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Enhancing Efficiencies and Sustainability of Photovoltaic Systems

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Abstract—*Photovoltaic cells (PV cells) are the fundamental building blocks for manufacturing solar panels. Every photovoltaic cell works on the principle of photoelectric effect. Energy carried by photons from the sun is transferred to an electron inside the cell. This causes an excitation of the electron to a higher energy state, which then generates an electric current. This research paper aims to elucidate the various photovoltaic technologies and highlight the differences between them. The most important factor is the efficiency, which is the ratio of the number of photons received to the electricity generated. Over time materials used to make PV cells have changed and the efficiency has increased allowing solar panels worldwide to become more economical. Thus, solar technology is playing a pivotal role in the transition of energy generation from fossil fuels to renewable sources.*

While power generated by harnessing the solar energy through the use of solar panels is a non-conventional and renewable source of electricity, the actual process of manufacturing these solar panels is not completely free from emissions and may also result in generation of highly toxic materials in the process. Some PV technologies have a lower carbon footprint, often at the expense of efficiency and cost. This paper attempts to investigate the advantages of each technology, while taking into account the efficiency, carbon footprint and cost.
This paper attempts to investigate the efficacy of future research to improve PV technology and also consider technologies with the potential to significantly alter the structure and composition used in the manufacture of solar panels. It might be possible to substantially reduce the carbon footprint of solar panels, while increasing their life span. This paper summarizes the ways to increase the efficiency of solar panels - capture more quantum of light, loose less energy, lower reflection from the glass, ensure higher absorption, etc. It also describes how electricity generated from a solar panel can be transferred to a traditional electrical circuit. Finally, it also describes the challenges of recycling solar panels once they reach the end of their life cycle and ways to improve their capability for being reprocessed by using alternate materials.

1. Crystalline and Polycrystalline Silicon PV Technology

Crystalline silicon is the most common technology in use today, representing about 95% of the total PV cell production in the world.

The highest energy efficiency reported for research crystalline silicon PV cells is 25%. However, standard industrial cells are limited to 15–18%, with the exception of certain high efficiency cells capable of having efficiencies greater than 20%. High efficiency research PV cells have advantages in performance but are often unsuitable due to their high cost of production because of their complex structures and the lengthy manufacturing processes required for fabrication.

Production of Standard Silicon PV cells

Standard cells are produced using one mono crystalline and polycrystalline boron-doped P-type silicon substrates. Cells are typically square shaped, 125 mm (5 inches) or 156 mm (6 inches) square, respectively.

Mono crystalline solar cells are produced from pseudo-square silicon wafer substrates, cut from column ingots grown by the Czochralski (CZ) process. Polycrystalline cells, on the other hand, are made from square silicon substrates cut from polycrystalline ingots grown in quartz crucibles. The front surface of the cell is covered with micro-meter sized pyramid structures (textured surface) to reduce reflection loss of incident light. An anti-reflection coating (ARC) of silicon nitride (SiNx) or titanium oxide (TiOx) is over laid on the textured silicon surface to further reduce reflection loss. A highly phosphorous doped n+ region is produced on the front surface of boron-doped P-type substrates to form p–n junctions.

The value chain for crystalline silicon solar cells and modules is longer than that for thin-film solar cells.

There are three industries related to crystalline silicon solar cell and module production, namely:

1. Metallurgical and chemical plants for raw material silicon production;
2. Mono-crystalline and polycrystalline ingot fabrication and wafer fabrication by a multi-wire saw; and
3. Solar cell and module production.

The cost of PV production is roughly divided equally between solar cell module production balance-of-and balance of system fabrication, which includes inverters, cables and installation.

The major component of the cost of fabrication for solar cell modules is the cost of the silicon substrate, accounting for 50% of the total cost, while the cost of cell and module processing account for the balance 20% and 30% respectively. Due to this, the cost of production is strongly driven by the market price for poly-silicon feedstock, and falling prices of the cost of the silicon substrate and its volatility remains one of the most important factors in the PV industry to sustain at present. The BOS (Balance of Supply) system items prices have a tendency to increase with the prices of silver, aluminium etc. There has been large cost cutting and process change to reduce the cost of BOS. Large manufacturers, especially in China, have resorted to subletting the module assembly to third parties. At the same time, the quality control on some of the BOS materials, especially the back contact sheet, etc., has led to poor performance or failure in the field.

Production of Metallurgical Grade Silicon

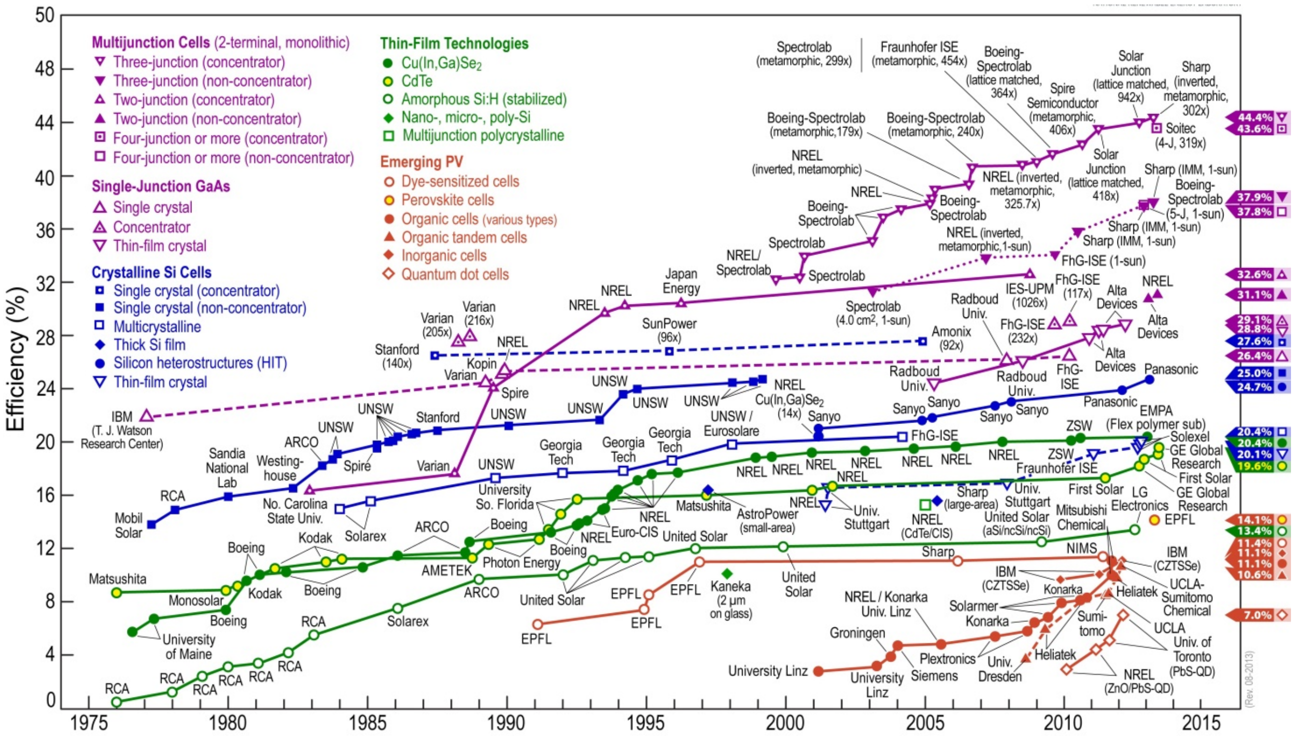
Silicon is commercially prepared by the reaction of high purity silica with wood, charcoal and coal in an electric arc furnace using carbon electrodes at temperature over 1900 degrees Celsius, temperatures at which the carbon reduces the silica to silicon.

This metallurgical grade silicon is at least 98% pure silicon. Pure silicon (>99.999%) can be extracted directly from solid silica or silicon by molten salt electrolysis. This method has the potential to directly produce solar-grade silicon without any CO2 emissions and at much lower levels of energy consumption.

Production by Chemical Methods

Siemens Process and REC's Fluidized Bed Technology using silane is mostly used to get $10^{\wedge -9}$ purity required for Solar Modules.

2. New technologies in PV systems



Currently, research is being carried out to improve inorganic cells (depicted by orange lines on the graph above). These are being developed to be stable and commercial. While their efficiency is low, inorganic cells are promising since they have a low carbon foot print and are less harmful to the environment. Solar energy is pivotal in mitigating the effects of climate change and inorganic cells have the potential to boost the positive impact of the technology. The EU has said that they will restart their PV manufacturing set up and they are doing cutting-edge research on inorganic cells. It is likely that, the efficiency of inorganic cells will increase and surpass the efficiency of traditional cells.

Thin film technology research has stagnated due to high manufacturing costs, making it non-competitive. It has the potential to reach 19% efficiency on ground.

In crystalline Silicon cells, there have been minor changes in terms of Mono, Polycrystalline, Mono double-sided, Polycrystalline double-sided structures. While PERC[1] Mono and PERC poly are prevalent in the market, they have been 1% efficient in the installations paying off the extra manufacturing cost involved. HIT technology, developed by Panasonic, has not been able to gain sufficient momentum, losing out to the more affordable Chinese Mono PERC. It might gain momentum if there are efforts to reduce material input and silver paste. These make cells more expensive, requiring manufacturing technology to be improved. There is a patent now on this technology and therefore, a royalty cost which is going to end very soon. These technologies of Crystalline Silicon are estimated to continue to rule the commercial market for the next decade until 2030.

Multi junction Devices

Department of Energy in the US is investing in multi-junction III-V solar cell research to drive the costs of materials, manufacturing tracking techniques, and concentration methods used with this technology. The following section elaborates on the salient features and benefits of the production and manufacturing of this technology.

High–efficiency multi junction devices use multiple band gaps (or junctions), that are tuned to absorb from a specific solar spectrum to create solar cells having record efficiencies of over 45%. The maximum theoretical efficiency that a single-band gap solar cell can achieve with non-concentrated sunlight is about 33.7%, primarily because of the broad distribution of solar emitted photons. This limiting efficiency, known as the Shockley-Queisser limit, arises from the fact that the open-circuit voltage (V_{OC}) of a solar cell is limited by the band gap of the absorbing material. The photons, with energies below the band gap, are not absorbed. Photons that have energies greater than the band gap are absorbed, but the energy greater than the band gap is lost as heat.

Multi-junction devices use a high-band gap top cell to absorb high-energy photons while allowing the lower-energy photons to pass through. A material, with a slightly lower band gap, is then placed below the high-band gap junction to absorb photons with slightly less energy (longer wavelengths). Typical multi-junction cells use two or more absorbing junctions, and the theoretical maximum efficiency increases with the number of junctions. Early research into multi-junction devices leveraged the properties of semiconductors comprised from elements in the third and fifth columns of the Periodic table, such as gallium indium phosphate (GaInP), gallium indium arsenide (GaInAs), and gallium arsenide (GaAs). Three-junction devices using semiconductors have reached efficiencies of greater than 45% using concentrated sunlight. This architecture can also be transferred to other solar cell technologies, and multi-junction cells made from CIGS, CdSe, silicon, organic molecules, and other materials are being researched.

In the past, multi-junction devices have primarily found use in space related requirements, where there is a premium placed on lightweight power generation, which allows for the use of this relatively high-cost solar technology. For terrestrial applications, the high costs of these semiconductor substrates (compared to silicon, for example) may be offset by using concentrating optics, with current systems primarily using Fresnel lenses. The concentrating optics increases the amount of light incident on the solar cell, thus leading to more power production. Using concentrating optics requires the use of dual-axis sun-tracking, which must be factored into the cost of the system.

Multi-junction solar cells can be fabricated using molecular-beam epitaxy (MBE) techniques, but fabrication in large metal-organic chemical-vapor deposition (MOCVD) reactors is typical for commercial-scale production of GaInP/GaInAs/Ge devices. Layers can be grown from trimethylgallium ($Ga(CH_3)_3$), trimethylindium ($I_nC_3H_9$), arsine (AsH_3), and phosphine (PH_3) in a hydrogen carrier gas and using do pants such as hydrogen selenide (H_2Se), disilane (SiH_6), and diethyl zinc ($(C_2H_5)_2Zn$). Use of concentrating optics allows individual cells to be quite small - at times, as small as the size of the tip of a pencil. Therefore, these techniques allow hundreds of solar cells to be grown in single batches. Research is being carried out to further reduce the size of cells and increase the number of cells that can be grown from a single wafer, which will help reduce the cost per cell.

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[1] Refers to Passivated Emitter and Rear Cell / Contact

PERC Technology

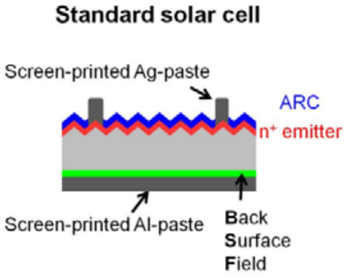
The main advantage of the PERC cell structure is that it enables manufacturers to achieve higher efficiencies than with standard solar cells, which are reaching their physical limits. With the current state of the technology, it is possible to achieve up to 1% absolute gain in efficiency. While there are more steps in the manufacturing process, the gain in efficiency enables costs decrease – not just of manufacturing but at an overall system level as well. The most important factor is to improve efficiency while reducing costs at the same time. And solar cell efficiency improvement is a contributor to the reduction of costs. So, this cell architecture is considered to have the most potential for producing high efficiency solar panels at competitive prices.

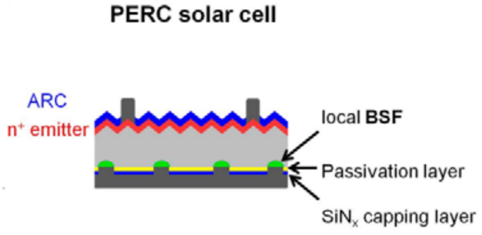
The PERC architecture is relatively old. First implementation of this technology can be traced back to the University of New South Wales (UNSW) in Australia in 1983 and the first paper has been published in 1989[2]. This concept of cell offered the best potential to reach high efficiency, the use of which enabled UNSW to achieve numerous records in terms of efficiency, improving efficiencies close to 25%.Two other competing technologies were the Back Contact technology (popularized by Sun power)and the HIT technology (commercialized by Panasonic).

It is interesting to underscore that standard solar cell architecture has been in use since the mid80s. Since then, the technology has gone through incremental improvement, with better pastes to form front contacts, thinner contact fingers, and optimized anti-reflective coating. It took almost 30 years for the industry to catch up with the efficiencies achieved at the research level.

There is always a gap between the performances achieved at the research level and what is achieved in mass production at the industrial level. If PERC cell technology has emerged now, it is purely for economic reasons. Indeed, there is always a trade-off between economic viability and technical viability. For 30 years, the steady incremental improvements brought about in standard cell technology were economically and technically feasible. Once the standard concept achieves its limits and that technical knowledge is available along the value chain to introduce PERC technology, it can constitute a new viable platform to manufacture high power and high efficiency solar panels.

As per forecasts by ITRPV3(a body that gathers a set of manufacturers at the different steps of the value chain and that works on technology trends), PERC technology will progressively grow on to take the biggest market share.


Standard solar cell


PERC solar cell

Unique hetero-junction structure developed for manufacturing has thin amorphous p and n layers and intrinsic amorphous layers on the front and rear surfaces by the Czochralski (CZ) process-type mono-crystalline –silicon substrate. Best output parameters in the lab conditions are Voc= 729 MV, Jsc = 39.5 mA-cm-2, FF=0.800, and η= 23.0% for a large 100.4 cm2 cell. VOC is improved by large band gap of the front amorphous silicon layer and the high interface quality between the a-Si and x-Si substrate. Low temperature coefficient of 0.30% k-1 at pmax is an advantage. The transparent conductive oxide and ARC reduces sheet resistivity of front a-Si layers. Lower Jsc in comparison to the high efficiency Si Cells due to weaker blue response. Generation / collection in the front a-Si layers and bulk Si is lower due by the effects of the lower transparency of the TCO layer compared to other ARCs and the lower internal quantum efficiency of the amorphous layers.

The high-efficiency back-contact back-junction (BC-BJ) silicon solar cells, which now have the capability of mass production, are being fabricated in order to utilize the full cost. These have the reduction potential of this elegant cell structure. At the same time, the performance of the solar cells was found in details by experimental work, analytical modeling and numerical device simulations. The complex and costly photolithography masking steps were replaced by relatively cheaper techniques, making it feasible for competitive mass production, such as screen-printing of the masking layers and local laser ablation of the dielectric and silicon layers. The highest solar cell efficiency of 21.1% (JSC = 38.6 mA/cm^2, VOC = 668 mV, FF = 82.0%) was achieved on 160μm thick 1Ω cm n-type FZ Si with the designated area of 4 cm2. A detailed study of the loss mechanisms, limiting the

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[2] Forty Years of Photovoltaic Research and UNSW, Australian Centre for Advanced Photovoltaics, UNSW Australia

[3] The International Technology Roadmap for Photovoltaic

efficiency of the developed back-contact back-junction silicon solar cell, was performed. The reduction of the cell efficiency was determined to be 3.9% abs. due to recombination processes, 2.0% abs. due to optical losses, 0.3% abs. due to series resistance effects and 0.7% abs. due to electrical shading. The developed model of the loss mechanisms is a powerful tool for the further optimization of the solar cell structure. Positive effects of the phosphorus doped n+ front surface field (FSF) on the performance of the BC-BJ solar cells were seen to improve the following:

(i) **Surface passivation and passivation stability:** The optimal surface passivation was obtained with a deep diffused Gaussian phosphorus FSF doping profile with sheet resistance of 148 Ω/sq. In contrast to solar cells without the FSF diffusion, the solar cells with the FSF diffusion profile did not show any performance degradation under exposure to UV illumination;

(ii) **Lateral current transport**: The front diffused n+ layer can be seen as a parallel conductor to the lateral base resistance. This way the lateral base resistance losses can be reduced;

(iii) **Low-illumination performance**: The front surface field improves the performance of the BC-BJ solar cells under low illumination intensity. Therefore, the BC-BJ cells with FSF seem to be the best ones suited for achieving a high energy yield when also operating under low illumination intensity.

Sun Power made BC-BJ cells for unmanned aircraft and solar race cars in the 1990s, followed by a large scale PV plants in the 2000s. Best efficiency for a large-area industrial BC-BJ cell is 23.4%. The BC-BJ cell has front and rear surface passivation layers, a random-pyramid light-trapping surface, FSF, interdigitated n- and p- doped regions on the back surface, n and p contact gridlines on n- and p- doped regions, a single layer of ARC and CZ n-type single-crystalline silicon substrate with a minority carrier. Of all the silicon PV modules in the market today, only those based on BC-BJ cells provide the possibility of module efficiencies exceeding 20%. BC-BJ cells have no gridlines or bus bars shading, a front surface with good passivation and improved ascetics due to the absence of front electrodes, which permits freedom in the design of back contacts.

Freedom in design of back contract also provides advantages in module assembly allowing the simultaneous interconnection of all cells on a flexible printed circuit. The low series resistance of interconnection formed by this type of surface mounts technology results in a high FF of 0.82 compared with around 0.75 for standard silicon PV cell modules.

3. Increasing solar efficiency

The industrial goal for photovoltaic power is to reduce the cost of generation of electricity in order to achieve grid parity in terms of tariffs. The energy conversion efficiency of solar cells is another important issue because the efficiency influences the entire value-chain cost of the PV system, from material production to system installation.

The solar cell efficiency is limited by losses on account of the following three phenomena:

- **Photon losses,** due to surface reflection, silicon bulk transmission and back contact absorption;
- **Minority carrier**(electrons in the p region and holes in the n region) loss due to recombination in the silicon bulk and at the surface; and
- **Heating Joule loss**, due to series resistance in the gridlines and busbars, at the interface between the contact and silicon, and in the silicon bulk and diffusion region.

In the design of solar cells and process, these losses are minimized without lowering the productivity of the solar cells.

Minimizing Carrier loss

- Passivation of front electrode (partly in contact with highly doped silicon layer) to reduce carrier recombination under front electrode;
- Shallow doped p-n junction with front surface dielectric passivation layer to reduce carrier recombination in the n+ - doped region and at the surface; hetero junction cell; front surface field and surface passivation for back contact in a back-junction cell;
- Locally P+ doped back surface field and point contact structure to reduce carrier recombination in highly doped P+ back region;
- Back surface passivation by a dielectric layer or hetero-junction structure to reduce back surface recombination.

Minimizing photon loss

- Front face has a textured surface of an inverted pyramid structure to reduce surface reflection loss;
- Single or double layer Anti-Reflective Coating (ARC) to reduce surface reflection loss;

- Back-contact cell structure to reduce front contact shadow loss;
- Flat back surface by Chemical etching of Silicon to improve back reflectivity and reduce photon absorption;
- Back surface reflector consisted of a dielectric layer and high reflectivity thin metal layer to reduce photon absorption.

Minimizing electrical loss

- Fine gridline front contact to reduce series resistance of n+ doped region;
- Selective emitter (deep and highly doped emitter under the contract) to reduce contact resistance of front contact with Silicon surface;
- n – type or p – type silicon substrates with minority carrier diffusion lengths longer than the base thickness.

4. Characteristics of energy systems and performance

PV Systems have several modes of operations and each has its pros and cons. An increase in components (depending on the type of system) causes the probability of failures to increase. Additional power sources increases availability and increases the percentage of solar energy used.

Direct Coupled DC system

- Simplest type of system;
- Low cost, due to fewer additional components;
- High reliability.

The ability to use direct coupled system depends on:

- Match between load and solar resource or ability to tolerate low availability;
- Tolerance of load to range of input voltage and currents;
- Ability of the load to take DC as input

Examples: Some home power systems, direct drive application (including water pumping and ventilation systems).

DC Photovoltaic System

- Traditionally, the most common type of system; still extensively used in smaller systems or specific purpose systems;
- Requires all DC appliances, but efficiency of DC appliances may be higher than that of conventional appliances;
- Requires different wiring, connector, and fuses;
- In most cases, charge controller (which may be parallel or series) as well as battery are included. Use of a power point tracker depends on load and system.
- High voltage DC connections and wiring requires caution;

Example: Specific use industrial system, small home power systems

DC-AC system with storage

- Most flexible system; can be used with any appliance at any time;
- Not uncommon to include a DC load; but, usually just AC;
- Efficiency depends on other components used in system;
- Maximum power point trackers increase efficiency;
- Efficiency of batteries and inverters (including operating point of inverters) affects system performance.

Hybrid

- Diesel only system; performs poorly under part load conditions, both from an efficiency and maintenance standpoint;
- Addition of batteries reduces requirement to run generator under part load conditions;
- Addition of solar (or other small generating source) reduces need for diesel;

Example: standalone home/village systems.

Grid Connected Systems

- No storage included in systems; when PV system generates, power is either used locally at generation source or fed into the grid;
- Inverter design must be substantially different for grid connected systems in order to meet power quality requirement and safety requirements of utility;
- Several types of grid connected systems:
  - Residential PV;
  - Building integrated PV;
  - Utility – Scale PV.

5. Module end of life challenges

Antimony is used in solar panel glass to improve stability of the solar performance of the glass upon exposure to ultraviolet radiation and/or sunlight. The combination of low iron content, antimony and patterning results in glass substrate with high visible transmission and excellent light refracting characteristics (Ref. US Patent US8802216B2 dated 12/8/2014). Antimony Containing Solar Panel Glass (ACSPG) is used worldwide. Glass in solar panel constitutes about 70 % of the weight of solar panel.

The number of PV installations is predicted to increase all over the world. Major installations of solar panels in India will stop functioning in 15-20 years. At the end of its life cycle, the glass in the panel can be recycled.

Improper treatment or disposal of waste may result in the loss of this recyclable material. The estimated waste production factor is about 75 MT of waste for every 1 MW of installed capacity. Solar panels with antimony containing glass (SPACG) would leach antimony from the glass when the waste panels after its end of life are exposed to wet conditions. Such conditions may occur, when waste glass from end of-life solar panels is disposed on land through an unsecured manner.

Recycling of PV modules is technologically and economically feasible; however, limitation in recycling may arise when there is limited quantity of PV waste for recycling. Countries like Germany have developed PV recycling technology and antimony containing glass may be recycled without affecting its properties. The recycling process of 1 ton of PV panel is likely to produce 686kg of clean glass and 14kg of contaminated glass.

Results indicate that samples of waste solar panel glass containing antimony do not fall in the category of hazardous waste as per the concentration limits stipulated for antimony in Schedule II of Hazardous and Other Waste Management Rules, 2016. However, waste antimony glass has the potential to leach antimony in wet conditions including wet landfill conditions.

Besides antimony, it may also be possible to recycle other raw materials such as boron and indium, which are becoming scarcer by the day.

References

[1] Mercom India (www.mercomindia.com)
[2] Research into Photovoltaic technology; National Renewable Energy Laboratory (NREL) (www.nrel.gov)
[3] Ministry of New and Renewable Energy, Govt. of India (MNRE) (https://mnre.gov.in)
[4] T. Saga, NPG Asia Mater. 2(3) 96–102 (2010)
[5] Sunpower (https://us.sunpower.com)
[6] Fraunhofer Institut für Solare Energiesysteme (ISE)
[7] United Nations Development Programme, www.lb.undp.org
[8] DREG (www.lb.undp.org/DREG)
[9] AE Solar Energy (https://ae-solar.com)
[10] GOI gazette Notifications
[11] Bureau of Indian Standards (https://bis.gov.in)
[12] Journals and proceedings of the Royal Society of New South Wales (http://royalsoc.org.au)