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Challenges in manufacturing and end-of-life recycling or disposal of solar PV panels

[1]Anupama Prakash, [2]Uma Rao. K, [3]SoumyaSaxena, [4]SushmitaT.Rayabagi

Abstract: *This paper deals with challenges faced in manufacturing and disposal of the solar panels. We see the solar energy as the green solution for the increased demand in energy, but at the same time we have to consider the problems that will occur after 20-30 years when solar panels will have to be disposed of. We cannot use these panels in bulk and make it to produce energy equivalent produced by thermal power plant till we have the skill to handle the waste produced by during the disposal of the panels. Some of the materials used in the solar panels are rare in nature and we cannot recover them later although they are used in small amount in the panels. Many of the compounds do not have the proper solution for its disposal so they are incinerated or landfilled which is very harmful for the environment. This paper contains the approximation of the waste produced by the solar panels if they produce one kW.*
Keywords: *electronic waste, environment, solar Panel, disposal.*

I. Introduction

With increase in today's energy demand, people are looking forward to solar energy as their future source of power. One of the best ways of harnessing solar power is to use solar panels. Initially the use of solar PV cells was confined to power bulbs and street lights. With reduction in cost and escalating energy costs, we now find extensive use of solar panels in large scale and small scale applications. Small scale uses include solar power pumps for circulating water, solar cooker, solar calculator, battery charger etc. Large scale includes setting up of solar farms to serve as micro grids or be integrated with main power grid.

Silicon-based solar PV production involves many materials similar to those used in microelectronics industry. These PV panels have a lifetime of around 20-25 years. Solar panels can be used efficiently for 20-30 years. Since the technology is new, majority of solar panels are less than 10 years old in India. So the knowledge of disposal of solar panels and the possible harmful effects caused by them to environment is not an issue of concern right now. The disposal of electronic waste is already a big issue as they are disposed inlandfills or incinerators and this can adversely affect the environment and living beings. The extensive use of solar panels like setting up a solar farm will definitely add to the electronic waste.The solar PV industry must address these issues immediately, or risk repeating the mistakes made by the microelectronics industry. Arsenic, cadmium telluride, hexa-fluoro-ethane, lead, and polyvinyl fluoride are just some of the chemicals used to manufacture various types of solar cells [1]. None of this poses much, if any; threat during a solar panel's working life. The problem, as the Silicon Valley Toxics Coalition pointed out in a 2009 report, comes at the beginning and end of a panel's life. Toxins potentially can be released during the manufacturing process, putting workers at risk, and when panels finally hit the scrap heap decades later. The main areas of potential concern are:

- The energy required to produce them.
- The procedure to dispose them at the end of their lifetime.
- Toxic and other potentially harmful materials used or produced during the manufacturing of PV panels/cells

In this paper we have highlighted the different components of solar power generation strategies, the possibility of recycling some of them and the harmful effects that may be caused by their disposal. Detailed analysis is made to calculate the amount of waste produced by a solar panel producing 1kW. The calculations include the PV cells, associated controls, batteries, power electronics and the materials used in each of them. The effects on environment and human health are discussed in detail.

II. Impacts of solar panels on environment

Potential adverse impacts to various resources associated with the construction, operation, and decommissioning of solar power plants are briefly outlined below.

Land Disturbance/Land Use Impacts

Utility-scale solar energy facilities require relatively large areas for solar radiation collection when used to generate electricity at utility-scale, i.e. of a capacity 20 MW and above. Since large area of land is occupied, this may displace some of the traditional uses of the land. A proper economic and social impact analysis has to be conducted before the installation of the solar farms, to quantize the effect. [4]

Impacts to Soil, Water, and Air Resources

The process of preparation of the land for construction of solar facilities requires clearing and preparation of the soil, probable alteration of drainage channels, which could lead to increased runoff and erosion.

Parabolic trough and central tower systems typically use conventional steam plants to generate electricity, which commonly consume water for cooling. This can be a drain on the local water resources and possible diversion of water towards this end, at the expense of water for conventional use, such as agriculture. Commonly used dust suppressants, dielectric fluids, herbicides, and other chemicals could result in contamination of surface or groundwater, making it unfit for consumption over a period of time.

Ecological Impacts

The clearing and use of large areas of land for solar power facilities can lead to loss of habitat of local wildlife. Further, particulate matter generated by solar facilities can cause significant pollution to nearby national parks and wilderness areas. Hence, these solar farms need clearance from the authorized local environment control boards, and cannot be randomly set up at any place, to preserve the local flora and fauna. Research on the actual impact of solar panels on animal behavior over a long period of exposure to the panels, in close proximity, is still not reported. Especially species like birds,reptiles, worms etc. which can come in direct contact with the panels, may be affected adversely. Solar PV cells are associated with electric and magnetic fields like any other power generation process. These fields can have more impact in this case, as the possibility of proximity to them is greater, since the panels are located in open space. Operation of solar facilities, and especially concentrating solar power facilities, involves high temperatures that may pose an environmental or safety risk.[4]

Other Impacts

The large solar facilities with numerous highly geometric and sometimes highly reflective surfaces,can have visual impacts and could possibly create the same visual impact as a mirage. Concentrating Solar Power (CSP) systems could potentially cause interference with aircraft operations if reflected light beams become misdirected into aircraft pathways.Aesthetic impacts are also present, though they are subjective and not necessarily a factor to be considered while setting up a solar farm. Cultural and paleontological artifacts and cultural landscapes may be disturbed by solar facilities.

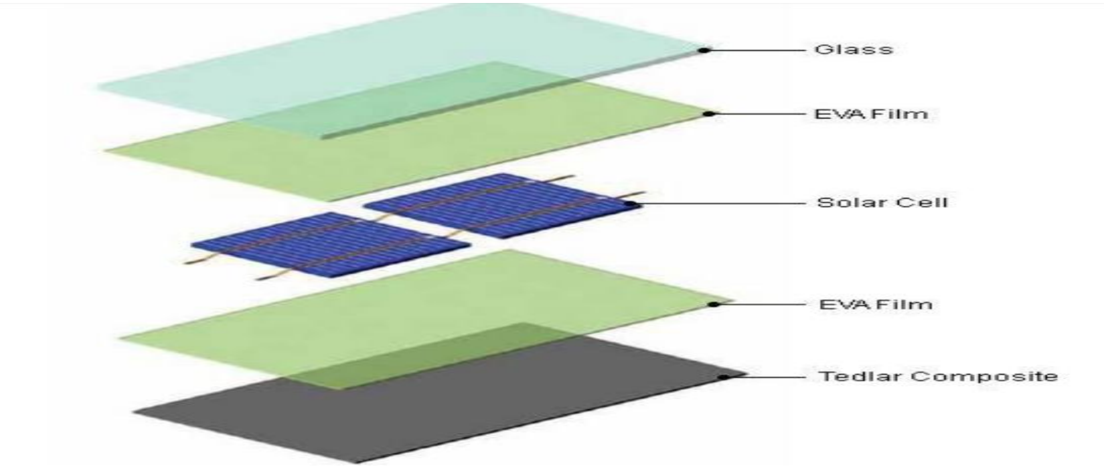
Photovoltaic panels may contain hazardous materials, and although they are sealed under normal operating conditions, there is the potential for environmental contamination if they were damaged or improperly disposed upon decommissioning. Concentrating solar power systems may employ materials such as oils or molten salts, hydraulic fluids, coolants, and lubricants that may be hazardous and present spill risks. Proper planning and good maintenance practices can be used to minimize impacts from hazardous materials.

III. Construction Of Solar Panel

The basic building block of a photovoltaic solar system is the solar cell. Solar cells are solid state,semiconductor devices that convert sunlight into electricity. Typically a number of individual cells areconnected together to form modules, or solar panels. A PV cell contains thecomponents as shown in the Fig.1. The major components are listed below:

1. The front cover is made of either glass or polymer film. It provides protection to the complete structure from the external elements.[5]
2. In order to provide electrical insulation and protect against environmental corrosion, the solar cells are encased in a transparent material referred to as an encapsulant.Encapsulate is made up of either Ethylene Vinyl-Acetate (EVA) or Poly Vinyl Butyral (PVB).
3. Solar cells are either Silicon mono-crystalline or poly-crystalline.[1]
4. To provide structural integrity the solar cells are mounted on top of a rigid flat surface called substratewhichis made from polyvinyl fluoride.

Fig.1. Components of solar panel



The composition of various materials used in Solar panels is tabulated in Table 1.

Table 1. Composition of solar panels

1.	Glass	65%
2.	Aluminium	20%
3.	EVA (ethylene vinyl acetate) or PVB (polyvinyl butryl)	7.5%
4.	Solar cells: Silicon of monocrystalline or polycrystalline.They are made up ofCdSe, Cds, CuO, FeS2, Mg2Si, SnS, ZnSe, CuInSe2 , CuS , MnS , Lead, Brominated flame retardant ,Crystalline silicone, Copper indium selenide and copper indium gallium selenide thin film PV, CaGs	4%
5.	TedlarFilm or substrate	2.5%
6.	junction box	1.0%

The solar panels are classified into two main categories as shown in fig.2.

Monocrystalline solar panels are made from a large crystal of silicon. They are the most efficient and most expensive panels.

Poly-crystalline solar panels are made from multiple silicon crystals. They are less efficient and also less expensive than monocrystalline panels.

Thin Film solar panels are thin and flexible. They are cheaper and are not affected by shading. The drawbacks are low efficiency, loss of wattage per sq. ft. installed and heat retention.They can be manufactured using silicon, copper indium gallium selenide (CIGS) or cadmium telluride (CdTe)

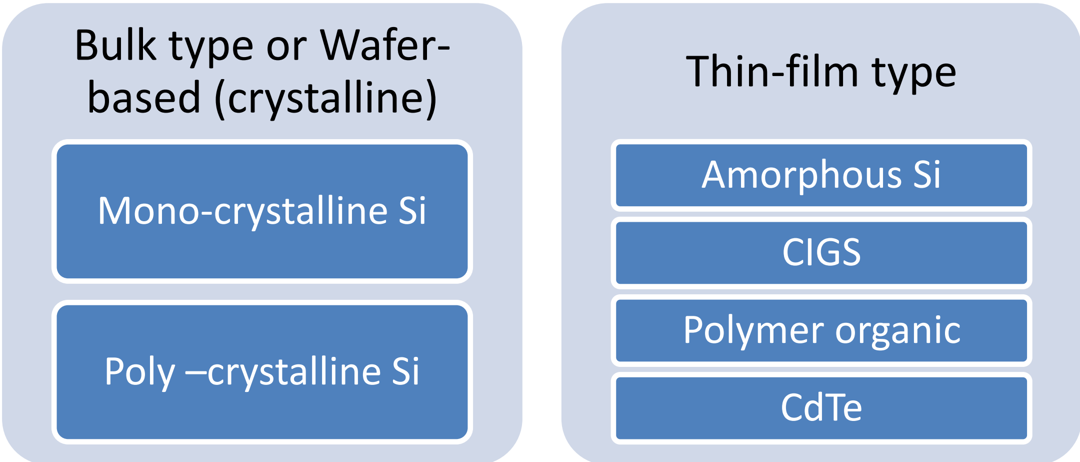


Fig. 2 classification of solar panels

IV. Environmental issues during manufacturing of PV cells

The most common material used is crystalline silicon which is obtained from quartz or sand.It isn't intrinsically harmful, but parts of the manufacturing process do involve toxic chemicals and these need to be carefully controlled and regulated to prevent environmental damage.The quartz is extracted from mines. A potentially harmful by-product associated with the mining and processing of quartz is crystalline silica dust. The initial refining turns quartz into metallurgical-grade silicon, a substance used mostly to harden steel and other metals. The metallurgical-grade silicon is then converted into a purer form called polysilicon. The refinement process involves combining hydrochloric acid with metallurgical-grade silicon to turn it into tri-chloro-silanes. The tri-chloro-silanes then react with added hydrogen, producing polysilicon along with liquid silicon tetrachloride. Silicon tetrachloride is highly toxic in nature.

Solar-cell manufacturers purify chunks of polysilicon to form bricklike ingots and then slice the ingots into wafers. The wafer is then subjected to high temperatures in the presence of phosphorous oxy-chloride in order to create the physical properties required to produce electricity.

An **anti-reflective** coating of silicon nitride is applied to the top surface of the cell to minimize reflection and increase efficiency of light absorption.

Finally, metallic electrical conductors are screen printed onto the surface wafer to facilitate the transport of electricity away from the cell. Individual solar cells are typically soldered together with copper wire coated with tin. Some solar panel manufacturers utilize solders that contain lead and other metals that if released into the environment can pose environmental and human health risks.

Issues:

Silica dust has been associated with silicosis, a lung disease where scar tissue forms in the lungs and reduces the ability to breath. Other health problems associated with regular, high exposure include chronic obstructive pulmonary disease, rheumatoid arthritis, scleroderma, Sjogern’s syndrome, lupus, and renal disease.

Silicon tetrachloride which is produced along with polysilicon transforms into acids and poisonous hydrogen chloride gas, when exposed to humid air. This can make people dizzy and can also make their chests contract. Silicon tetrachloride can cause skin burns and is also an eye and respiratory irritant Kerf dust, a byproduct of sawing the silicon ingots into wafers can be harmful if inhaled by living beings.Exposure to solvents, such as nitric acid, sodium hydroxide and hydrofluoric acid, used in wafer etching and reactor cleaning can be matter of great concern as they pose a risk of chemical burns. Handling of hydrofluoric acid requires extreme care, and it must be disposed of properly.Silanewhich is used in the deposition of anti-reflective coatings is highly inflammable and needs to be properly handled.

Lead present in solders is highly toxic to the central nervous system, endocrine system, cardiovascular system, and kidneys. The lead accumulates in landfills and thus discarded solar PV panels which contain lead have the potential to pollute drinking water. In one study, solar PV panels using lead solder exceeded the maximum allowable concentrations for lead by 30 percent in the Toxicity Characteristic Leaching.

Mitigation measures:

a. To give protection against silica dust one should air quality monitoring, automation of processes to limit human exposure, dust suppression measures and personal protective devices for workers such as respirators.

b. The facilities should use a closed loop process that captures system byproducts for recycling and reuse within the process loop because these recovery systems are necessary for the economic operation of a facility. Furthermore, any waste gasses not recoverable forrecycling are led through a series of pollution control technologies (e.g. wet scrubbers) prior to any environmental releases. Environmental releases include very low levels of particulate matter, hydrogen chloride and silicon tetrachloride.

Environmental effect in manufacturingThin- film Solar cell**:**

Although more than 90 percent of photovoltaic panels made today with polysilicon, there is a newer approach: thin-film solar-cell technology. The thin-film varieties will likely grow in market share over the next decade, because they can be just as efficient as silicon-based solar cells and yet cheaper to manufacture, as they use less energy and material.Makers of thin-film cells deposit layers of semiconductor material directly on a substrate of glass, metal, or plastic instead of slicing wafers from a silicon ingot. This produces less waste and completely avoids the complicated melting, drawing, and slicing used to make traditional cells. In essence, a piece of glass goes in at one end of the factory and a fully functional photovoltaic module emerges from the other.Moving to thin-film solar cells eliminates many of the environmental and safety hazards from manufacturing, because there’s no need for certain problematic chemicals—no hydrofluoric acid, no hydrochloric acid. But that does not mean one can term thin-film solar cell as green.Today’s dominant thin-film technologies are cadmium telluride and a more recent competitor, copper indium gallium selenide (CIGS). In the former, one semiconductor layer is made of cadmium telluride; the second is cadmium sulfide. In the latter, the primary semiconductor material is CIGS, but the second layer is typically cadmium sulfide. Soeach of these technologiesuses compounds containing the heavy metal cadmium.

V. Effectsand disposal schemes for substances used in solar panels

There are many substances in the solar panels which are toxic and are carcinogenic and pose serious threats to the environment and living beings. The ingestion of these substances can damage the bones; can have a serious impact on the functioning of vital organs like kidney and liver. The inhalation of some of these substances may even lead to lung cancer. There are many rare metals like indium and gallium used in solar panels. There can be permanent depletion of these rare metals if they are not recovered at the end of life of solar panels. An attempt has been made to list the effects and disposal procedure of all the materials used in solar panels.

1. Encapsulant

The ethylene vinyl acetate encapsulant and polyvinyl butyral substrate are typically not recoverable and removed through a thermal process. If not properly decommissioned, the greatest end-of-life health risk from crystalline solar modules arises from lead containing solders. Under the right conditions it is possible for the lead to leach into landfill soils and eventually into water bodies. If removed through a thermal process theby-product ash is land-filled.

Disposal Methods:

- Thermal Dismantling: The thermal dismantling process involves heating ethylene-vinyl acetate compounds up to their melting point i.e. 1,472 degrees Fahrenheit. [2]
- Vacuum Blasting: Vacuum blasting is a technique that uses vacuum instead of air pressure.
- Wet Mechanical Treatment Attrition: Mixing devices fitted with rotating agitator are usually used to separate soil from toxic substances. There is usually no use of chemicals as only the addition of water is important.
- Hydro Cyclones: Burning of ethylene vinyl acetate compounds leads to release of toxic and carcinogenic compounds to the atmosphere. As a result, people have turned to density cyclone separation methods. These methods are based on particles of plastics floating or sinking in a separation media of a given density usually under the force of gravity. These methods are applicable for recycling large volumes of plastic materials such as ethylene vinyl acetate of different sizes.

2. Substrate/ Tedlar film:

It ismade from polyvinyl fluoride. TedlarFilm in itself is non-hazardous but releases hydrogen fluoride on heating. The inhalation of this might lead to choking, coughing, severe eyes, nose, and throat irritation. The overexposure of this can even injure liver and kidney. It also has dimethyl acetamide which can cause several skin problems.

Disposal method: The preferred option for disposal is landfill. It can also be incinerated, if incinerator is capable of scrubbing hydrogen fluoride and other acidic components.

3. Solar Cell:

Bulk type/Wafer-Based Solar cell

It consists of various substances as listed in Table1. These materials and their disposal methodsare discussed in brief in the following section:

a. **CdS,CdSe:**These used in solar cells to improve the efficiency. The exposure to this can cause nausea, respiratory problems, abdominal pain, and cancer.

b. **CuO**: It makes a good absorbing layer because of its high solar absorbance and low thermal emittance.It can cause damage to the endocrine and central nervous system. Contact to the eyes or skin can cause irritation.

c. **FeS2**:It demonstrates extremely promising results for use as the active layer in solar photovoltaic and photoelectrochemical cells.Sulfate released from decomposing pyrite combines with water, producing sulfuric acid, leading toacid rock drainage and potentially acid rain

d. **Mg2Si**: Magnesium silicide is primarily used in thin film applications due to its difficulties in crystal growth.

e. **SnS**:SnS is an absorption layer in n-type solar cells with a wide band gap. It has little toxicity to humans and the environment.

f. **ZnSe:**It is a bufferlayer that has reached total area efficiencies of up to 9.6% (under AM 1.5 illumination), an open circuit voltage of 482 mV, a short circuit current of 31.0 mA/cm2 and a fill factor reaching 64%.
g. **CuInSe2**:.$CuInSe_2$ is used in the absorber layer.
h. **MnS:** is a dilute magnetic semiconductor that is used in solar cells as a window/ buffer layer. If Manganese enters soil then it causes disturbance in the plant mechanism. It disturbs the division of water into hydrogen and oxygen and their distribution in the palnt.
i. **Brominated flame retardant**: Polybrominated biphenyls (PBBs) and brominated diphenylethers (PBDEs) are used in circuit boards and solar panel inverters (which convert DC to AC power). PBDEs, which bioaccumulate in fatty tissues, are recognized as toxic and carcinogenic and are described as endocrine disrupters.
j. **Crystalline Silicon (c-**Si): Crystalline silicon is made using silane gas, the production of which results in waste silicon tetrachloride which is toxic. It can be recycled into more silane gas but has the potential to cause harm.
k. **GaAs**: crystals will release arsine or arsenic if deposited in landfills. Arsenic is highly toxic and carcinogenic. The limited toxicological data on GaAs suggest that it could have profound effects on lung, liver, immune, and blood systems. No recycling method is available.
l. **Sulphur Hexafluoride** is used to clean the reactor used in silicon production. If it escaped it would be a very potent greenhouse gas. It can also react with silicon to create a range of other compounds. (SF_6), a substance 22,800 times more dangerous to the environment than CO2, according to the Intergovernmental Panel on Climate Change (IPCC).

Disposal method of above materials: As outlined above, c-Si PV circuitry and inverters contain hazardous materials such as lead, brominated fire retardants, and hexavalent chromium. Toxics contained in the modules themselves are below levels regulated by the EPA. Recycling options: Used silicon (Si) wafers can be melted into Si ingots and cut into new wafers.

Thin- film Solar cell

Thin film silicon reduces the volume of material needed by spraying a thin layer of silicon on toa surface, so has the potential to reduce impacts and waste. A part of the thin film cell contains cadmium telluride, a highly toxic substance that cannot be allowed to come in contact with the atmosphere. It needs to be captured and recycled. Most manufacturers refrain from using the substance in the first place to avoid dealing with the difficult recycling process.Instead, most resort to crystalline silicon, which is made up of easily recyclable materials like glass, aluminum, copper and plastic foil, along with silicon. These are also easier to dispose [3].

Copper Indium Selenide (CIS) and Copper Indium Gallium Selenide (CIGS) Thin-Film PV modules rely on new semiconductor materials. CIS and CIGS are much less expensive than c-Si because they can be printed onto glass, and, as thin films, use less material. In this the primary semiconductor material is CIGS, but the second layer is typically cadmium sulfide. Companies based in California and Massachusetts are using nanotechnology to increase CIGS efficiency,but with the use of nanotechnology comes uncertainty about environmental, health, and safety hazards.

Selenium is a regulated substance that bio-accumulates in food webs and is considered highly toxic and carcinogenic by the EPA. CdTe is often used in these modules as a buffer material, which also introduces the CdTe toxicity issues noted above. CIGS has toxicity levels similar to CIS with the addition of gallium, which is associated with low toxicity. CIS and CIGS use CdS (cadmium sulfide) as a buffer layer.So each of these technologies uses compounds containing the heavy metal cadmium, which is both a carcinogen and a genotoxin, meaning that it can cause inheritable mutations.

In an acute toxicity comparison of CdTe, CIS, and CIGS, researchers found CIGS to have the lowest toxicity, and CdTe to have the highest.

Disposal and Mitigation: The best way to avoid exposing workers and the environment to toxic cadmium is to minimize the amount used or to use no cadmium at all. Already, two major CIGS-photovoltaic manufacturers—Avancis and Solar Frontier—are using zinc sulfide, a relatively benign material, instead of cadmium sulfide. And researchers from the University of Bristol and the University of Bath, in England; the University of California, Berkeley; and many[2] other academic and government laboratories are trying to develop thin-film photovoltaics that do not require toxic elements like cadmium or rare elements like tellurium.

VI. Analysis of waste generated by PV cells

Without effective and safe recycling programs, broken, defective, and decommissioned solar PV equipment will enter the waste stream. It will end up in landfills (where toxic materials can leach into groundwater) or incinerators (where burning can release toxic materials into the air). One disposal option is to recycle solar PV panels at existing responsible e-waste recycling facilities or at facilities that recycle batteries containing lead and cadmium, thereby keeping toxics out of municipal incinerators and landfills. However, these hazardous waste recovery facilities are often use sub-standard technology and are in need of substantial research and development to improve their environmental footprint. For example, most recycling facilities reclaim metals using smelters, which are known to increase the risk of lung cancer (from cadmium exposure) in nearby communities and the workplace.

If the solar panels are not reused or recycled, overtime there will be a significantloss of precious resources such as glass and aluminum. As solar panels also use some rare metals like indium and gallium, not recovering them at the end life could cause their permanent depletion. An analysis indicating the amount of solar waste generated per year in India is done to give an insight of the actual problem.

It is known that maximum efficiency of solar panels is approximately 20%.

India receives approximately- 4-7 kWh per m^2 per day (assuming 6 kW per hr)

If 1kW is incident per m^2 then 200W is harnessed to electrical power.

So we need 5 m^2 for 1000W but considering other factors like wind and dust that will reduce the efficiency and will result into the loss of 20% so actual production is around 800W. Therefore, we need around 6.25 m^2 for 1 kW of power. The weight of the solar panel is approximately 13-14 kg/m^2. This gives us around 82 kg for 1kW. The component weights are as follows: glass - 65%; Aluminium-20%, 7.5% is ethylene vinyl acetate and 2.5% is polyvinyl fluoride substrate which is usually not recycled. These numbers, give an idea about the quantities involved when the panels have to be disposed. The substances which are not recycled are either incinerated or deposited by landfilling. This causes harmful effects as these substances can enter any living organism through ground water, soil, absorption by plants in the vicinity etc.

VII. Conclusion

In this paper, some aspects of solar PV manufacturing and disposal mechanisms have been discussed. Irrefutably solar power is going to play an important role in the power sector of the next generation, and hence we cannot avoid increased penetration of solar PV cells, both at small scale and large scale. However, it comes at a cost. Technologies have to evolve for efficient recycling and disposal of these panels, along with leading research in the manufacturing processes, to enable the world to be prepared for it, when the time for massive disposals arrives. We cannot afford to postpone solutions or turn a blind eye to the problem, since the problem exists and its nature is extremely harmful, if not handled properly.

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