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Aluminium Alloys in Solar Power – Benefits and Limitations

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1. Introduction

It has been widely accepted that fossil fuels have played significance roles in human's daily life and industrial developments. However, fossil fuels are associated with some problems like air pollution. Moreover, fossil fuels have limited sources in the world that will be finished in near future if the consuming rate of fossil fuels does not decrease. So, scientists have been encouraged to find suitable sources of energy as replacements for fossil fuels.

Sunlight, wind, sea waves and hydrogen are examples of renewable sources of energy that have been subjects of researches for many years.

Among all of the mentioned renewable sources of energy, the sun is the most abundant and most renewable source that provides the energy for human much more than they need. If we can collect 0.01% of the sun's energy reaching the earth, it would be more than energy that all human use today.

Amount of the energy that reaches from the sun to a specific location on the surface of the earth can be 1000 W/m^2 [1]. Solar energy has had been received great world wide attention during the last decades as the most ideal renewable source of energy, which is mainly due to the points that this energy is safe, clean, free and unlimited [2]. Basic of fusion reaction in the sun and solar energy production have been discussed in many monographs [3-6].

The sun sends out huge quantity of electromagnetic radiations to the earth, which transfer approximately 4000 trillion kWh of energy to the earth surface each day [7]. This amount of energy is much higher than human's demand and also more than any other source of energy on the earth like nuclear power or fossil fuel burning. Solar energy is associated with

some economic and environmental advantages, and has been considered as replacement source of energy for traditional sources of energy [8].

History of employing solar energy goes back to 212 BC, when Archimedes. The Greek scientist used metallic mirror to burn a Roman fleet [9]. Cooking food, heating water and home, and drying grains were the first applications of the sun's energy [10-12]. In 18th century, solar furnaces were constructed by glass lenses, mirrors and polished iron, which were capable to melt metals like iron and copper. During 19th century, solar energy was used to operate steam engine and convert solar to electrical energy [13].

Nowadays, solar energy are used in wide range of industrial, business and residential applications such as electricity generation, water heating, industrial processes, daylighting, heating and cooling [1]. As a consequence of rapid development of the solar power technologies, it is expected that solar systems will provide 12% to 25% of global electricity by 2050 [8].

Growing demand for heat and electricity generation in developed and developing countries causes rapid development in solar power generation systems. Quality and physical properties of materials that are used in solar systems determine the efficiency of each solar system. Different materials are used in various kinds of solar power systems such as glass, silver, steel, stainless steel and aluminium.

Among all of the mentioned materials, aluminium has special properties that make it an interesting material for many solar power companies. Light weight, high strength, proper corrosion properties, high surface reflectivity, excellent electrical and thermal conductivities, as well as special optic properties of its anodic coating are such as interesting properties of aluminium that make it inseparable part of solar power systems.

To sum up, aluminium plays an important role in various kinds of solar power systems include concentrating solar power (CSP), photovoltaic solar power (PV) and solar thermal collections. The application of aluminium and its alloys in these solar systems are explained in this chapter. Besides, its economical effect and future market are explored here.

2. Aluminium applications in solar power systems

In order to find the role of aluminium and its alloys in solar power systems, it is necessary to review different types of solar power plants, their properties, requirements and applications. Generally, solar power systems are divided into three widely used categories, which called concentrating solar power (CSP), solar thermal absorbers and photovoltaic solar cells (PV). Aluminium alloys have become a significant and inseparable part of each of the mentioned group of solar power systems, mainly due to special properties of aluminium and its alloys. Properties and applications of each kind of the mentioned solar power systems as well as the role of aluminium alloys in each of them will be discussed separately.

2.1. Concentrating solar power (CSP)

Concentrating solar power systems include reflector materials that concentrate heat energy of the sun to a point or line to generate steam in a boiler, drive steam turbine and produce electricity [14-36]. Generation electricity, however, is not the only application of the CSP systems. Concentrated solar energy is suitable source of energy that can be used in wide range of materials processing such as producing metallic foams [37], synthesis of nanomaterials like carbon nanotubes and ceramic nanoparticles [38], fast heating of ceramic materials close to thermal shock [39], breaking down metal oxides to its metal counterpart [40-42], surface treatment [38] and metal sintering [43].

Cost of energy generation by CSP is much lower than that of PV, which is mainly due to higher average efficiency of CSP (42% compared with 15% for PV) and requires smaller field to produce certain amount of energy [8,44]. The cost of energy generation by solar collection devices is also lower than thermal solar collecting systems[45].

CSP has facilitated a system for production of energy which is neither noisy nor toxic. Therefore, this system can be used in cities without any safety problem [2,44].

Based on the focus geometry and receiving technology, CSP has been divided into four types.

2.1.1. Parabolic trough

In this kind of CSP, a series of curved mirrors concentrate sunlight on to a tube that located in the trough's focal line. This tube contains oil and is used as heat transfer medium. Temperature of the oil in the tube can reach as high as 400°C [46]. Figure1 shows a real and a schematic of a parabolic trough CSP system. This system was used in 1912 in Egypt for the first time [8]. The parabolic trough system is able to concentrate sunlight by 70-100 times and transfer solar to electrical energy with efficiency of 15% [47].

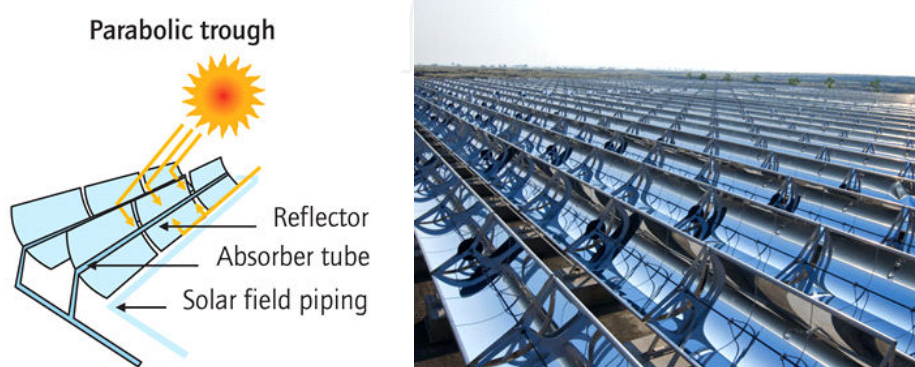


Figure 1. Parabolic trough concentrating solar power plant [47]

2.1.2. Solar tower

Solar tower plants use many reflectors called heliostats to collect sunlight reaching a field to a certain point on top of a tower, where a collector is located (Figure 2). The concentrated energy can generate electric energy with efficiency of 20-35% [8,46].

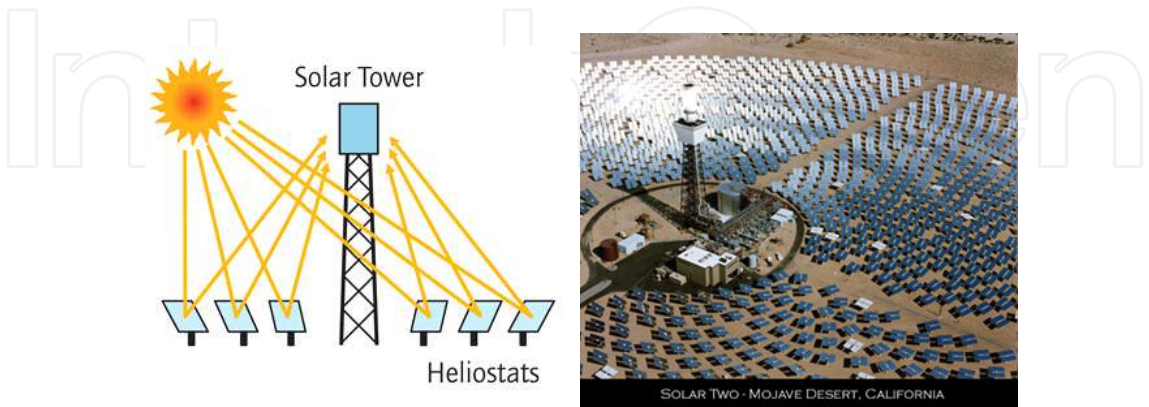


Figure 2. Solar tower concentrating solar power plant [47].

2.1.3. Parabolic dish

Parabolic dish concentrating solar system uses a reflector dish and concentrate sunlight onto its focal point. Figure 3 shows the schematic of this solar system. A receiver that located in the focal point of the dish can increase the temperature of the gas or fluid up to 750°C in a sunny day. Capacities of parabolic dish plants and their efficiency in changing solar to electrical energy are in the range of 0.01-0.4 MW and 25-30%, respectively. Due to its design, its optical efficiency is significantly higher than two other mentioned categories of CSP plants. Parabolic dishes are currently used in some simple application like cooking oven [8,13,46].

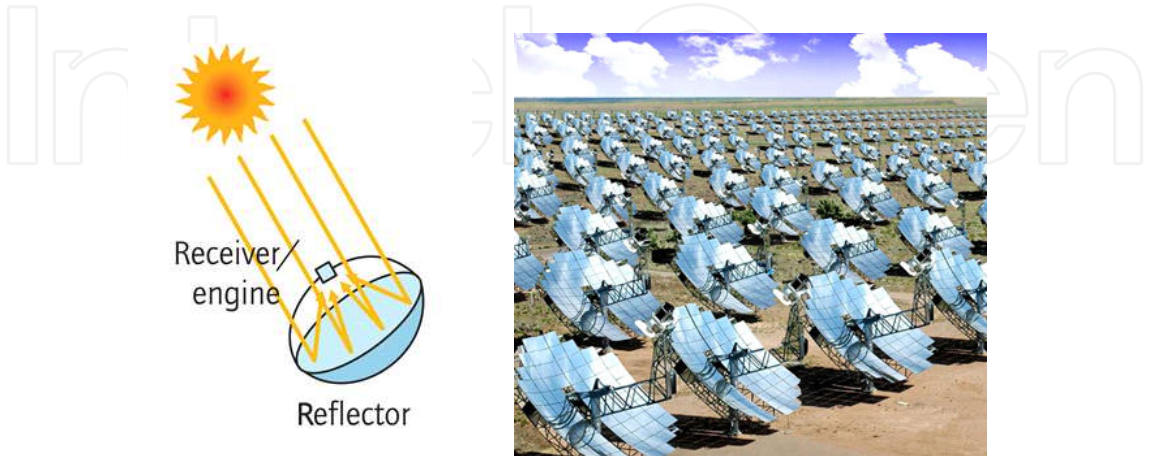


Figure 3. Parabolic dish concentrating solar power plant [47].

2.1.4. Linear fresnel

Linear Fresnel is a line-focus collector that consists of series of Fresnel lens behaving mirrors (Figure 4). Capacity of this solar concentrator is 10-200Mw and its efficiency to generate electric energy is between 8 and 10% [8].

Table 1 compares various properties of the mentioned CSP plants.

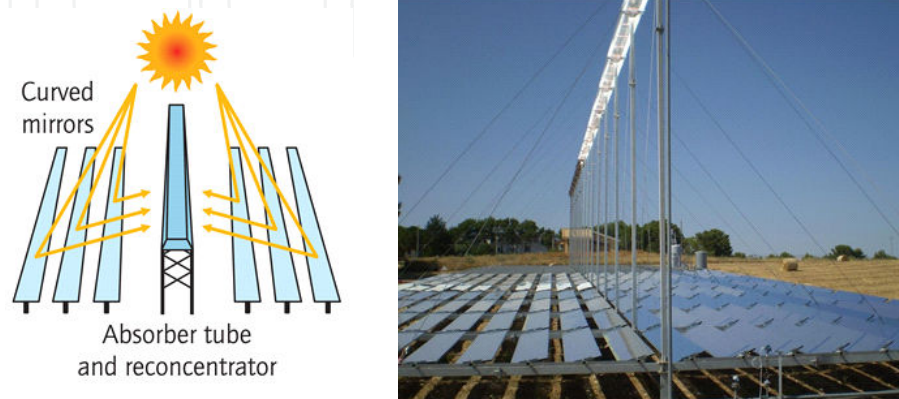


Figure 4. Linear Fresnel concentrating solar power plant [47].

	Capacity (MW)	Concentration	Annual solar to electric conversion efficiency	Cost (Dollars /ft ² field)
Parabolic trough	10-200	70-80	15%	40
Solar tower	10-200	300-1000	20-35%	45
Parabolic dish	0.01-0.4	1000-3000	25-30%	
Linear Fresnel	10-200	25-100	8-10%	20

Table 1. Properties of CSP technologies [8,46,47]

Currently, capacity of installed concentrated solar power plants is 516MW in the world. 90.2% of this capacity belongs to parabolic trough systems, followed by 8.5% for solar tower, 0.8% for Fresnel trough systems and 0.24% for solar dishes [48].

Reflectors of concentrated solar power should have some properties, such as high reflectance ratio and low absorption, good wetability and low cost. Aluminium and silver are the most common reflectors for CSP systems due to their high reflecting efficiency in solar wavelength range [45].

Reflectors of concentrated solar power should have some properties, such as high reflectance ratio and low absorption, good wetability and low cost. Aluminium and silver are the most common reflectors for CSP systems because of their high reflecting efficiency in solar wavelength range [45].

Aluminium has some special properties that make it a useful mirror in various applications of solar cells, lasers and astronomer's instruments [2].

For example, aluminium can be deformed easily to have the best shape of reflectors and achieve the highest concentrating efficiency. Unlike glass mirrors, aluminium reflectors can not be broken easily, which is a favourite property for outdoor applications [49].

Aluminium mirrors not only have better surface reflectivity than glass mirrors, they are much lighter. Compared to glass mirrors that have average weight of 11kg/m^2 , aluminium reflectors have only weight of 7 kg/m^2 .

Due to mechanical properties of aluminium and its low cost compared with silvered glass mirrors, aluminized reflectors found applicability to high temperature solar concentrating technologies [50].

Rolled aluminium also can be suitable for certain solar energy applications since it is cheaper than other reflector materials and can be cost-effective material in this application [45].

Thermal evaporation is one of the most practical methods to prepare aluminium reflector in order to use in concentrated solar power systems [2].

Ling et al. [2] studied performances of aluminium reflectors produced by thermal evaporation method on different substrates include galvanized iron, acrylonitrile butadiene styrene (ABS) and aluminium alloy. Experimental results clarified that reflection of thermally evaporated aluminium on ABS is comparable with that of silver mirror of ultra-white glass. It was also found that smoothness and roughness of the substrate have important effects on optical properties of the aluminium reflectors.

2.2. Solar thermal collectors

Solar thermal collector is a kind of solar power system that transforms solar energy from the sun rays into thermal energy. This solar system is widely used for generation of hot water, home heating and electricity generation [1,48].

Based on the kind of used collectors, solar thermal collecting systems divided into three types [1,13,48]:

2.2.1. Unglazed plastic collectors

This technology of solar thermal collectors provides a low cost heat and is used only for public bath heating and hay drying. Aluminium and its alloys have approximately no special application in unglazed plastic collectors.

2.2.2. Flat-plate collectors

Lower radiation and convection heat transfer losses in this solar thermal collectors compared to unglazed plastic collectors enables it to warm up to higher temperature. This system is widely used for space heating and hot water generation.

2.2.3. Evacuated tube collectors

Due to special design of this kind of solar thermal collectors, its conductive and convective losses are very low. So, it is capable to warm up the heat carry fluid up to 150°C.

According to figures recently released in Solar Heat World-wide report, the amount of energy that was generated by solar thermal collectors in the world in 2007 was approximately 147 GW. Fabrication of this amount of energy by solar thermal collectors requires approximately 210 square kilometres. Solar heating capacity of these solar systems had increased by 15% in the year of 2008, and became double compared to 2004. Capacity of solar thermal collectors does not equally divided among the mentioned solar thermal categories. According to published figures, approximately 50% of total amount of energy resulted from solar thermal collectors has been generated Evacuated tube collectors. Contributing proportions of Flat plate and Unglazed plastic collectors are 33% and 17%, respectively.

As mentioned before, Unglazed plastic collectors do not provide significant opportunity for aluminium usage. However, both of the other groups use aluminium and its alloys in different parts.

Figure 5 shows a Flat-plate collector and introduces its various parts; casing, absorber and frame. Aluminium, copper and steel are the materials that are used for absorbers. Casing and frames are usually made of aluminium and steel. However, aluminium is predominantly used because of lower weight of this alloy in that that of steel. Moreover, using aluminium as absorbers is growing. Special optic properties of anodic layer of aluminium and some aluminium alloys make aluminium a useful material for solar absorption. These qualities will be explained later. Today, approximately 35% of the solar absorbers are made of aluminium [1,13,48].

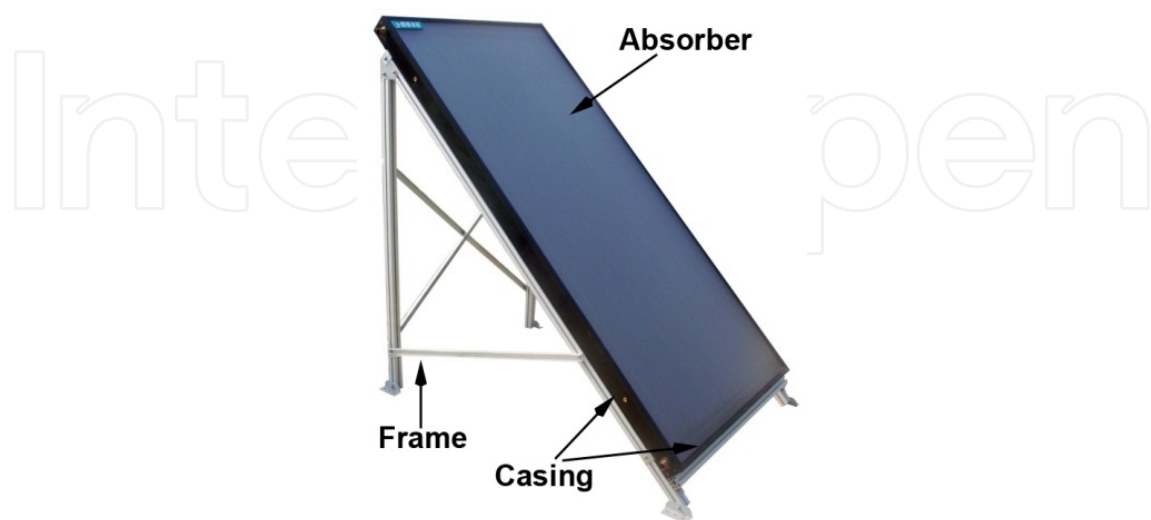


Figure 5. Different parts of a Flat-plate collector

Figure 6 shows main components of Evacuated tube solar thermal collectors, which are absorber, frame, heat pipes, header pipe and casing. Like what was mentioned for flat-plate collectors, using aluminium as absorber is growing. Low density of aluminium satisfies solar companies to use aluminium alloys for frames instead of stainless steel. Aluminium is also widely used in casing and header pipes [1,13,48].

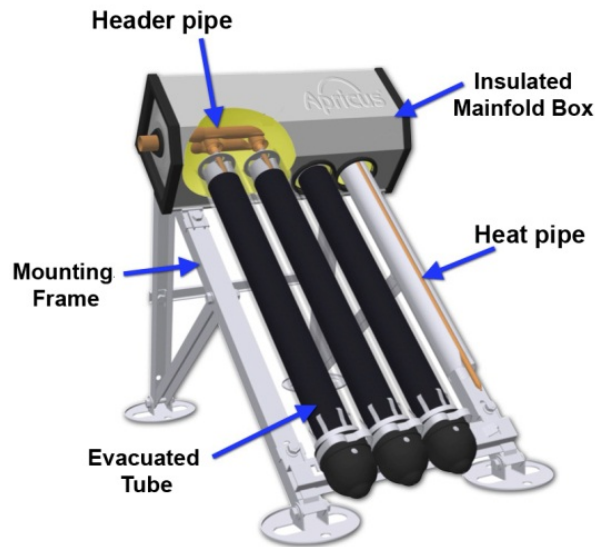


Figure 6. Different parts of a Evacuated tube solar thermal collectors

As mentioned before, aluminium is one of the most important materials utilized in solar absorbing, which is mainly due to special structure of the anodic layer that can fabricated on aluminium surface by anodizing process. This anodic layer is porous; with various pore sizes depend on the kind of anodizing electrolyte and anodizing process conditions [51-56].

It has been shown that these pores can be filled with metals by electrodeposition to have a coloured surface layer composed of metal particles in alumina dielectric matrix [57,57,58]. Using some special metal particles or ions, like nickel, provides suitable optical properties in anodized layer of aluminium for solar absorption application [57,59]. It was found that surface reflection of coloured aluminium anodized layer, as an undesirable property of solar absorbers, is a function of colouring time. It also was shown that reflectance decreases with electrolytic coloration time [57].

The effect of coloring time on solar absorption of aluminium anodized layer is more obvious in thicker anodic layers [53].

The proposed model of coloured and sealed anodized aluminium layer is shown in Figure 7. This model shows that the aluminium anodic layer composed of three parts, which have different properties. The top region (part 1) is protective layer that composes of Al_2O_3 and aluminium hydroxide; the middle region (part 2) is optical absorption layer that filled with metallic pigments; and the lowest region (part 3) is barrier layer that is a compact layer and has the highest density among all of the mentioned parts [57].

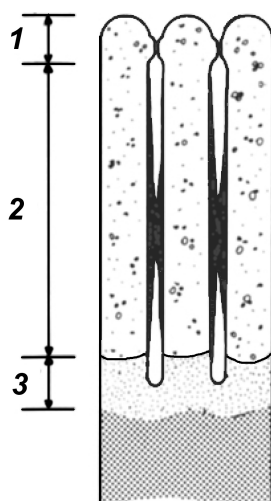


Figure 7. Proposed model of coloured and sealed anodized aluminium layer [57].

Absorption mechanism of solar radiation in colored anodic aluminium layer has been described by Granqvist [58].

For a photothermal conversion, the highest efficiency will be provided when the thermal losses by surface radiation are low enough, and solar absorption is high.

Microstructure of an alloy plays an important role on its efficiency as an absorber. As shown by Cody and Stephens [60], surfaces that its dielectric constant change gradually from the material/air interface to that of solid materials have low reflections.

Eutectic binary aluminium alloys such as Al-6wt.% Ni, Al-33wt.% Cu and Al-7.5wt% Ca have such microstructure and have acceptable optic properties to be used as absorber; i.e. low reflection high absorption [61,62].

Mechanical and thermal stability of the mentioned aluminium alloys, as well as possibility of regeneration of their surface by retching make them useful materials in this application [61].

2.3. Photovoltaic solar system

Photovoltaic cells directly convert solar to electrical energy using semiconductor materials. Semiconductors can generate free electrons using energy of sunlight [63]. Photovoltaic property of materials had been discovered by Becquerel in 1830, when he found this effect in Selenium [13]. Various aspects of photovoltaic solar systems have been reported in different books and references [64-72].

Space was the first application of photovoltaic solar cells because sun is the only source of energy in space [13]. Photovoltaic solar cells have been used in wide range of applications include water pumping, solar home systems, remote building, solar cars and airplanes, satellites and space vehicles. Such a vast variety of applications is the main cause for increasing demand for photovoltaic solar cells [63].

Photovoltaic solar power system has experienced great development rate. The capacity of this solar system had increased from 0.1 GW in 1992 to 2.8 GW in 2007 and 5.95 GW in 2008. Table 2 compares the market demand of PV in some countries in 2007 and 2008 [1].

Countries	USA	Japan	Germany	Spain	Rest of Europe
Demand in 2007 (MW)	226	226	1328	650	170
Demand in 2007 (MW)	360	230	1860	2460	310

Table 2. Photovoltaic solar system market in different regions of the world [1]

Various advantages of photovoltaic solar systems make it a favourite technology in many industries. It has been observed that PV is one of the fastest growing industries in the world. This rapid growth requires new developments with respect of applicable structural materials [73].

Construction and structure of photovoltaic solar systems are the main part of this system that can be made of aluminium. Steel and aluminium are the most common materials that are used in construction of solar power systems.

However, the advantages of aluminium alloys over steel, other aluminium alloys and composite materials make it the core material in building of large scale solar generation fields. Significant proportion of the cost of solar generation system is related to supporting materials and frames. For instance, approximately 25-30% of the budget of CSP plants should be allocated to frames and support materials.

Some of the aluminium alloys can perform same as steel, but its weight is one-third of steel. Although aluminium alloys are more expensive than steel, using aluminium instead of steel can be economical. Lower density of aluminium gives the opportunity of easier, faster and cheaper transportation. Moreover, construction of a solar field would be faster if extruded aluminium is used instead of steel because it does not need crane and permanent joining process like welding. These properties of aluminium enable engineers to design and produce complex, efficient and stable structures.

6061 aluminium alloy that contains magnesium and silicon alloying elements is an example of useful aluminium alloys for structure of solar plants. This aluminium alloy is widely used in solar fields because of its high strength and machinability[74].

Another advantage of aluminium over steel is its higher corrosion resistance in outdoor environments, even if steel is galvanized. Even though aluminium is more chemically and electrochemically active than steel, a thin oxide layer that naturally formed on the aluminium surface in the air provides suitable protection for aluminium and enables it to have good performance for a long time. To illustration, consider the aluminium cap used in Washington monument was corroded only 0.13 mm after 73 years performance. The mentioned ox-

ide layer is stable in pH range between 4.5 and 8.5. So, it may not provide enough protection if the aluminium is located in soil. However, most of solar collectors are mounted on concrete pads, which make the aluminium performance independent of soil conditions [74].

Since using solar power for electricity generation has become a serious competition among various companies, designing and using the most possible available, effective and efficient materials became very important. Extruded aluminium can be considered as one of these effective materials as it enables companies to create next generations of solar power plants with long life time and very low negative environmental effects.

PV inverter, which changes direct current to alternative current, and panel frame are the other components of a photovoltaic solar system that can be made of aluminium

Approximately 72% of aluminium input in photovoltaic solar systems is used in construction, while the proportion of aluminium used in panel frames and inverters are 22% and 6%, respectively [48].

2.4. Perspective of aluminium applications in solar power systems

Currently, CSP systems use approximately 55000 kilograms of aluminium per one megawatt generated energy, while used aluminium for photovoltaic cells is 45000 kg/MW.

CSP provides over 1000 MW of worldwide electricity, which looks to reach to 15000 MW in near future regarding to new solar projects in US, Spain, China, Morocco and India. Building these solar fields with the mentioned total capacity by aluminium frames requires 1080 million pounds of extruded aluminium [75].

If it can be assumed that the proportion of extruded aluminium that is used in construction of CSP plants remains 34%, the amount of the required aluminium for CSP plants will be approximately 635,000 tons in the next 20years [75].

Today, the amount of energy that is generated by CSP plants is approximately 0.5GW. Predictions reveal that capacity of solar collecting power plants will be 30GW in 2020, 140GW in 2030, and 800GW in 2050, which show a very rapid growth.

Based on these predictions and estimation of average use of aluminium, total amount of used aluminium in CSP plants will be 1.1 and 8 million tons in 2020 and 2030. The average amount of aluminium used in CSP plants in 2050 will be 51 million tons, which has the potential to be double. As a result, approximately 0.3% and 1.9% of annual aluminium production will be used in CSP plants in the decades of 2010-2020 and 2020-2030, respectively. This proportion will be 5.7% in average for the period of 2031-2050 [48].

Today, extruded aluminium used in photovoltaic solar plants is approximately 12% of total amount of aluminium that are used in this kind of solar power plants. If, like what mentioned in future market of CSP plants, it is assumed that this proportion remain constant in future, approximately 1,500,000 tons extruded aluminium will be used for these systems in the next two decades [75].

As mentioned before, these calculations are based on the assumption that the proportion of used aluminium in solar systems will not increase. Considering the growth of aluminium usage in solar systems during the last years, however, clarifies that the solar industries prefer to use extruded aluminium instead of steel frames. Consequently, demands for aluminium related to steel will increase in the course of time.

According to the report of International Energy Agency published in 2010 [47], about 14GW energy are produced by photovoltaic solar system in the world. It also is predicted that the average capacity of this solar system will be 87GW in 2020, 225GW in 2025 and 597GW in 2050. Based on this prediction, total amount of aluminium used in photovoltaic solar system will be 3, 7 and 19 million tons in 2020, 2030 and 2050, respectively. Consequently, 0.64% of total annual aluminium production will be used in PV systems in decade 2010-2020, which will reach to 1.21% in decade 2020-2030 and 1.63% in period of 2030-2050.

Temperature is another important factor in efficiency of the photovoltaic solar systems. Researches have revealed that increasing temperature reduces the efficiency of PV solar cells. So, it is important to set a cooling system for PV cells, which provide an excellent opportunity for aluminium to extend its role in solar cells in near future [75].

Another advantage of aluminium over other kinds of materials that encourages many companies in different fields, especially in solar power systems, to use this metal and its alloys is successful and cheap recycling process for aluminium.

Recycling is an important industrial process that can reduce energy usage, air and water pollution and save money. So, recycling should be considered in any kinds of materials that will be employed in industrial or home applications. Recycling is not successful for all materials. Recycling of plastics, for example, is very problematic, but glass can successfully be recycled. Aluminium is the most successful material in recycling. Its recycling is much cost saving process as producing aluminium goods from recycled aluminium cost less than 10% of producing from bauxite ore. Low melting point is the main cause for cost-saving property of aluminium recycling [49]

2.5. Photovoltaic modules and corrosion

The performance of solar fields and their power sale revenue are directly dependent on the reflectivity (for solar thermal) and solar panel absorptivity (for solar PV). Unfortunately the mirrors and panels are subjected to exposure to dust moisture and aerosols resulting in a significant drop in system efficiency [76].

Field data has shown that without any external cleaning, reflectivity dropped off with time at a rate of 0.45 percentage points per day and a loss of 16 percentage points in a month (figure 8). Currently the mirrors are cleaned using demineralized water by high pressure spray, deluge type cleaning methods, and fixing of piping spray systems. These methods, however, require demineralized water in the order of 0.23gallons/m² of the area [77].

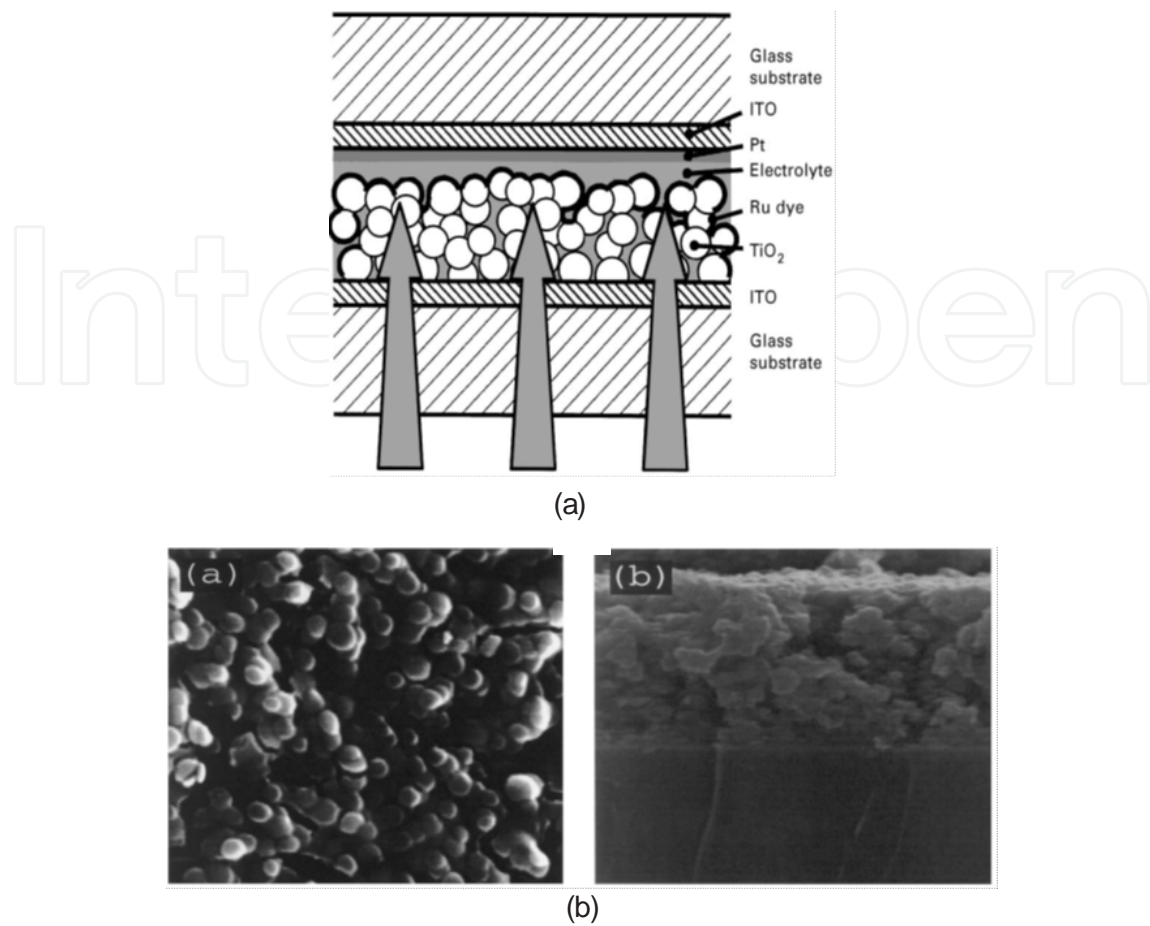


Figure 8. a): Schematic sample setup of the photoelectrochemical cells using nanocrystalline TiO_2 . The arrows indicate the direction of incident light [79]. (b): SEM micrographs of a sol-gel TiO_2 layer with a thickness of $5\ \mu\text{m}$ on an ITO glass substrate. (a) surface (magnification 15000). (b) cross section (magnification 9000) [79].

Due to high accumulation rate of dust large quantities of water are require. The washes unfortunately recovered only 1-3% of the loss in reflectivity. Photovoltaic systems use semiconductor technology in dust and moisture laden region such as the east coast of Saudi Arabia. There is insufficient experience in dust laden and moisture laden region and the problem is very serious. It has been stated that the accumulation of dust on a PV panel causes a loss of 0.5% in PV efficiency. Currently commercially available films have a barrier property of water vapor transmission rate of 10^{-3}g/m^2 per day or one thousand gram square meter per day at 90%. The barrier oxide film therefore develops cracks and pinholes. The life of PV cell is drastically reduced in desert with expended span of humidity and suspended particles (SO_2 , NO_x , Cl) [78].

The harsh environment has put a serious demand for fabrication of moisture resistant, corrosion resistant, water and dust repellent surface to prevent PV cells and module. This problem needs three approaches,

- a. A dry approach
- b. A wet approach

2.5.1. The dry approach

This approach is based on surface modification without using water. In certain cases the surface chemistry may be modified by applying low pressure compressed air and installing the system against the direction of winds, and creating conditions which do not allow the dust particles to settle down. Nanostructured surface could be created with ultra-fine grain size which may provide self-cleaning.

2.5.2. The Wet approach

The wet approach would depend on fabricating hydrophobic films. One good example is provided by Titanium dioxide films for photovoltaic cells derived from a sol-gel process.[79]

Figure 8 describes the set-up of photo electrochemical cells using nano crystalline TiO_2 . A sol-gel process is used for spin coating. After being sensitized with a type the films are for transport of electrons in the photo electrochemical cells.

The particles having a size of $\sim 100\text{nm}$. In this process the heating process and application of TiO_2 coating by spin coating technique needs to be controlled to produce high efficiency. The demand to produce dust and water repellent coatings is increasing because of its application in MEMS/NEMS and photovoltaic cells. However a considerable progress has been made in producing hydrophobic and dust repellent coating. The best symbol of hydrophobicity is lotus leaf which exhibits water repellent and self-cleaning characteristic. A detail study of lotus leave shows two levels of structures a nano like hair structures with wax covering the surface and micro scale mounds protruding from the surface figure 9 [80].

Attempts have been made to fabricate nano coatings with inherent self-cleaning properties. The lotus coating is microscopically thin and optically transparent. The coating sheds dust particles utilizing anti- contamination and self-cleaning properties. It is designed to preserve optimum long time performance. The coating can be applied to metal glass surface and epoxy composite substrates. In a desert there may be no rain, however, this technology needs to be complemented by dust management technologies which include, electro dynamic dust shields, thermal control systems and surface power systems. Tribo electric charging has been conducted under Mars surface conditions. The charging showed that large amounts of dust could be accumulated [81].

The super hydrophobicity or wettability is characterized by contact angle formed a liquid droplet and solid surface. A surface is consider hydrophobic if the water contact angle (WCA) is greater than 90° and super hydrophobic if the WCA is between 150° and 180° . The contact angle hysteresis is the difference between the advancing angle (ϕ_{adv}) receding (ϕ_{rec}) contact angles. Roughening a surface enhances its water repellent property. The effect of surface roughness has been described by different theories [82].

$$\cos\phi_w = \gamma \cos\phi_y$$

Where ϕ_w and ϕ_y are contact angle on the rough and smooth surface and γ is the roughness factor define as the ratio of solid-liquid area A_{SL} to the projection on a flat plane A_f .

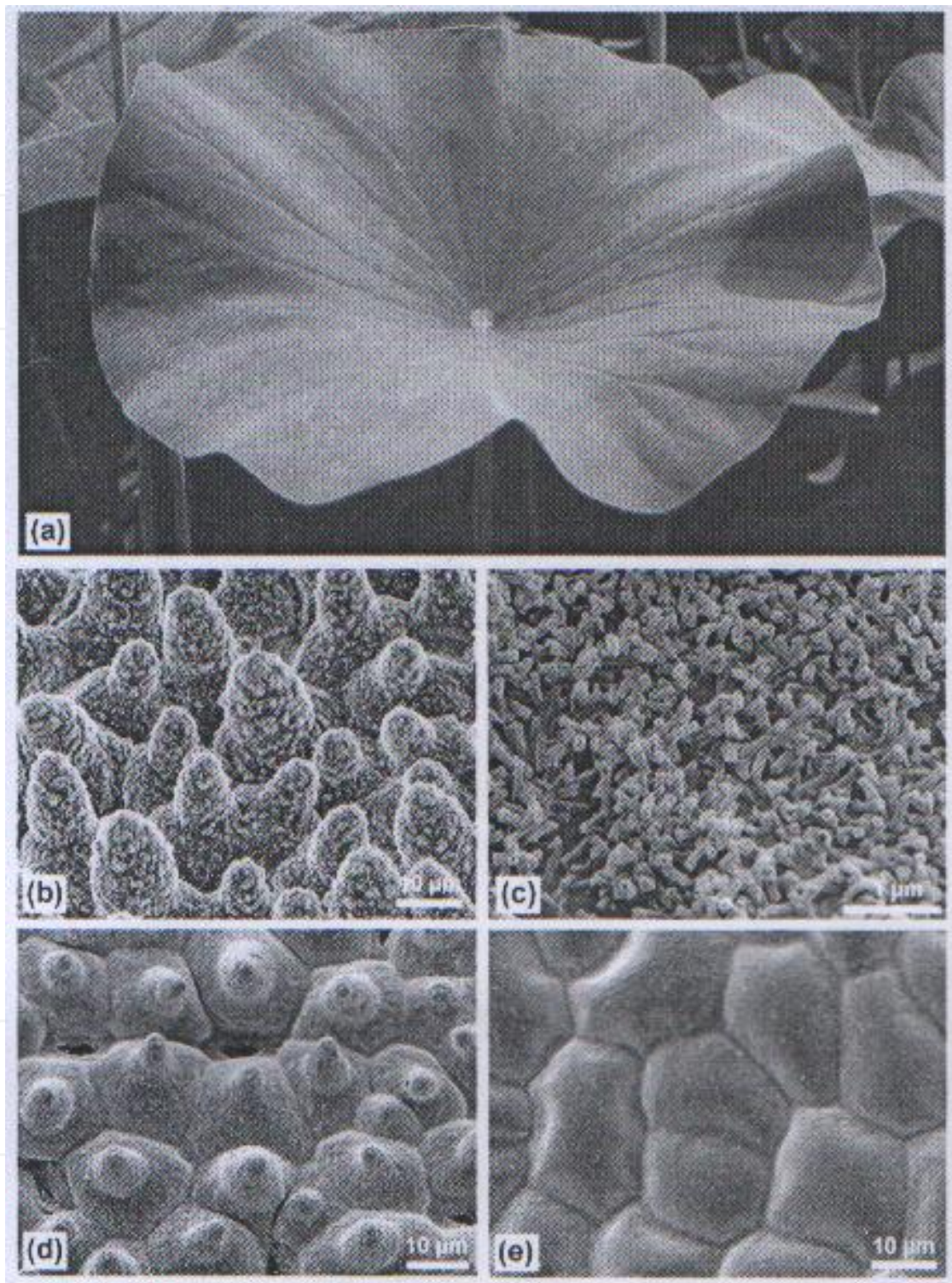


Figure 9. a) Lotus leaves, which exhibit extraordinary water repellency on their upper side. (b) Scanning electron microscopy (SEM) image of the upper leaf side prepared by glycerol substitution shows the hierarchical surface structure consisting of papillae, wax clusters and wax tubules. (c) Wax tubules on the upper leaf side. (d) Upper leaf side after critical point (CP) drying. The wax tubules are dissolved, thus the stomata are more visible. Tilt angle 15°. (e) Leaf underside (CP dried) shows convex cells without stomata [80].

$$\gamma = \frac{A_{SL}}{A_f}$$

According to Wenzel, the space between protrusions is filled by liquid. Cassie and Baxter model [83] assumed that air trapped by asperities of hills on the surface and a composite interface is formed. The composite interface may form air pockets trapped in the cavity. The relationship between apparent contact angles C_β and ideal contact angle is given by

$$\cos C_\beta = r_f f \cos \phi_f + (f - 1)$$

Where r_f indicates roughness factor of the wetted area and f is the area fraction of the projected wet area. The product r_f is called solid fraction of limit f reached to zero the macroscopic contact angle C_β approaches to 180° leading to a super hydrophobic behavior. If ϕ_r is high, the drop would be in a Cassie and Baxter and low it would be Wenzel region. Both regions are shown in figure 10 [84].

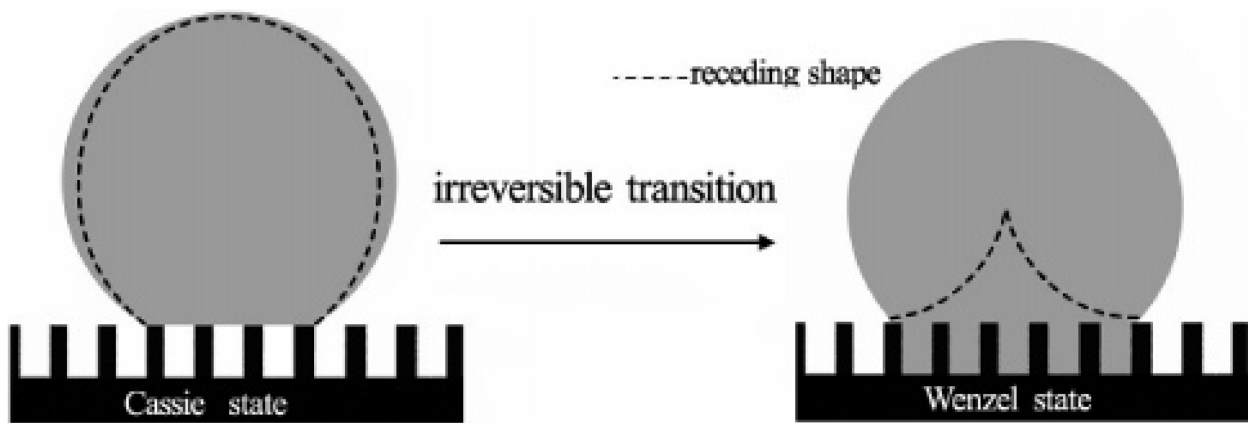


Figure 10. Irreversible Transition from the Cassie State to the Wenzel State by the Wicking Test [84].

Two methods are in used for fabrication of super hydrophobic surface; a) making a surface with low energy materials or making a rough surface and coating with low surface materials like tetrafluoroethylene (TEFLON) or polydimethylsiloxanes (PDMS).

Modifications of a surface with low energy compounds the process such as plasma etching [85] laser etching [86] chemical etching [87] lithography [88] and sol get techniques have been used to produce super hydrophobic surfaces.

Wet coating techniques have been used with success to obtain super hydrophobic surfaces base the critical factor is the preparation of an optimal rough surfaces. Processes such as sand blasting and annealing have been used to obtain a rough surface with grain size in nano dimension [88].

In a study on making a super hydro surface on aluminum samples were mechanically polished to obtain a rough surface in the range of 0.05 to 1.5 μ m. The surface was modified by treating polydimethyl siloxane vinylterminated (PDMSVT) with 1 weight % Curing agent as cross linked perfluoroethylene (PFPE).

PFPE film was applied by spin coating (3000 rpm). Curing was done for C_9F_{20} at 80°C and PDMSVT and PFPE at 120°. Sol gel process titanium coating have been produced and they are extensively reported in literature. Optically transparent super hydrophobic silica based films have been formed by control of hydrolysis and condensation reaction.

In a work under taken [89] three types of originally modified silica gels have prepared as shown in the Table 3.

Sols	Composition	Catalyst	pH	surface bonds after etching
A	TEOS,MPS	HCL	2	Si-O, Si-OH
B	TEOS,MPS	HCL	6	Si-O, Si-OH
C	TEOS	NH ₄ OH	10	Si-O ₂ , Si-OH

Table 3. Types of Modified Silica Gel

After mixing, the surface chemistry was modified with self assembles monolayers using chlorotrimethylsilane (CTMS) (CH₃) (SiCl) and tetra fluorotetrahydroxydimethylchloro silane, hydro phobicity followed the order C, B and A.

Substrate of soda lime glass coated with a thin layer of tin oxide was doped with fluorine (SnO₂:T). The transparent conductive oxide (TCO) form, the contact for the solar cell layers deposited on tin oxide. An ethylene vinyl acetate provides both electrical isolation between solar cells and binds the glass back sheet to the module. An extruded aluminum sheet provides structured mounting points and grounding points. Damp heat tests were applied to the modules [90]. A voltage of +600V was applied to the output of one modules and -600V to the other module. The modules work placed in an environmental chamber. Module biased at -600V (amorphous silicon) visible damage occurred. Modules subjected in positive bias showed no or little damaged. The dependence of corrosion damage to polarity suggests the reaction of Na⁺ of the glass with fluorine. Humidity acts as an electrolyte for corrosion to take place. Virtually no damage was observed under positive biased polarity. the positive biase only reacts with contaminants outside the glass surface and does not need the mobility of ion.

on subjecting the modules to -600v and 85% RH at 85,72 and 60 °C/ leakage current were observed (fig 11). It was shown that water vapor enhance the leakage of current [89].

Electrochemical corrosion is the result of transport of metal ions between the cell and module frame. under the influence of large cell frame voltage(100-500-V) cell frame voltage present in applications with high system voltages above or below the ground potential [90].The problem is being solved with microencapsulation with low conductivity and control of ionic conductivity of encapsulated free surface and interface. The leakage current is highly dependent on ionic conductivity and moisture level. The transport of ionic elements is associated with corrosion of internal cell material by leakage of current from the cell string to the module exterior. Both processes electro migration and ionic migration need to be controlled [91].

Numerous experiments have been conducted on module, fabricated on the oxide coated glass and operated at voltages and elevated temperatures in a humid climate. The phenomena of electrochemical corrosion appeared to be in all cases related to humidity. Experiments conducted BP Solar a-Si/a-SiGe tandem module fabricated on tin-oxide coated glass and encapsulated with another sheet of glass with EVA, showed that sodium reacted with water to form sodium hydroxide and hydrogen and highly alkaline solution $\text{PH} > 9$ such that sodium hydroxide will dissolve Silicate glass rapidly at temperature ($\geq 100^\circ\text{C}$).

In addition, the generation of hydrogen bonds near the interface may lead to a weakening of interfacial bonds because of reduction of tin-oxide. The relative durability of Zinc Oxide appeared to be due to the fact that Zinc oxide is not reduced [92].

A common observation in all investigations shows that corrosion can be minimized by use of low alkali or high resistivity glass, by increasing the adhesion of the transparent conducting oxide to the glass surface or using zinc oxide rather than tin-oxide as a transparent conductive contact. The use of anti-reflection coated (ARC) glass is being used in an increasing percentage of PV modules due to expected high power energy output. The use of ARC glass declined because of the inability of the coating to maintain performance over long period of time. Recent progress made has given some confidence to the consumers to use it again. Several defect such as coating degradation, soiling and optical degradation have been observed. Recent progress in ARC glasses has been shown by ARC glass is developed by the sun power. It has been shown that a well-designed ARC coating protected the glass from humidity and sand blasting, whereas the uncoated glass showed chippings. More than three years of field data showed that the energy gain from ARC significantly exceeded by 3.5 to 5% over uncoated glass which is the consequence of the improved coating gains in diffuse and off angle lights, due to effect of refractive index and light scattering within the coating. The sun power modules are slowly emerging in the market.

Metal electro migration is a big concern in electronic industry along with corrosion, module and discoloration. The metal migration reduces the service life of module. SAFlex PS-41 is the first module to be produced to suppress electro migration by exploring the activity of embedded encapsulation which prevents electro migration when in contact with metals such as silver, copper and nickel. The first encapsulant Saflex PS41 is specifically designed to protect against metal diffusion from solar cell stacks, adhesive and bus ribbons [93].

Whereas enough evidence has been shown how the adverse effects of humidity vapor pressure and current leakages on the glass substrate the back sheet materials in ARC also play a pivotal role. In recent year high moisture barrier and high resistivity coatings on polyethylene terephthalate (PET) have been fabricated for application in PV module back sheet application. It is necessary for the back sheet completely insulating to prevent a conduction path from the back contact to the grounded metal frame. To prevent the penetration of moisture and create low water vapor transmission rates WVTR, g/m^2 , d., cost effective coatings have been created on inexpensive polymers such as polyethylene terephthalate (PET) and biaxial oriented polypropylene (BOPP). Table 4 shows the thickness and transmission rates of various coatings applied PET [94].

Material	Thickness(mm)	WVTR(g/m ² d)
Tedlar/ Al/Tedlar C	0.1	
NREL coated PET	0.18	0.1-0.2
Tedlar / PET/ EVA (TPE)	0.2	3.0
PET	0.1	3.4
EVA	0.4-0.5	27-33

Table 4. WVTR for Polymer laminates at 37.8° and 85% Relative humidity

These back sheets can be used as a substitute for glass if they resist the ingress of moisture and transport of current. The treated polymer has a dramatic improvement over the untreated polymer. The peel strength for different back sheets is shown in Table 5.

Material	t=0	t=1week	t=2weeks
Uncoated PET	1-1.7	—	~ 0.8
NREL coated PET	7-8	7.10	6.5-6.8
TPE	—	—	~4.0

Table 5. Peeling Strengths

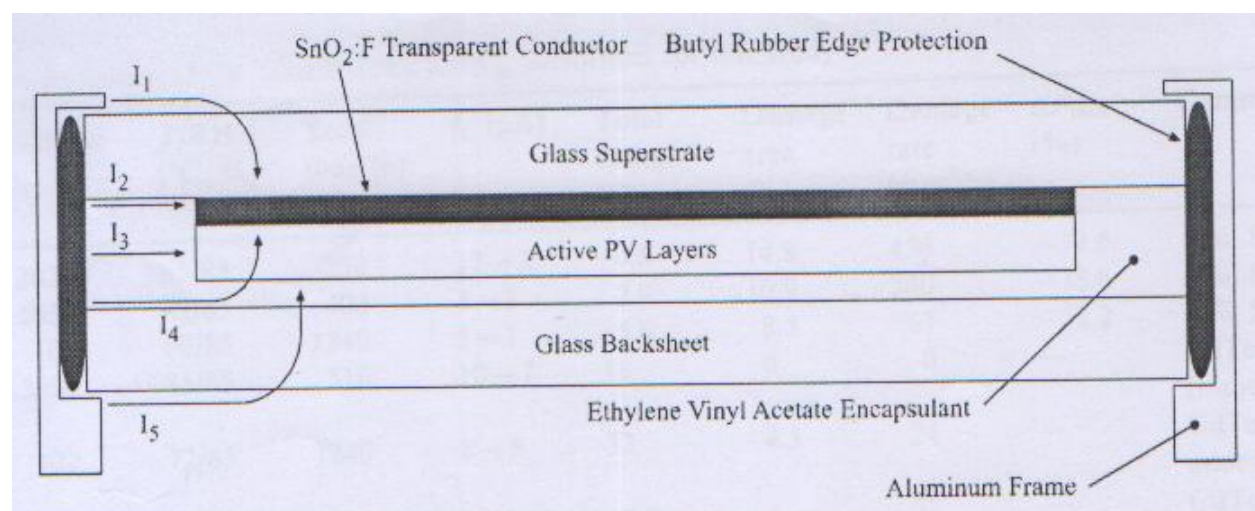


Figure 11. A cross section of a PV module constructed with an SnO₂:F transparent conducting oxide(TCO) layer deposited on a glass superstrate. The active semiconducting layers are deposited over the tin oxide, and the entire package is encapsulated with ethylene vinyl acetate (EVA) between another sheet of glass. Not shown are the laser scribes that form the individual solar cells connected in series. Five possible current paths between the frame and the TCO are illustrated (1) along the surface and through the bulk of the glass superstrate, (2) along the glass superstrate-EVA interface, (3) through the EVA bulk,(4) along the glass backsheet-EVA interface and through the EVA bulk, and (5) along the surface and through the bulk of the glass backsheet, and through the EVA bulk [95].

The above coating shows good adhesion, weather ability and low water vapor transmission rates. These coatings have a good adhesion to EVA after UV or damp heat exposure. The amount of water vapor that diffuses into EVA controls the stability of glass EVA surface. It may that glass/ EVA interface favors condensation reactions and the hydrolysis reactions are difficult to achieve. The exact mechanism is not known, however it is confirmed by research studies that humidity and leakage current play a very predominant role in degradation of PV modules. The important pathways are showing figure 11 [95].

In a study H-V induces leakage current from eight modules, a pair from each module type of C-Si, Pc-Si. (Bulk Si) and tendem junction and multi-junction a-Si were monitored for eight years. It was observed that the leakage currents from C-Si Pc-Si module were thermally activated and the activation energy varied with RH ranging from 0.86-1.0ev at high RH to 0.8ev as low RH. The leakage currents for a-si modules were much lower than bulk Si modules by a factor of 10 to100 times. After operation of HV tests for 24 hrs a day the loss rates were 0.0% year for pL –s, 0.1% year for c-s, (positive polarity) between 0% as 0.05% year for ja-si module. The bulk of the modules degraded compared to modules not biases at HV. For thin film modules the losses were insignificant. The detail of modules discussed as shown in Table 6 [94].

Module type	Structure front to back	Area (m²)	Perimeter (m)	Mounls
C-Si	Glass/ C- Si cells/ Tedar	0.60	3.4	All edges frames
Pe-Si	Glass/ Pc- Si cells/ Tedar	0.52	3.1	All edges frames
2 Ja-Si	Glass/ TCO/a- Si /Al/ glass	0.76	3.7	Rear Brackets
3Ja- Si	Flouro polymer/TCO/a-Si/ SS	0.45	3.3	All edges frames

Table 6. Construction and size of PV Modules Tested

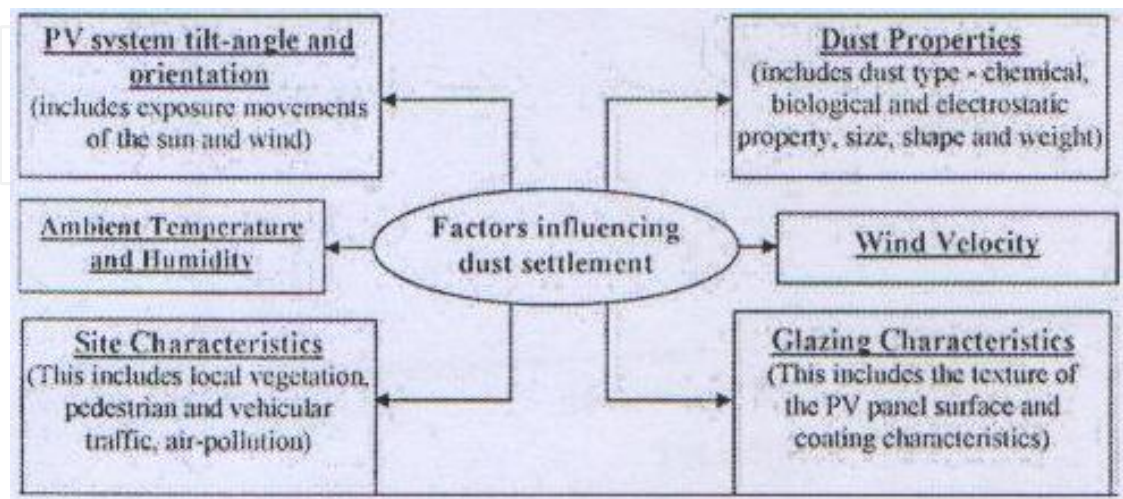


Figure 12. Factors influencing the dust settlement [96].

2.6. Importance of dust

Dust is a term which is applied to solid particle with less than 500 μ m. The main sources of dust are; dust laden winds, volcanic eruptions etc. It also includes micro pollens, microfiber, which are scatter with atmosphere. The factors influence the dust settlements are shown in figure 12 [96].

Dust promotes dust. It settles in region of low vapor pressure induced by the high pressure movements on inclined /vertical surface. The PV system is affected by several environmental factors as shown in figure 13 [96].

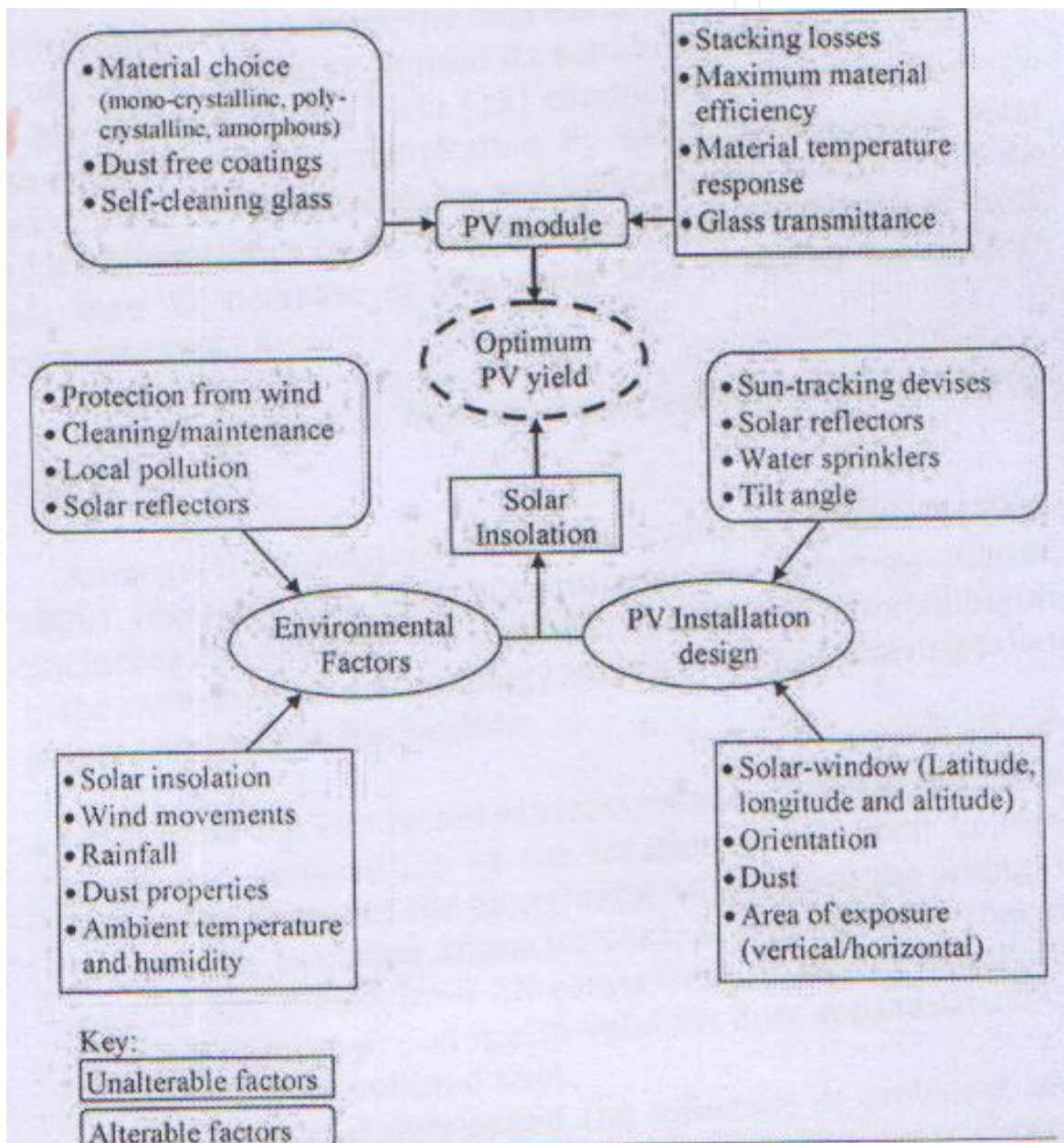


Figure 13. Alterable and unalterable factors determining maximum PV system yield [96].

Amongst all the environmental factors; removal of dust is the most complex factors in PV module. As reported in the literature degradation of 26-40% in the efficiency of thermal panels are photovoltaic cell was reported for installation in Saudi Arabia which is prevalent with dessert wind [97].

The impact of the dust on the reflection of glass in shown figure. Despite few developments in surface technology such as lotus surfaces of work in program with NASA, cleaning by wet method is still predominant.

Future exploration on moon would require mitigating the difficulties posed by Lunor regolith includes dust. NASA is tasked with the development of mitigation strategies of lunar dust. What has been achieved so far is the development of an Electrodynamics dust shield to minimize dust accumulation, a technique which also could be used to remove dust from PVC modules. The dust removal is achieved by applying a multiphase travelling electric field to the electrode that are embedded in the surface to lift and transport charged and uncharged particles off the surface. Following is a brief description of the electrodynamics dust shield technology being developed by NASA. A schematic of three phase Electrodynamics dust shield is shown in figure 14 [98].

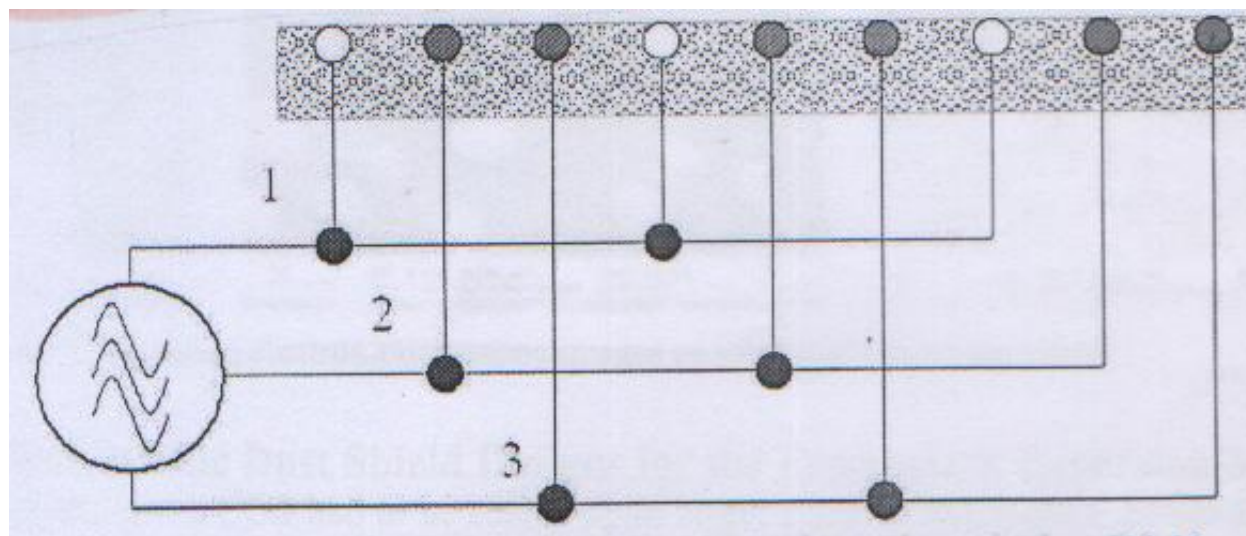


Figure 14. Schematic diagram of a three-phase Electrodynamics Dust Shield [98].

It consists of a series of a parallel electrodes connected to a multiphase AC source that generates a propagating electrodynamics wave. The wave transports the dust particle to a specified location. An electric field is generated by the signal output. The strength of electric field varies proportional to the potential difference between electrodes which is controlled by phase shift. The uniform field carries the charged particle [99].

NASA developed transparent 20cm diameter EDS Indium tin oxide (ITO) electrodes on a polyethylene (PET) film. For testing three electrodes of copper 20cm X 25cm for EDS were constructed and two of them were coated with a lotus film. A lotus coating is a two layer system containing microfills (protrusions) ~2.0 mm, and micro valleys containing epicuticu-

lar wax crystals and nano hairs with nano pores. The two layered hierarchical surface is covered by low energy compounds with very low surface energy like PDMS, fluorocarbons and other low energy compounds. Such a two level surface can be created by chemical etching or laser etching to make it a rough surface where the average grain size is in nano region. Sandblasting and short penning or cavitation shotless penning can also be used to make a two level surface. Work on stainless steel has shown the effectiveness of this process. Nano-structured films of TiO_2 were produced by mixing tetra-n-butyltitanate, ethylacetoacetate and ethanol by sol gel technique [100].

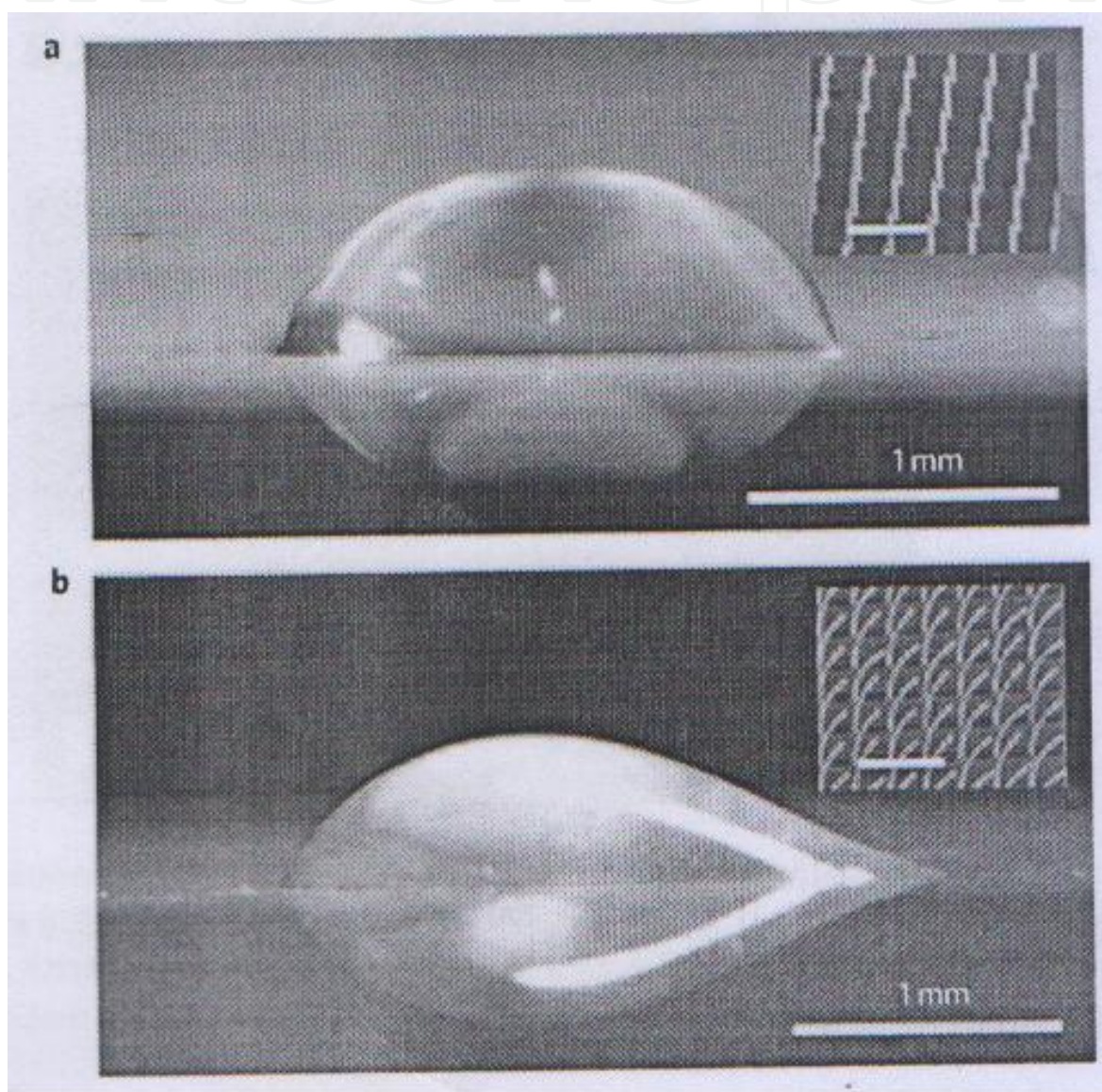


Figure 15. Comparison of wetting behavior on symmetric and asymmetric nanostructured surfaces. a, Axially symmetric liquid spreading of a $1\ \mu\text{l}$ droplet of deionized water with 0.002% by volume of surfactants (Triton X-100) deposited on typical vertical nanopillars with diameters of $500\ \text{nm}$, spacings of $3.5\ \mu\text{m}$ and heights of $10\ \mu\text{m}$ (inset). b, Unidirectional liquid spreading of a droplet on the same dimension nanostructures as a, but with a 12° deflection angle (inset). The images show the characteristics of a spreading droplet at one instant in time. The scale bars in the insets are $10\ \mu\text{m}$ [102].

The secret lies in preparing a tailored morphology of the surface. The surface can be textured for hydrophobicity (water repelling). The surface exhibit micro convexity with clusters of nanoparticles (99,100). Such surface can trap a large amount of air which has the ability to induce large wet contact angles for hydrophobicity (170°). Water drops on such surfaces become detached, rolls down and carries the dust with them. However in arid regions, there is hardly any rainfall for this phenomena to occur. Super hydrophobic surfaces can be prepared on metals, glasses and plastics. Similarly a hydrophobic surface can be prepared by depositing films of TiO_2 by hydrolysis of titanium aloxides and hydrolysis of TEOT (Triethylorthotitanate). These films are hydrophilic (water repelling) and also remove contaminants and microbes by the photocatalytic reaction induced by TiO_2 particles. Hydrolysis and condensation of titanium aloxide yield Ti-O based network.

The above surface obtained is hydrophilic. It is also possible to control the direction of flow of water (uni-directional) on asymmetric nanostructured surface by allowing the liquid to flow in one direction and pin on other direction which can be very helpful for various geometries of photovoltaic modules [101]. Figure 15 shows a comparison of wetting behavior on symmetric and asymmetric nanostructure surface [102].

The lotus coatings being worked out by NASA is developed on the principle described above.

The lotus surface developed is expected to mitigate dust without use of water as in the case of hydrophobic surface. The lotus coating two level would shed particles utilizing anti contamination and self cleaning properties which would minimize dust accumulation. Such coatings based on the structure of lotus flower such as hydrophobic coatings on glass and plastics would have the capability to repel dust. NASA is developing both hydrophobic and hydrophilic coatings which are next generation coatings to minimize dust on solar cells and thermal radiation. Self cleaning and anti-contamination systems being developed have also the capability to kill bacteria, chemical agents, pathogens and environmental pollutants. In future the super hydrophobic coatings would play a leading role not only in lunar environment but also in solar cells and most importantly in space exploration. The hybrid coating for photovoltaic solar arrays are shown in figure 16 [103].

In order to understand the working of EDS, it is important to understand the forces which are responsible for lifting the sands. Two types of forces are applied by the electrodynamic field; a: Electrostatic force and b): di electrophorelectric force.

Most airborne dust particles acquire an electrostatic charge during their detachment process. Each sand particle is subjected to a sinusoidal excitation voltage generated by the electric field. A charge particle experienced two forces of repulsion, one tangential and other normal to the contact angle. The lift force for the particle is provided by centrifugal force which is induced by the curvilinear motion of the particle. Another particle charged with $-q$ will be subjected to repulsive force and it would levitate if the lifting force is larger than the adhesion force due to the cumulative effects of lifshitz -vander walls forces, electrostatic forces and capillary forces. There is hardly any capillary force in the desert region. On energizing of three phase voltage, the charged particles are lifted from the surface by the vertical com-

ponent of the field and the travelling wave component as mentioned earlier carries the dust to the screen. Single phase excitation lifts the particles. This process becomes more effective when a three phase voltage is applied.

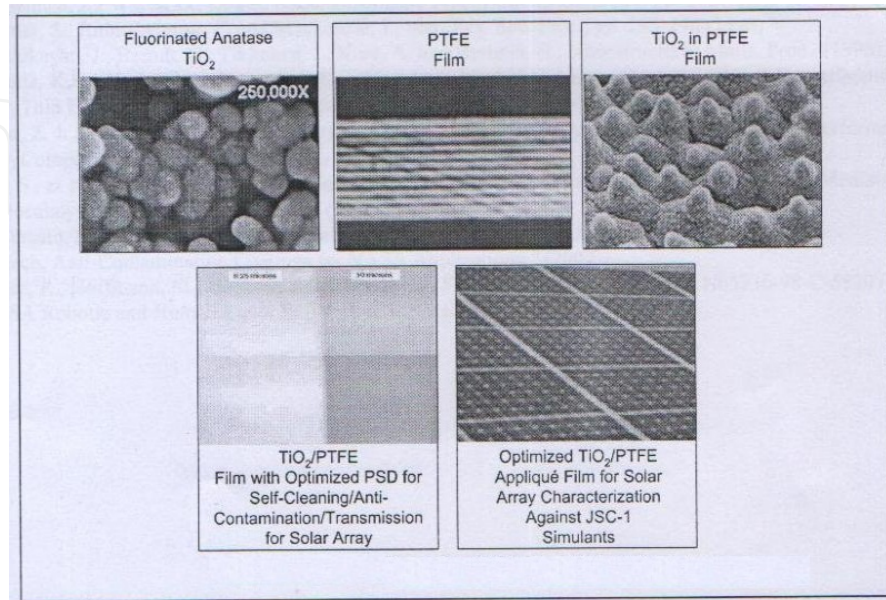


Figure 16. Hybrid coating for Photovoltaic solar arrays [103]

Another force to be considered is dielectrophoretic force. It is experienced by charged or uncharged particles in any AC or DC field (E). Because the particles $+q$ and $-q$ are charged and separated by a distance, a dipole moment (qd) is formed. Because of induced dipole moment these particles experience dielectrophoretic force. The applied voltage creates a gradient in the electric field. The divergence of electric field applies a dielectrophoretic force F_d and a torque T . This force causes the movement of neutral particles on the surface and induces electrostatic charging by triboelectrification. This acquired charge would induce to the columbic force of repulsion to lift the particles. In summary, columbic and dielectrophoretic forces move the dust particles to the surface and hence the particles acquire charge. These charge particles are repelled by electrostatic forces.

This mechanism applies also to conducting particles deposited on the shield. The charge q is proportional to E^2 . Particle in the vicinity of electrodes acquire electrostatic charge and they are repelled when the force of repulsion $F_{\text{Repulsion}} = 9 E_0^2 r^2$ is $>$ force of adhesion (F_{Adhesion}). The particle would be lifted.

By applying a three phase voltage 90% of the dust is removed in about two minutes.

The energy requires for dust removal is only a small fracture of the energy output of the modules [104].

The electrode grid uses indium tin oxide or carbon nanotubes. Figure 11 shows transparent EDS coatings in glass. The role of aluminium has become very predominant in solar power system. The solar power system has been divided in four distinct groups, parabolic trough,

parabolic dish, linear fersenel and solar tower. Aluminium is one of the most important material utilized in solar absorbing due to the capability of its anodic layer formed on its surface by the process of anodization. Eutectic binary aluminium alloys such as Al-0 wt% Ni, Al-33 wt% Cu and Al-7.5wt% Ca have been successfully used as absorber (low reflection and high absorption). The mechanical and thermal ability of aluminium alloys and regeneration of surface is etching enhances their properties in solar power system.

Aluminium extrusion provides a clear economic advantage in the product of solar application. White steel costs less than aluminum on a dollar per pound basis, the lower weight of aluminium ($1/3^{\text{rd}}$ of steel) allow far more material to be used at a lower cost.

Because of its recyclability, light weight, high strength and high corrosion resistance, it has become a preferred material. By using aluminium Alcoa is saving on costs of solar pond and transportation.

Hydro in Germany is making mirrors for concentrated solar power as well as absorber sheets for solar thermal application. This company launches the first tailored Hybridlife solar aluminium alloy for concentrated solar power and launched high select coatings for solar thermal systems. Hydro serves its customer in solar thermal concentrated solar power and photovoltaic for all area of solar energy product.

Ali Baba has manufactured 1 KW, 2 KW, 3 KW and 10 KW solar power systems, aluminium based with a life span of 25 years. (AliBaba.com). Light technology is a leading and provides standard aluminium profile for mounting systems for solar energy.

Pacific power management (PPM) has announced the installation of a 800 KW power plant for Sierra Aluminium Company. It contains 4,480 Mistzubish Electric, 180 watts modules and 2 satcons 500 Kw invertors. It generates 1.4m Kwh per year.

It would reduce Sierra carbon footprint by 48% and supply power to 28,000 homes over a 25 year period.

The use of solar mirrors could reduce the cost by 20%. For a 50 megawatt power plant, a saving of 20 million euros could be made.

2.7. Conclusion

Aluminum is playing a predominant role in solar power system because of its technical capability, ease of fabrication and ease of transport use, recyclability and resistant to corrosion. The promising future of aluminium in solar power is reflected by the projections on market growth from 210 mm² to 11 bmm². By 2050, the amount could reach 39 mtons from the existing 17 mtons. The major attributes are large energy area for collection, solar directed installation and dynamic development. However there are several technical problems associated with solar power such as the ingress of moisture causing corrosion and leakage of current causing deterioration of modules. The water vapours ingresses through the edges and increases the conductivity of the front glass surface and also the magnitude of leaking current. In the four types of modules a). C-Si, b). PC-Si, c). 2J a-Si (Glass/TCO/a-Si/Al/Glass) and 3 Ja-Si (Fluoropolymer/TCO/a-Si/stainless steel), the two modules containing a-Si showed the

maximum resistance to HV operation. In HV operation, all modules degrade at rates higher than the modules not biased on HV. Films on PET showed promising properties as a back sheet replacement for glass. These coatings exhibit excellent moisture resistance properties and a good cohesion after exposure to damp heat. The corrosion effect can be minimized by increasing adhesion of transparent oxide by using Zinc oxide in place of Tin oxide and by using low acetate and high resistivity glass.

Dust is still haunting the scientists and engineers working on solar and space equipment. It is of vital importance to solar panels and equipment used in space exploration. A substantial amount of research has been done on electrostatic system to remove dust. This is coupled with creating a lotus surface (two level) hierarchical surface (nano/micro hybrid) to create self cleaning properties for removal of dust by mimicking the surface of a lotus flower. Various paints containing self cleaning agents have also been designed to remove dust. The wet chemistry route creating a superhydrophobic surface is an outstanding achievement but it cannot be applied in desert conditions. Intensive work is undertaken by NASA to create dust shields. It appears that new techniques would be developed to mitigate the degradation of PV modules and the use of aluminum would continue to rise.

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