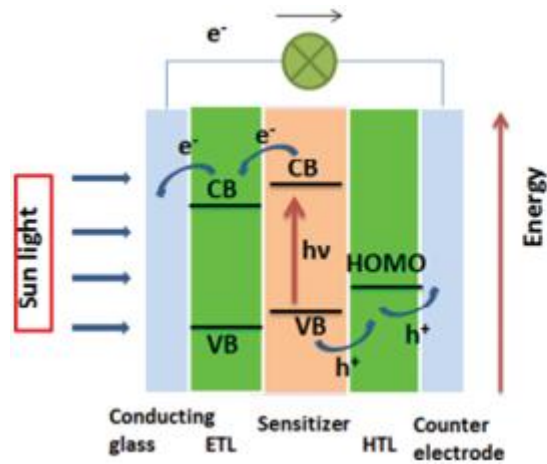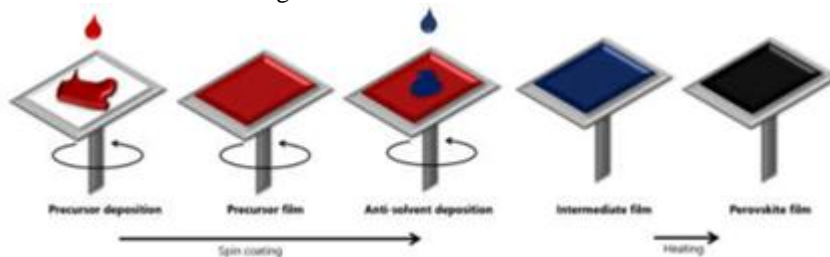
2.3 Fabrication

Typically, the active layer of a perovskite solar cell is deposited via either a one or two-step process. In the one-step process, a pre cursor solution (such as a mix of CH3NH3I and PbI2) is coated that then converts to the perovskite film upon heating. A variation on this is the 'anti-solvent' method, in which the precursor solution is coated in a polar solvent, and then quenched during the spin coating process by a non-polar solvent. Precise timings of the quench and volumes of the quenching solvents is required to give the optimal performance.

In the two-step process, the metal halide (such as PbI2) and organic components (such as CH3NH3I) are spin-coated in separate, subsequent films. Alternatively, metal halide films can be coated and annealed in a chamber filled with the organic component vapour, known as 'vacuum-assisted solution process' (VASP).

The main issues for practical device fabrication of perovskite solar cells are film quality and thickness. Thelight-harvesting (active) perovskite layer needs to be several hundred nano metres thick–several times more than for standard Organic photovoltaics, and creating such thick layers with high uniformity can be difficult. Unless the deposition conditions and annealing temperature are optimised, rough surfaces within complete coverage will form. Even with good optimisation, there will still be a significant surface roughness remaining. Therefore, thicker interface layers than might normally be used are also required. Improvements to film quality have been achieved through a variety of methods. One such method is the addition of small amounts of acids, such as hydroiodicorhydro bromic acid.

2.4 Advantages

Firstly, the materials possess excellent photoelectric properties, lower exciton binding energy, and high optical absorption coefficients (upto10^4cm^{-1}). Secondly, perovskite as the light-absorbing layer can absorb solar energy efficiently. Thirdly, the materials possess a large dielectric constant and electrons and holes can be effectively transmitted and collected. Lastly, electrons and holes can be transmitted simultaneously and the transmission distance is upto 100nm or more and even more than 1μm.

3. Perovskite Solar Cells Over Conventional Silicon Solar Cells

3.1 Why better than Present Solar Cells?

One of the most exciting parts of perovskites is their high efficiencies. Based on lab calculations, scientists believe that perovskite solar cells are capable of beating the efficiencies of traditional mono-or poly-crystalline silicon cells. Although they have been in development for far less time than silicon cells, perovskite cells are already reaching lab efficiencies above 20 percent.

Another advantage of perovskite solar cells is that they are based on a man-made material that can be produce data low cost. Standard solar PV cells are made with crystalline silicon, which has to be extracted from the earth and processed extensively before it can be used to make high-quality solar cells.

Like other thin-film technologies, perovskite solar cells have unique properties that make them attractive for reasons beyond their low-cost potential and energy production capabilities. Thin film panels are typically flexible, light weight, and semi-transparent. From a design perspective, this makes perovskites highly appealing, as they appear much lower-profile than traditional silicon solar panels and

can be incorporated into parts of buildings besides just the roof.

The graph below show same teoricrise compared to most other technologies over a relatively short period of time. Within 4years of their breakthrough, perovskite solar cells had equalled efficiencies of Cadmium Telluride (CdTe), which has been around for over 40 year. Furthermore, as of June 2018 they have now exceeded all other thin-film, non-concentrator technologies-including CdTe and Copper Indium Gallium Selenide (CIGS). Although it could be argued that more resources and better infrastructure for solar cell research have been available in the last few years, the dramatic rise in perovskite solar cell efficiency is still incredibly significant and impressive.
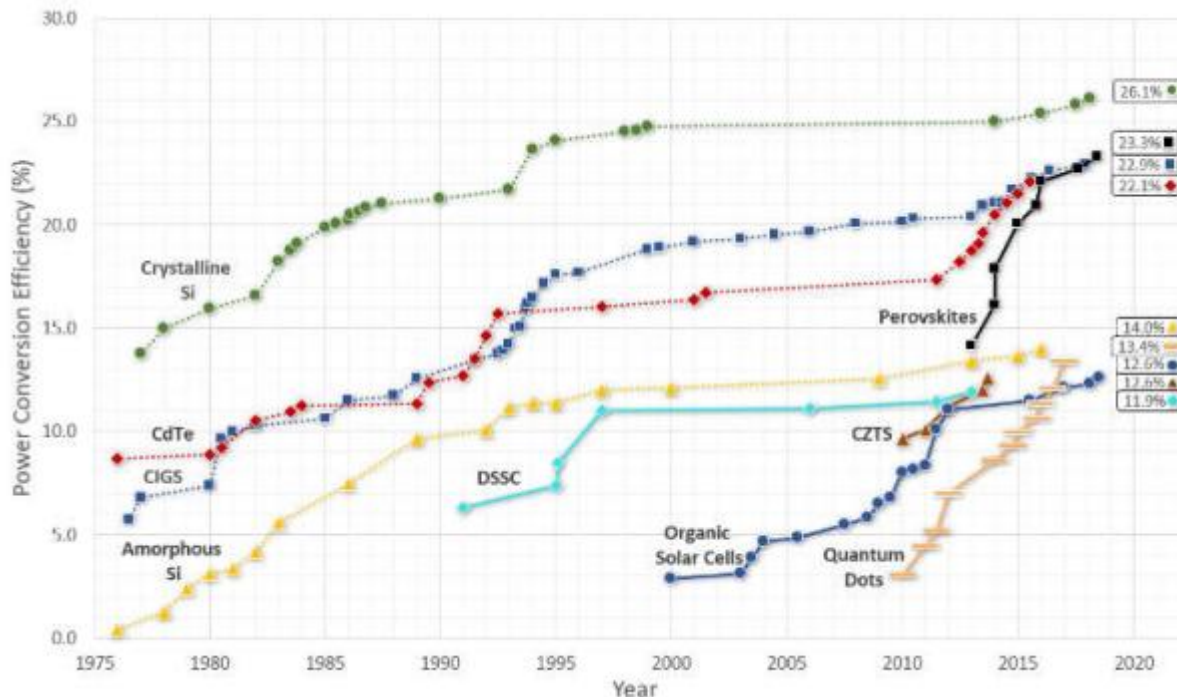

It is quite evident from the above graph that there has been an exponential growth in the efficiency of the perovskite solar cells. It started off at around 14% in 2013 has become 23.3% efficient in year 2018. Scientists say that it will pass the crystalline Si in a decade or so given the present rate of technological development. This rise in the efficiency of perovskite solar cells is because of solid state technology in which we replaced the liquid electrolyte with the solid one. Also coming up of different advanced of these solid state perovskite cells like mesoscopic and planar further increased the efficiency.
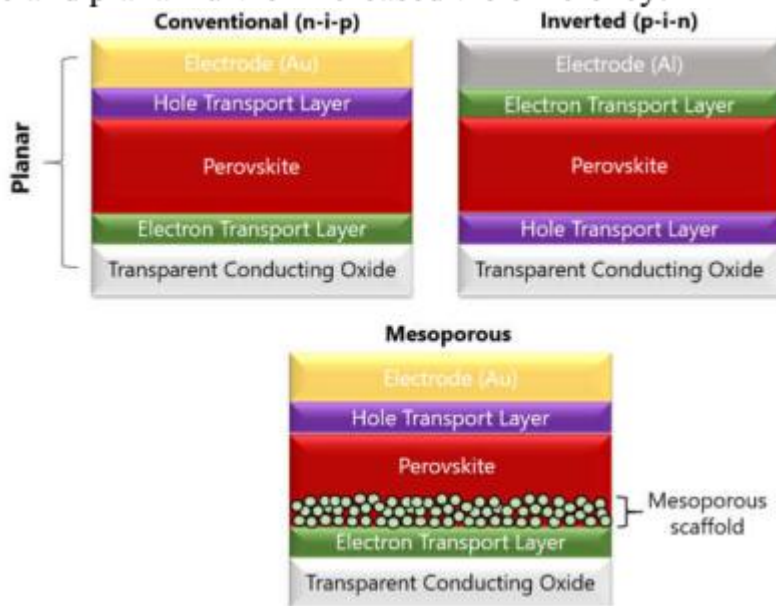
The second key graph below is the open-circuit voltage compared to the band gap for a range of technologies that compete against perovskites. This graph demonstrates how much of a photon's energy is lost in the conversion process from light to electricity. For standard excitonic-based, organic-based solar cells, this loss can be as high as 50% of the absorbed energy, whereas perovskite solar cells regularly exceed70% photon energy utilisation, and have the potential to be increased even further.
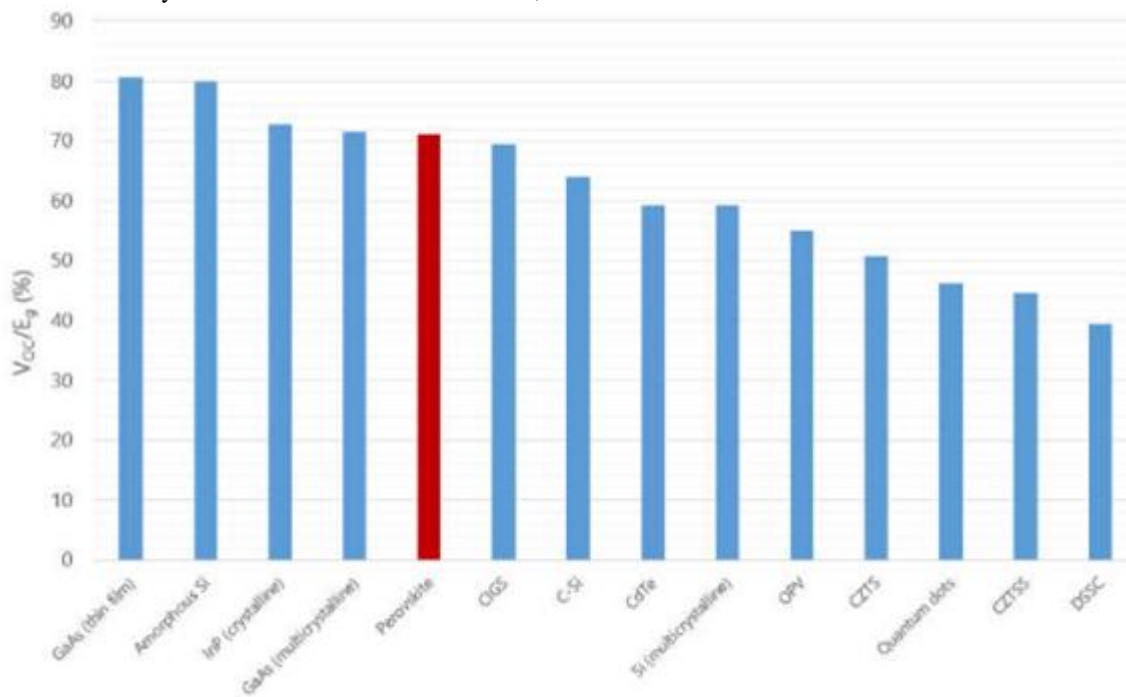

One more advantage of perovskites is that it can be made of common metals and industrial chemicals, as opposed to the expensive raw materials used in other silicon substitutes. Perovskite based materials could also be used to print photovoltaic electronics directly on to glass or other materials, which would be a lot more cheaper than the more complex methods used for producing thin-film solar cells. Also spraying the perovskite as a liquid coating on to a substrate material allows solar cells to be manufactured at high volumes and at a much lower cost than the currently used silicon solar cells, this are called tandem solar cells.
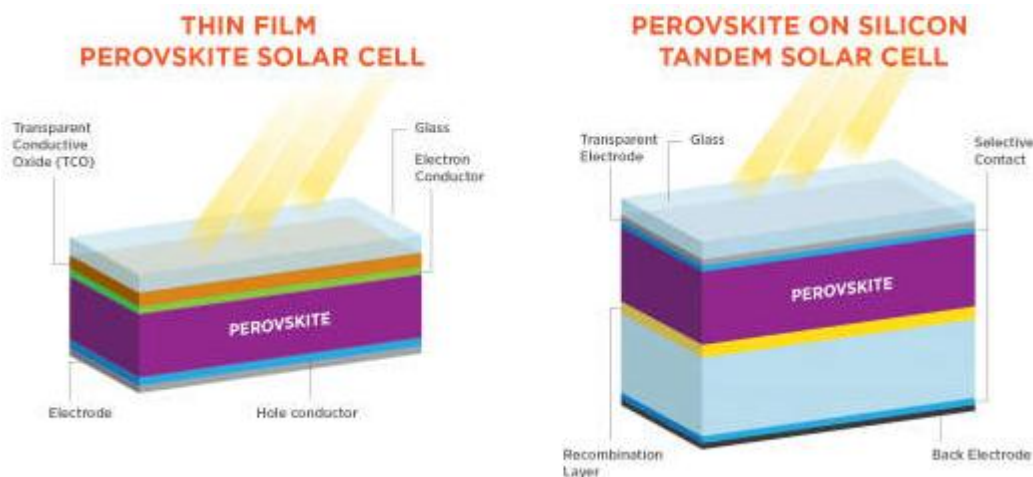
Another interesting factor of perovskites solar cells is that if we alter the compound composition, the solar cell color can be adjusted to any color as desired, they can be even made transparent. This gives a huge advantages of being able to be fabricated in aesthetically-pleasing ways, which may result in consumers willing to put them on their roofs as building integrated photovoltaic applications become more attractive. They can be used as windows or glasses incorporate building which work both as a decoration and energy generation unit. They can also be altered so as to absorb a particular wavelength of the EM spectrum.
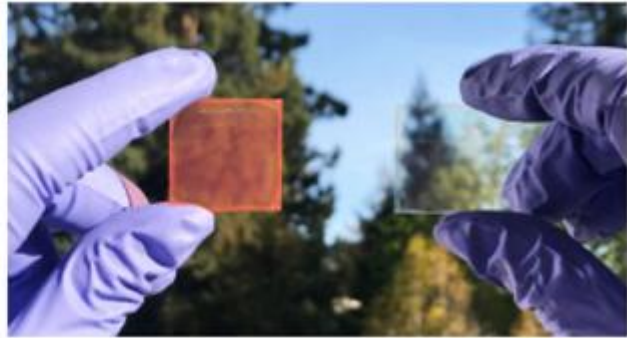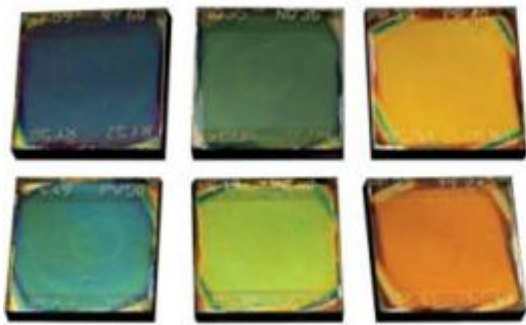
Thus perovskite have alot of advantages and plus points over the present Si crystalline solar cells which needs to be carefully manufactured as even a very small amount of impurity can reduce the overall efficiency of the solar cell. Further more, Si crystals are still expensive even though there price has been reduced in past decades, it is still not available as self sufficient energy generation system for household. But even though perovskite are very efficient the reproduction for commercial purposes have not yet began, which will be discussed in the next part.
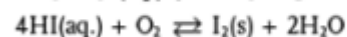
3.2 What issues do perovskites face?

Like any technology, perovskite solar cells need to be perfected and proven in the laboratory before they become available to the general public. Perovskites are currently still in the development phase as scientists try to work out the road blocks to the technology becoming widely available.

The biggest issue in the field of perovskites currently is long-term instability. This has been shown be due to degradation path ways involving external factors, such as water, light, and oxygen, and also as a result of intrinsic instability, such as degradation upon heating, because of the properties of the material. The present commercial Solar cells have a life of around 20 to 25 years whereas on the other hand the perovskite cells only have a fair working condition of months, after which they become inefficient., but there has been technological development since the time they were introduced, earlier they used to last just for days. When exposed to moisture, perovskite materials tend to hydrolyze, which results in their disintegration back into their precursors and finally irretrievable degradation of the perovskite structures. X-ray photoelectron spectroscopy (XPS) has been used to investigate the compositional changes caused by device degradation over the period of 1000 hrs. XPS spectra confirm the migration of metallicions from the bottom electrode (ITO) as a key factor causing the chemical composition change in the perovskite layer besides the diffusion of oxygen

The lifetime of PSCs is affected by many factors, which can be classified into two categories: extrinsic (environmental) and intrinsic factors. Environmental factors such as moisture and oxygen can be settled by encapsulation. There are three main intrinsic factors leading to perovskite instability: hygroscopicity, thermal instability, and ion migration. The hygroscopicity is related to the environmental factors and can also be solved by encapsulation. The thermal instability can be addressed by composition tuning to increase the decomposition energy or barrier, e. g. , with FA cations.

Lastly, the issue of ion migration is currently treated by Asite alkali doping and replacement, multiple dimensional perovskites engineering (MDPs), and organic molecular additives.

One of the major influence factors of degradation is the moisture. Therefore, the preparation of PVSCs should be in a humidity relatively low level of <1% atmosphere. Scientists have presented a series of chemical reactions considered responsible for the degradation of CH3NH3PbI3 in moisture in the following Equations

$$CH_3NH_3PbI_3\,(s) \rightleftarrows PbI_2(s) + CH_3NH_3I(aq.)$$
$$CH_3NH_3I\,(aq.) \rightleftarrows CH_3NH_3^+ + HI(aq.)$$
$$4HI(aq.) + O_2 \rightleftarrows I_2(s) + 2H_2O$$
$$2HI(aq.) \rightleftarrows H_2 + I_2(s)$$

Therefore, moisture degradation of perovskite is related with the MAPbI3 transforming to MAI salt and metal halides, while removal of metal halide can also accelerate perovskites device degradation.

Another issue yet to be fully addressed is the use of lead (Pb) in perovskite compounds. Though it is used in much smaller quantities than those currently present in either lead- or cadmium-based batteries, the presence of lead in products for commercial use is problematic. Concerns still remain about exposure to toxic lead compounds (through leaching of the perovskite into the environment), and some studies have suggested large-scale implementation of perovskites would require complete containment of degradation products. In contrast, other life cycle assessments have found the toxicity impact of lead to be negligible in comparison to other materials in the cell.

Several ways have been proposed to reduce the issues with perovskite such as using tin-based perovskites, but the power conversion efficiency of such devices is still significantly behind lead-based devices, with the record for a tin-based perovskite currently standing at 9.0%. Some studies have also concluded that tin may actually have a higher environmental toxicity than lead, and other less toxic alternatives are required. Another proposed way is using titanium. The titanium-perovskite upper layer would absorb the higher-energy photons from the sun that the lower silicon layer can't absorb because of its smaller band gap. Mean while, lower energy photons would pass through the semi-transparent upper layer to be absorbed by the silicon, thereby increasing the cell's total absorption capacity.
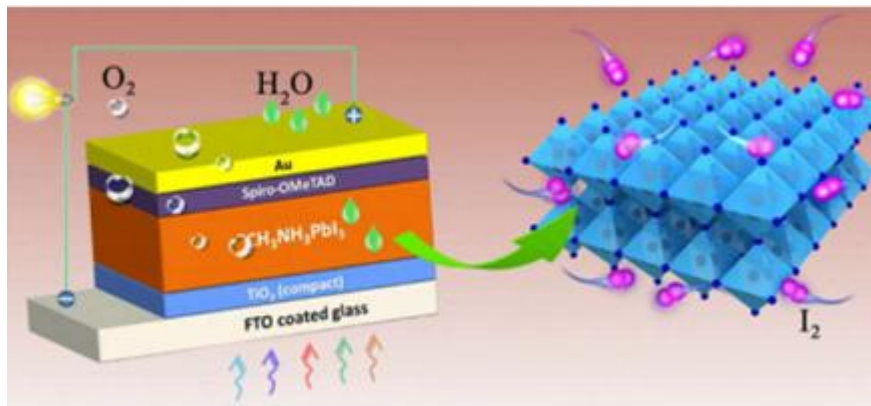
4. Future of Perovskite Solar cells (Conclusion)

We may still see perovskite solar cells become available in the near future. It has taken over 60 years of development and improvements for consumers to be able to purchase silicon solar cells with efficiencies over 20 percent, and perovskites have already reached those numbers in the laboratory. At the current rate of progress, some scientists predict that perovskites will be ready for solar installations within several years. Another potential product that may emerge from perovskite research is a combination of solar technologies, known as a "tandem cell". This technology may involve perovskites combined with traditional silicon to create a solar cell with benefits from both types of photo voltaic technology.