Review of Organic Solar Cells

Kanishak Katahra

Abstract--- This study relates to organic solar cells, more specifically, selection of polymer, extracting maximum power, stability, degradation and manufacturing. Basic principle, along with feasibility of some printing and coating methods have been studied and the best method has been selected. The characteristics of cells and polymers such as stability, degradation, power conversion efficiency is studied.

Keywords--- Organic Solar Cells, OPVs, Polymer Selection for OPV, Photo Voltaic, Stability, Degradation, Manufacturing, Coating, Printing, Lamination

I. INTRODUCTION

All the harms done to Earth by humans raise a need of another method to get energy. Therefore, it would be correct to say that organic solar cell (OPV) is the way to go if the efficiency could be enhanced and factors could be improved but it is always worth a look. It is required to use organic solar cell is because fossil fuels are limited, the world needs renewable resources and what can be better than using the ultimate resource as one. Organic solar cells are clean technology and less CO2 is emitted. The energy needed in 2007 was 15TW, it is expected to reach 30TW in 2050 and as high as 50TW in 2100. Comparing these values with available and accessible renewables like biomass which can help extract energy approximately equivalent to 5-7TW, hydroelectric (1.2TW), geothermal (1.9TW), tide or ocean current (0.7 TW), wind energy (14 TW) [1]. The values mentioned are the accessible energy values.

Extracting energy from these resources invites many complexities and challenges depending on location, cost and other factors. Whereas solar energy at Earth's surface is $1*10^5$ TW but the technical or theoretical output is 10,000TV. Solar energy is little explored but has vast potential. It comes in, of course, as photons. The ways of doing it is solar fuels which directly fixes CO2 using sunlight and sea water or hydrogen to convert it into gaseous or liquid fuels like methane, formaldehyde. Solar thermal converts light into heat. The main advantage of using solar cell is that it directly converts light into electricity. Efficiency order of these three ways used to extract energy is:

Solar thermal > Solar electric > Solar fuel.

More reasons for choosing organic solar cells over other types can be:

- Materials required to make other cells are scarce.
- The manufacturing cost of others cells are high.
- They can be toxic.

To measure the impact of the processing, operation, decommissioning, end of life management of polymer solar cells technology special methodology called LCA (Life cycle assessment) is used. [2]

All non-negligible impacts are kept in mind along with aim, scope and inventory. Talking about aim which is obviously generating electricity using OPV (Organic Photovoltaic) and guide the research towards green energy technology. Our inventories include inputs such as materials, processes, transport, releases. The third step is impact assessment which includes climate change, eutrophication, ozone depletion, human toxicity, etc. The flow chart of LCA is shown in figure 1.

Kanishak Katahra, Department of Instrumentation and Control Engineering, Manipal Institute of Technology, Manipal. E-mail: kanishak14@gmail.com

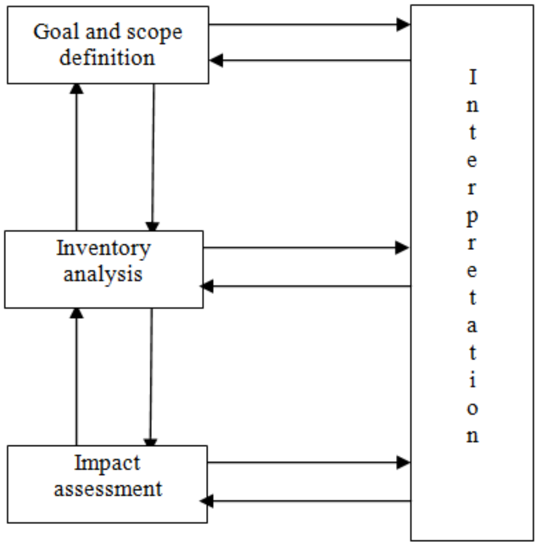

Figure 1: Flow Diagram of Life Cycle Assessment

Two more parameters are to be kept in mind when conducting LCA in energy technologies. They are

1.) Energy payback time: It is for our OPV module, the time that it takes to produce as much energy as was invested in its production and in its whole lifetime. Therefore, it can be found using equation 1.

$$\text{EPBT} = \frac{\sum Einput}{Egen/year} \quad \text{........ (1)}$$

2.) Carbon footprint: It is the kilograms of CO2 equivalent per generated output as shown in equation 2.

$$\text{Carbon footprint} = \frac{\sum CO2-eq}{Egen.lifetime} \quad \text{........ (2)}$$

The last step is interpretation which is to check if assessment is meeting its goal. Key parameters such as energy balance, material fluxes, emissions, wastes are analyzed. Then consistency is checked and data uncertainties are checked.

II. GEOMETRY AND MANUFACTURING

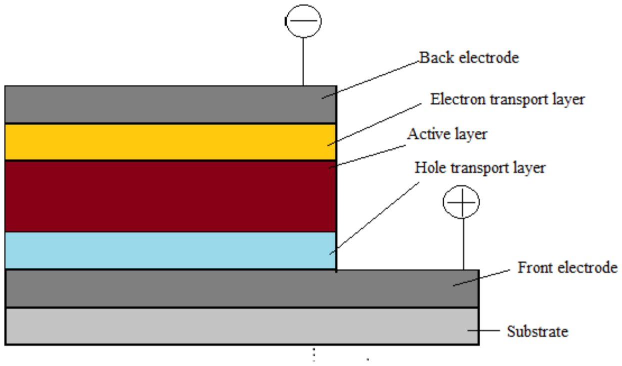

Figure 2: Geometry of an Organic Solar Cell

The working includes a cascade if events that starts with the absorption of photons in active layer which creates exciton bond electron hole pair which diffuses through a phase boundary between the polymer donor and an acceptor. Here the charge separation happens. A typical solar cell has outer electrodes, one is transparent. There is an electron transfer layer and hole transfer layer and the active material. The active material has two parts:

1.) The donor material (polymer) which absorbs light and has a great affinity for the holes.
2.) The acceptor which has a larger affinity for the electrons.

This active material is a semi-conductor. In normal solar cells silicon is used, which is an indirect band gap material. Therefore, to excite an electron to excited state lattice vibrations are needed. This is called phonon. The transition becomes less likely and a thicker slab of material is needed. It will be correct to say that silicon solar cells are rather thick and consume a lot of material.

Therefore, direct band gap materials are needed, which can be thinner and organic solar cells fulfill this criteria. Silicon solar cells have a band gap of 1.3eV this means that maximum power efficiency is about 33%. Most power energy has higher band gap therefore they absorb less sunlight, the power conversion efficiency is low. The efficiency can be increased by using multiple junctions. Theoretically 86% efficiency can be reached with infinite junctions, but that is just theoretical value. While implementing it practically, a lot of limitations are faced.

In conventional geometry (as shown in figure 2), electrons are extracted at back electrode and the holes at the front. The active layer consists of two components in the polymer solar cells. A donor which absorbs the light and an acceptor which extracts the electron from the excitonic bound electron hole, resulting in an electron travelling in the acceptor phase of the active layer and a hole travelling in the donor phase. The most commonly used electrode material has been indium tin oxide (ITO), due to a high optical transmission combined with a low resistance; on glass a transmission of >85% at <10 Ohm/sq. is often seen. The main issue with choosing the electrodes is to find electrodes with a suitable energy level and with one of the electrodes being transparent to allow sufficient light to enter the solar cell.

III. EXTRACTING HIGHEST POWER

The most important parameter is power conversion efficiency which is defined as the ratio between electric power output of the cell and the incoming output power of the light (eqn. 3).

$$\text{Power conversion efficiency} = \frac{Power.output}{Power.input} \quad …..(3)$$

To measure this a light source which has intensity of one sun (one sun = 1000 W/m^2) is required. Source measure unit to control the voltage while the current is being measured, multimeter and a variable resistor as a load is used. The resistor is set to the solar cell and set to different values while measuring the voltage and current. The circuit is show in figure 3.

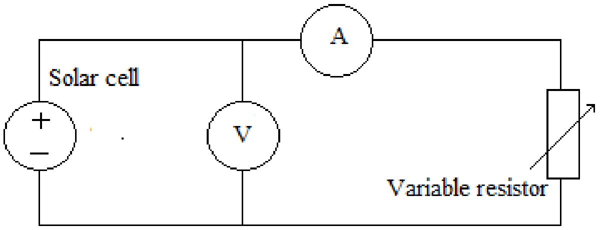

Figure 3: Circuit for Measuring Power

After making a note of the readings and plotting them, a V-I graph is obtained as shown in figure 4.

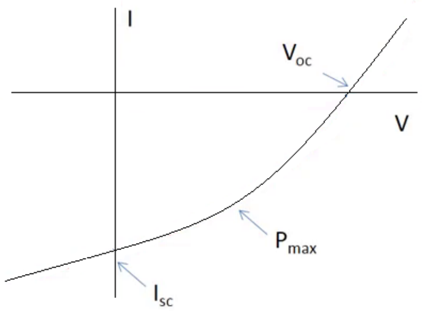

Figure 4: V-I Characteristic to Measure Maximum Power

At zero voltage short circuit current (I_{sc}) is obtained and at zero current open circuit voltage (V_{oc}). The power output is, of course 0. Maximum power point is found using equation 4 and 5 which is recorded as power conversion efficiency.

$$P = V*I \quad (4)$$

$$\text{Power conversion efficiency} = \frac{P\max}{Pin} \quad (5)$$

Another way of characterizing polymer solar cell is by using the parameter fill factor [3]. It is the relation between maximum power that the cell could give and open circuit voltage and the short circuit current, and the maximum power point as in equation 6.

$$\text{Fill factor} = \frac{\mathrm{Pmax}}{Voc.Isc} \quad (6)$$

It should be as high as possible.

IV. SELECTING A POLYMER

Active layer consists of two types of material. Polymer: a small molecule which acts as a donor and then an acceptor material. It absorbs light and then an electron is excited which is transferred to the acceptor, and charge separation takes place. C_{60} (Buckminsterfullerene) was earlier used as an acceptor but this wasn't soluble in common organic solvents which let it evaporate onto the active layer. C_{60} was further developed to form a derivative of PCBM to prepare a heterojunction, where the donor and the acceptors are mixed and the charge transfer becomes more efficient. Derivative of PCBM can also be developed using C_{70} which gives an advantage to select a band gap. This way more efficient polymer solar cell can be made. The derivative of C_{60} is shown in figure 5.

Using polymers as acceptors has an advantage that absorption takes place from two polymers, energy level of the polymer is easier tune. Viscosity control becomes easier too. Polymer should have side chain which ensures solubility which makes it necessary to synthesise polymer using coating and printing. Side chains can be alkyl chains or ester. The polymer should be conjugated. Conjugated polymers have ∏ bonds which diffuses into polymer. These electrons belonging to this type of bonds can be shifted upon absorption of visible light. All colours of polymer represent different absorption spectrum as shown in figure 6. A long chain has higher absorption. P3HT/PCBM is relatively stable and it is possible to process them on large scale. The poor matching of solar spectrum requires more study in this area using other polymers.

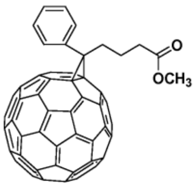

Figure 5: P_3HT

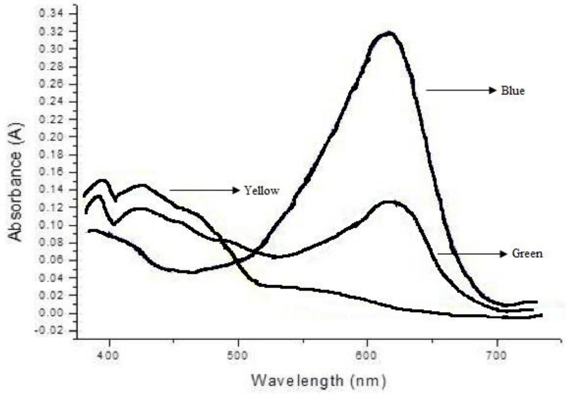

Figure 6: Absorption Spectrum of Different Colours of Polymer

Important parameter to be considered when selecting a polymer are:

1.) Efficiency: While studying or selecting efficiency of solar cell it is important to study the solar spectrum graph as shown in figure 7. Photon flux is plotted with the current corresponding to it. Polymer P3HT is taken which has a band gap of 1.9eV and the polymer absorbs light up to 600nm. This polymer will absorb about 17% of photons. On converting these to electrons, current of 11mA/cm^2 is obtained. If the band gap is lowered up to 1.2eV, 53% of photons can be absorbed corresponding to a current of 34mA/cm^2. The highest efficiency attained is 10% by reducing the band gap. To reduce the band gap the polymer should have an efficient inter-chain charge transfer. Donor and acceptor should be varied within the polymer backbone. Band gap is also affected by the qionid structure which is known for PITN-(1.3-dihydroisothianaphtene) polymer. This structure is very stable and the band gap is 1eV.
2.) Stability: A material should have different parameters of stability fulfilled. One is photochemical stability which is obtained by using different types of stable monomer unit. Morphological stability can be increased by

selecting suitable side chains. A stable grid of polymer is formed. Thermal stability can be measured using thermal gravimetric analysis in which a weight of the polymer is plotted over a range of temperature. This is helphul to study the thermal stability. This can also be used to know the temperature at which a polymer degrades. The graph is shown in figure 7.

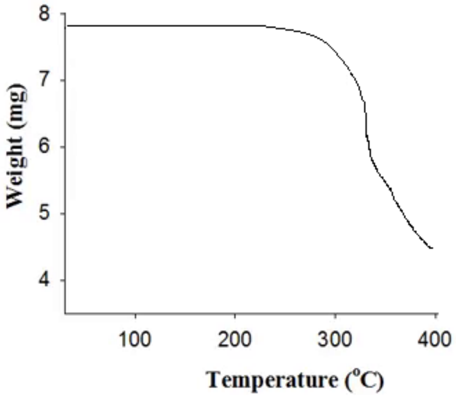

Figure 7: Weight vs. Temperature of Stability

3.) Process: Side chains ensure the solubility of polymer in common solvents, like chloroform or chlorobenzene. A side chain can be selected to make a polymer soluble in desired solvent. Processing should be carried out in large scale.

V. POLYMER SYNTHESIS

Polymer synthesis is carried out by polymerization. Three methods used to carry out polymerization are:

1.) Stille cross coupling
2.) Suzuki cross coupling
3.) Direct arylation

These are palladium catalysed polymerization.

In stille cross coupling polymerization halogen activated polymer is used as a monomer, it acts as an acceptor. An organic tin compound acts as a donor. [4]

In Suzuki cross coupling polymerization also, a halogen (usually bromine) activated monomer is used as an acceptor but a boronic ester activated monomer is used as a donor. A specific size of boronic ester chain can be selected. Direct arylation method developed recently, it does not require activation of monomer. Bromine activated monomer and non-activated monomer are coupled only by using hydrogen. It is more environment friendly method and it requires less time as no activation is to be done. [5]

Monomers are also selected in such a way that they are economical, the synthetic steps should be minimum and they should give high yield. The polymer once obtained should be purified, to do that Soxhlet purification is used. Through this the purified polymer fraction gets a narrow molecular weight distribution. It is carried out by placing a purifying solvent in a round-bottom flask and heat it under reflux. The evaporating solvent goes through the distillation path to the condenser where it drips into a thimble, which contains the polymer. The soluble parts of the polymer material will be dissolved. When the chamber for the thimble is full, the solvent flows back into the flask through a backward drain and the purifying cycle can start again. The soluble parts will be collected in the flask, whereas the polymer which is insoluble in this solvent will stay in the thimble. Generally purification by Soxhlet extraction is carried out in methanol and hexane to remove low molecular weight fractions. Afterwards, Soxhlet extraction is done in chloroform to dissolve the polymer which can then be precipitated in methanol, filtrated and dried.

VI. STABILITY AND DEGRADATION[6][7]

These types of solar cell decompose when exposed to oxygen and sunlight. Each layer of solar cell (Fig 2) degrades in different ways. Degradation mechanism are either physical or chemical. Physical degradation can be delamination, stress induced cracks, particle formation, quenching, interlayer mixing whereas chemical degradation can be O_2/H_20 induced oxidation components. There are different ways of dealing with types of degradation, some require choice of material and for some the cell needs to be protected. To protect cell from physical degradation, it should be ensured that the cells withstand bending during manufacture. The active layer should have a nanophase separation hetero junction to function properly. To prevent the chemical degradation the polymer should be chosen in such a way that the cell is not prone to oxygen or water. The reason behind the degradation that the water or oxygen diffuses between the layer. Electron transport layer is made up of ZnO which is reactive towards oxygen. Aluminium is used for electrode which is a very reactive metal. To improve the stability of polymer solar cells, steps have been taken in past years. One of the technology used is called encapsulation that can protect the material from environmental factors. Organic semiconductors are made resistant to oxidation by tuning of glass-transition temperature. Thermo-cleavable polymers are used to eliminate side chains. The reactive metal is capped with the less reactive metal to make the electrode less stable.

Stability is a function of time. The relation between stability and time of an organic solar cell is shown by decay curve. Decay curve is a characteristic graph between power conversion efficiency (PCE) and time. Electrical measurements of a solar cell is taken at regular intervals. All the degradation processes are summed up and the characteristic is obtained as shown in figure 8.

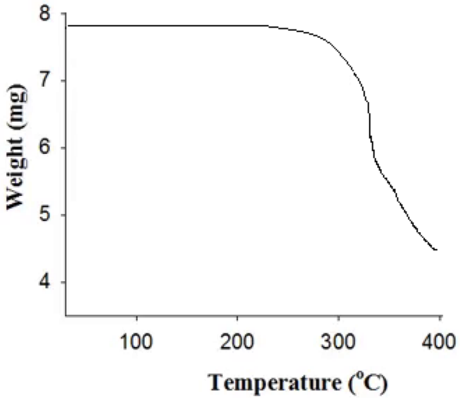

Figure 8: PCE vs. Degradation Time

Here, E_0 is initial efficiency which decreases overtime. The time it takes to reach at 80% of its value (E_{80}) is called T_{80}. It can be observed that there is rapid initial decrease in PCE followed by more stable phase.

VII. ELECTRICAL DEFECTS

Organic solar cells go under electrical defects, they can be in the form of particles or delamination in the layers of the device. These defects can be studied by using two methods:

1.) Light beam induces current (LBIC).
In this method a small spot of light is scanned over the solar cell while the current generated is measured. The helps understanding the defect. [8]
2.) Lock-in thermography (LIT)
When energy wave penetrates the object's surface, there is a phase shift observed. The wave is partially reflected when there is any irregularity in thermophysical properties. The phase shift can be used to examine the internal structure of the object.

VIII. MANUFACTURING

A. *Coating Techniques*

A solar cell can be coated using different techniques. They can be:

1.) Spin coating [9]: The liquid is dispensed on the cell which is kept on a platform that rotates. High rotational velocity is applied and the film thickness becomes uniform. This method provides well defined thickness but it is difficult to coat the cells on large scale using this technique.
2.) Spray coating [10]: The ink is supplied to pneumatic-based system where pressurized gas is used to break up the liquid into droplets at the nozzle as shown in figure 9. The waste produced is less even for large scale production.

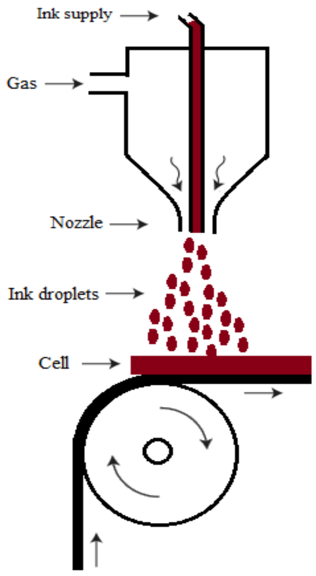

Figure 9: Basic Principle of Spray Coating

3.) Slot die coating: It is suitable for large area production. This process can be carried out even in high range of viscosity. The working principle is shown in the figure 10.

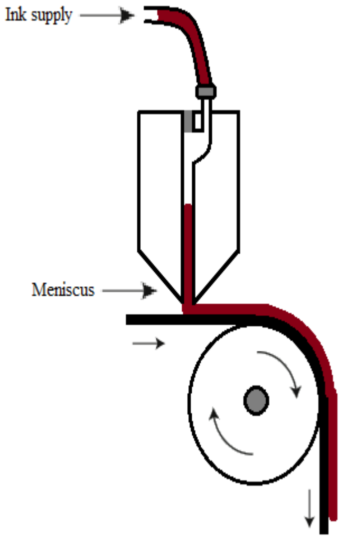

Figure 10: Basic Principle of Slot Die Coating

B. *Printing*

An organic solar cell can be printed using different techniques:

1.) Inkjet technique is not feasible as it requires to ink the solar cell which leads to thick layer of cell. A thin layer of cell (10-20 nanometres) is desirable.

2.) Other useful printing techniques with less number of limitations are:

3.) Flatbed screen printing: The process is illustrated in figure 11. The setup involves a mesh which is placed on the top of substrate. The squeegee moves and spreads the ink on the surface. The ink is evenly distributed.

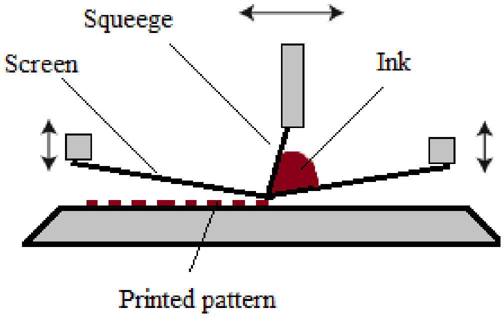

Figure 11: Basic Principle of Flatbed Screen Bending

4.) Rotary screen printing: Flatbed screen printing comes with a limitation which doesn't allow it to work while printing large number of cells continuously. Therefore, rotary screen printing is used. The squeegee is installed inside a cylindrical screen which is allowed to rotate and the process becomes faster and continuous. The mechanism of rotary screen printing is show in figure 12.[11]

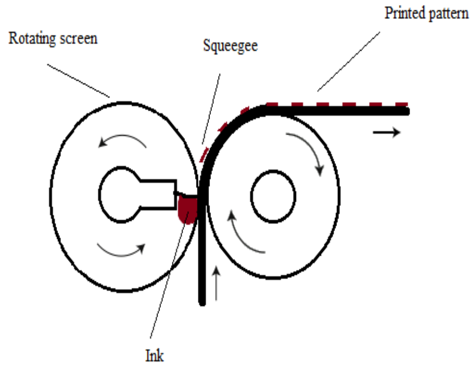

Figure 12: Basic Principle of Rotary Screen Printing

5.) Flexographic printing [12]: It is commonly used method since it is very fast and desirable for wide range of substrate. The principle is illustrated in figure 13.

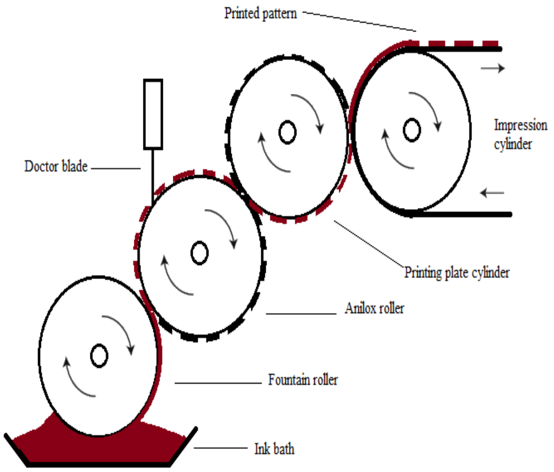

Figure 13: Basic Principle of Flexographic Printing

C. Lamination

To laminate a solar cell, two foils are taken and forced together using adhesive and a thin adhesive layer is obtained. There are different types of lamination methods that could be used:

1.) Pressure sensitive: In this method the glue is already prepared on the liner and glue is applied to other foil and pressed against the cell. The permeability of water and oxygen is high therefore, the quality of lamination is not ideal.

2.) Ultraviolet (UV) curable: In this method ink is cured by UV.

3.) Hot melt: In this method the glue is already applied in dry form which is then heated and melts. Then two foils are forced, the foil is cooled and the glue solidifies.

IX. CONCLUSION

It can be concluded that OPVs have low efficiency, but it is required to take a look into because we have limited fossil fuels.

There is a rapid decrease in stability initially. This decrease in stability is due to the exposure of cell to environment. Therefore, encapsulation of OPVs is required. By controlling the glass-transition of temperature of organic semiconductors, their life can be increased. [13]

The best way to coat OPVs when going large scale is slot die coating as the process can be carried out in high range of viscosity, the production speed is high. The coating liquid is distributed uniformly. This system is a closed system which gives better waste management.

The screen printing has so far been considered to be advantageous as the low cost mass production method of organic solar cells because of availability of formation of the accurate patterning in a large area. [11]

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