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# END – OF – LIFE MANAGEMENT OF PV PANELS IN INDIA

**Balaji M[1], Rahul Hiremath[2]**

[1,2] Symbiosis Centre for Management and Human Resource Development Symbiosis International (Deemed University), Pune, India
Email: [2]rahul_hiremath@scmhrd.edu

**Abstract**

There has been a rapid growth in Indian photovoltaic (PV) sector in terms of capacity and production but there is no initiative towards disposal or end of life (EOL) of solar PV panels. Considering an average panel lifetime of 25 years, solar PV waste quantity in India is estimated to grow to 2 lakh tonnes by 2030 and around 1.8 million tonnes by 2050. Currently, there is no policy or guidelines for proper disposal in India. Existing global practices and policies of various countries like Germany, UK, China and Japan are compared in order to bridge the regulatory gaps in India regarding PV recycling. This paper enhances the understanding on the harmful effects of improper disposal, reason/challenges to move towards an advanced recycling of PV panels. Further it recommends for circular economy and also discusses various challenges associated with it..

**Key words:** End of Life, E – waste management, Photovoltaic solar panels

## Introduction

Solar PV technology is a rapidly growing technologies for energy security improvement and as well as step towards an environmental friendly and sustainable energy sources. With backing and support from policy makers and political aspect providing green source of energy a drastic push mainly the solar energy throughout the country. The recent trend in solar energy sector suggests at a rapid rate of increase in India and also across the entire world (Kabir et al., 2018). The capacity addition being in limelight, an important aspect of photovoltaic module disposal is ignored. (Chaudhary & Vrat, 2018).

The waste quantity of solar photovoltaic module is estimated to rise to two lakh tonnes by 2030 and approximately 18 lakh tonnes by 2050 (Suresh et al., 2019). The manufacturing of a solar PV cell includes a wide variety of materials like silicon, glass and fractions of polymer. Major constituent consist of glass and aluminium which accounts for approximately 80% of total weight. These materials are not hazardous in nature.(Weckend et al., 2016) But there are a minority materials which are hazardous in nature. These consists of materials like polymers, metals and its alloys.

Currently the recycling regarding the Photovoltaic waste is at a nascent stage and around 75% - 80% of the material is recovered by the metal and glass recyclers (Corcelli et al., 2018). The potentially hazardous materials are often left unrecovered. The basic reason behind this issue is that it is not feasible and the cost of recovery overruns the value of the materials recovered.

In India, the unwritten rule and usually followed practice is that the solar PV manufacturers are responsible for the end of life or disposal. Even in tender document it states the same but there is no mention of it in e – waste rules and eventually it leads to nobody's responsibility (Suresh et al., 2019).

## Literature Review

A study regarding *Recycling of photovoltaic panels by physical operations,* (Granata et al., 2014) , was focused on the working process of photovoltaic cells recycling. Two methods of approach was studied : heating treatment after a two blade rotors is used to crush and another one is hammer crushing after two blade rotors is used to crush the panels. These experiment has led to the conclusion that a combination of above two methods lead to effective recovery of materials. Even though solar PV panels was a growing industry, it talked about its efficient way of recycling.

The need for efficient recycling arises because of the improper handling of solar PV cells This was highlighted in *Life Cycle Assessments of an innovative recycling process for crystalline silicon photovoltaic panels,* (Latunussa et al., 2016). The study focuses on the impacts of incineration of photovoltaic panels. It also focusses on the various methods available to extract silver, silicon and other valuable materials. This incineration of photovoltaic module contributes around 20% of the global warming impact and approximately 30% from the after effects of this incineration or being disposed off to land filling which leads to leaching of potentially hazardous materials into the soil and thus affects the ground water table.

With every problem lies a business opportunity, *Analysis of long term impact of the end of life solar panels as e-waste in India,* (Chaudhary & Vrat, 2018) talked about increasing PV waste and its huge scope associated along with it. Major Companies could take over as key player in end of life management. The stakeholder awareness and education regarding end of life panels is discussed. It emphasizes the need for photovoltaic-specific regulations, which includes collection, segregation and eventually recycling to manage the ever increasing volume.

European Union being the first to bring in policies and framework regarding solar PV ,*Policies and Measures for Sustainable Management of Solar Panel End-of-Life in Italy,* (Malandrino et al., 2017) emphasizes the opportunities evolving from the managerial and technical options available for a better recycling and recovery of photovoltaic panels in Italy. The conclusion of this paper stated the importance of circular economy in PV panels through awareness of stakeholders, in order to achieve a green energy life cycle.

With the policies in place it was necessary to make it feasible, *Management of end-of-life photovoltaic panels as a step towards a circular economy,* (Sica et al., 2018) provides a basic framework by analyzing various environmental and technological issues arising from photovoltaic module production. Eventually, it emphasizes on huge scope in this solar PV industry as whole and its untapped recycling industry potential. The suggestions provided were meant to be helpful for future research works regarding this topic and stressing on the point that circular economy will lead to a feasible advanced recycling of PV panels.

*An overview of solar photovoltaic panels' end-of-life material recycling*, (Chowdhury et al., 2020) gave importance to the European Union directives and its possible future issues faced during disposal or manufacturing of PV panels and it also suggested the need of better policy and recommended solutions for the same. This review paper was based on the present state of solar photovoltaic panel recycling, its technology used to achieve it and feasibility of recycling.

**Methodology**

The above stated research papers were mainly focussed on the process of advanced recycling, its methods or a better way to achieve it. Due to the fact that advanced recycling is not feasible, often these panels are sent to traditional glass recyclers. Few other research were based on foreign regulatory policy but not in context of Indian situation but of EU directives. Eventually (Chowdhury et al., 2020) talked about the circular economy but not about the challenges in it.

The purpose of the study is to enhance the understanding on the harmful effects of improper disposal, reason/challenges to move towards an advanced recycling of PV panels and bridging the existing gaps in PV module disposal regulation in India. Further it focuses on challenges in circular economy and an approach towards feasible recycling. The data was collected through secondary sources like reports, government websites, research papers, journal articles etc.

**Analysis**

**Effects of improper disposal**

Solar energy in India is quite captivating source and widely regarded as the future energy source throughout the world. It also has a good support in terms of capacity addition from government policies and its feed in tariff reducing over the years, its simplicity in operation and marginal maintenance has led to a rapid growth in solar industry in India (Kabir et al., 2018).

On the other hand solar photovoltaic module disposal is quite challenging due to the use of hazardous materials present in it and improper recycling leads to harmful effects on environment and human health. In order to call solar energy as clean fuel we must justify its disposal plan which is end of life management in solar PV cells.

Some of the materials used in manufacturing of solar PV panels include polymers, silver and lead components. These materials are hazardous in nature if disposal is not carried out in a proper way which can lead to underground leaching thus affecting the ground water table. This could lead to potential environmental losses in reproductive rates in animals and plants, loss in biodiversity (Bogacka et al., 2017). In case of human health, various issues affecting kidney, immune system and nervous system is possible. The cadmium present is at a great toxic level and also has a great chance of potential accumulation in human bodies (Tammaro et al., 2016).

The material like polymer constitutes of encapsulation with fluorinated plastics and back sheet. These material are usually difficult to recover and are mostly sent to incineration. Improper disposal of such material or burning affects the environment and all the life forms around due to toxic gases emitted during the burning process (Dubey et al., 2013). In case of burial, these waste leaches into the soil and gets mixed with the groundwater and soil which in turn has a huge impact on environment.

The classification of solar photovoltaic waste is based on the impact it creates on environment, commercial value and recyclability. In case of environment impact, Ministry of environment - Hazardous and other wastes rules 2016, GOI is followed. (Management and Trans boundary Movement). According to these rules, definition of hazardous waste is defines as any waste which because of its toxic, chemical, physical, flammable, corrosive or explosive nature is likely to cause danger to environment or health.

**PV Waste Management**

The photovoltaic solar waste recycling is at a nascent stage all over the world. Many countries consider solar photovoltaic waste as industrial waste or e-waste. In some place of Europe, it is separately defined as solar PV waste nut still they end up at traditional metal and glass recyclers.

The E-O-L management of solar photovoltaic panels will give rise to a new industry which in turn can create a sustainable and economic value creation in long term. It can provide job opportunities in public or private sector (Hussin et al., 2018). In case of PSUs, job can be created through local bodies who might be responsible for public waste management and in case of private players, photovoltaic solar module manufacturers or producers could turn out to be a critical beneficiary. In developing countries, these opportunities could be utilized by the informal players who usually dominate this waste management sector. Not only in end of life management but employment opportunities could be created for repair and reuse industries which promotes to a holistic betterment of solar photovoltaic waste management. (Domínguez & Geyer, 2017)

**Conventional recycling method**

The widely used method by glass and metal recyclers for separation of laminated structure is mechanical process. It starts with the removal of copper and aluminium through automated or manual techniques. It is then crushed by crusher and sieved thoroughly. Magnets and inductive are used to extract the fractions of polymers and glass substances. These fractions of metal particles are sent to recyclers for smelting. Some bits of polymers, metals and silicon will be present in Glass fractions. Usually lower quality glass is not used for solar

PV module manufacturing and hence sent to construction industry (Nevala et al., 2019). A combination of chemical and thermal process is required for glass recycling which is currently followed by the traditional recycling plants.

The materials like polymer constitutes of silicon, glass and some metals (Kusch & Alsheyab, 2017). Countries without any rigid policy do not follow any proper disposal guidelines and hence end up at landfills or burnt which leads to serious health and environment hazards. On the other hand using a special incinerators would cost the recycling plants a extra 10% to 15%. In case of such traditional method, only 70% to 80% of the materials by weight is recovered and glass being the majority of it (Ardente et al., 2019). But an important issue regarding this traditional methods is that valuable materials like silicon and silver and potentially harmful materials like polymers are not recovered.

With new developments in solar PV technology, valuable materials like silicon and silver are reduced in order to cut the manufacturing cost. Within 10 years silver content present in the PV module is expected to reduce by 50% (Louwen et al., 2016).

**Advanced Recycling Method**

A combination chemical and thermal process is used to extract the materials like copper, tin, aluminium, silver and lead. Some fraction of polymer around 8% to 10% by weight is not recovered and has to be landfilled or burnt accordingly (Chowdhury et al., 2020; Huang et al., 2017).

Such process of recycling is not that common and has a data gap on the accuracy of recovered material. Recent studies state that approximately 90% of the solar photovoltaic waste could be recovered ("The Opportunities", 2020). Such advanced process of recycling is currently not feasible due to the fact that cost of mobilization is more than the value of material extracted (Suresh et al., 2019).

Recent research and development is focussed on enhanced recovery of such valuable materials like silver so as to make this process feasible. By 2030, the advanced recycling of solar photovoltaic panels is expected to become feasible due to the influx of increasing volume (Weckend et al., 2016).

**Challenges in Advanced Recycling**

The major challenge in moving towards an advanced recycling from conventional method is its economic feasibility and lack of proper government policies and regulation. The solar panels life span is around 25 years (Ludin et al., 2018) hence the panels which currently comes in for recycling have either been installed 25 years back or got damaged before its life span.

Currently this volume is not sufficient and economical for advanced recycling as the cost of mobilization is more than the value of extracted material. This challenge is mainly due to the lack of proper recycling facilities throughout India which makes transportation cost a major concern (Tansel, 2017). India is currently lagging behind in terms of technical capability to build such advanced recycling plants. These issues can be dealt by having a proper policy and guidelines which mandates the use of it (Weckend et al., 2016)

Another challenge is behavioral and awareness of manufacturers as well as consumers about the improper disposal of solar PV panels and the need of an advanced recycling. Even though these panels do not have any harmful effect during its operation, it's the quite opposite during its disposal (Zhang et al., 2012) Along with the benefits of solar panels, awareness for the need of better disposal should be emphasized. Solar energy is not a green energy unless and until it's End – of – Life management is taken care of.

**PV Waste Policies and Regulation**

**Germany with solar PV Waste Policy**

Germany follows a specific solar photovoltaic waste management policy with European Union - directed. The Waste Electrical and Electronic Equipment (WEEE) of European Union was revised and transformed into a 2015 law. According to the new policy, proper collection, segregation, and disposal of solar photovoltaic waste has been in effect since then. National Register for Waste Electrical Equipment is responsible for regulating the E- waste in Germany (De Boeck et al., 2016). It has a record of all the electronic waste producers. It manages the pickup and allocating containers. Moreover, National Register for Waste Electrical Equipment is not the only body responsible for all the tasks like collection, segregation or disposal of solar PV waste. These operations come under the producer responsibilities and are accountable for disposal in a proper way which is advanced recycling ("Elektrogesetz", 2013)

Germany has multiple solar photovoltaic waste collection point throughout the country and a separate disposal and treatment is executed. So if an owner of solar photovoltaic module wants to dispose it, they can simply walk into any collection point where it will be freely accepted and is widely followed by Germany for private residential owners (Mehta, 2017). But the dismantling of the solar Photovoltaic setup requires professional skills, so it is most suitable that the PV panels should be routed through the manufacturers' network. The basic idea behind this is that the producers who dismantle the panels are more favourable to take the responsibility of disposal. Such panels will be brought back to B2B e- waste process or to the advanced recycling factories set up by the manufacturers.

**United Kingdom with solar PV Waste Policy**

United Kingdom is a futuristic market with proper solar photovoltaic waste specific policies and regulation as per European Union Directive. On 1st January 2014, WEEE directive was implemented for proper disposal of PV waste through collection, segregation and recycling. Before this enforcement, the unwritten rule was that the producer was responsible for disposal of solar PV modules and was a voluntary act done by them (Reid & Wynn, 2015). Before the implementation of proper policy in 2014, majority of the E-O-L arising would be covered through manufacturer's warranty and gets back through B2B channel.

The United Kingdom government has laid out some rules and regulations for defining a solar photovoltaic manufacturer. A solar photovoltaic module manufacturer under this policy must follow as a UK producer and selling under their own brand or imported by some other person under own brand ("Regulations", 2018).

For the financing of B2C and B2B sales, the UK government has a differed from European Union directive. Solar photovoltaic module manufacturers are supposed to finance their collection on the basis of their market share (Suresh et al., 2019). For example, a manufacturer has set up around 10% of the panels in a particular year is expected to pay for the disposal of 10% of the PV waste collected the next year while the placing year being ignored (Sharma et al., 2019).

The solar photovoltaic manufacturers are supposed to fund for the disposal of commercial panel set up, panels which has a wheelie bin symbol and must be replaced if those symbols are missing.

**Japan without solar PV Waste Policy**

Japan is a forerunner in solar PV setup without a proper policy for disposal in place. As it does not have a policy or guidelines to manage the disposal of solar PV panels, all e- waste including solar PV panels are treated under one roof which comes under Waste Management and Public Cleansing Act (Mansouri & Kacha, 2017). This act states the solar photovoltaic waste, industry waste and the responsibility of the producer. A new policy called feed-in-tariff is in proposal stage for renewable energy which comprises of E-O-L management of solar PV panels without any penalties or obligation.

Due to the lack of solar PV specific policies in Japan (Chowdhury et al., 2020), the PV waste are expected to be treated similar to other e – waste. Even though there is a lack in present data on E-O-L management in Japan, the volume of PV waste is expected to be low in near future, provided the recent market growth to rise significantly (Komoto, 2018). Even though the country lacks a proper policy, many trends in political and R&D helps them to create a base for recycling and recovery.

**China without solar PV Waste Policy**

China is the market leader in solar photovoltaic capacity installation but still lacks a specific policy for disposal. The estimated waste of PV modules is 8,000-100,000 tonnes in 2020 and a surge to 13.5-19.9 million tonnes by 2050 (Weckend et al., 2016). Currently, the country lacks a specific policy to manage the disposal and recycling of waste PV panels but according to the 2011 regulation, it mandates the e- waste to be recycled and collected in a centralized system. The manufacturers can do this by themselves or can outsource the collection or disposal process to qualified companies (Chen et al., 2016). At present, solar photovoltaic modules do not have a separate processing directory of the regulation.

The present waste volume is low which does not rise the seriousness of China not having a proper disposal policy which in turn led to improper recycling infrastructure for PV specific disposal or recovery. However, China has sponsored extensively on R&D on solar photovoltaic module which mainly focuses on 2 recycling methods. These research come under China's National High-tech R&D Programme, Solar PV Recycling and Safety Disposal Research from 2012 to 2015 (Hong et al., 2016). The methods focused were mostly based on thermal or physical recycling. In physical method, processes like grinding, crushing, and separation is carried out which gives out a powder mixture of copper aluminium, back sheet particles and glass cullet. The productivity of such recycling is around 85% by weight ("The Opportunities", 2020). The drawback in this recycling is that silicon extracted cannot be used again due to its poor quality. On the other hand the thermal method is used for experiments involving recycling of aluminium, silicon and silver.

Even though the country does not have a specific policy for disposal of solar photovoltaic panels, the work related to it has begun already (Man-Tung, 2018). Policy and future technology related research are being carried out extensively by National High-tech R&D Programme. With respect to regulatory policy, need for solar PV specific disposal guidelines, financing the process and responsibility allocation is expected (Xu et al., 2018). On the other hand, technology advancement and R&D, is moving towards developing high efficiency, less energy and low cost solar PV panels. Improvement of onsite or mobile recycling for disposal of solar photovoltaic cells are considered.

**India without solar PV Waste Policy**

India is a country without solar photovoltaic disposal policy or guidelines. The power sector in India at present faces 2 critical challenges. Firstly, it is expected to provide energy security to a great extent. Secondly, it must meet the demand arising yearly due to rapid economic growth. Even though 2020 may be a setback due to covid 19 pandemic, the country is expected to bounce back ("Fitch rating", 2020). There is a significant scope for renewable energy especially solar energy. (Mohan, 2017). The Government of India initially planned to install 100 GW of solar panel capacity by 2022 (Hairat & Ghosh, 2017). This renewable energy also depicts an alternative to the conventional grids.

Currently, the country does not have a mandatory collection or disposal of solar photovoltaic panels which typically means that the waste generated due to solar PV waste modules comes under the general waste regulation only (Sheoran et al., 2020). These waste come under Waste is managed by the MoEFCC under the 2016 Solid Waste Management Rules and the Hazardous and Other Wastes Rules. More recently the Hazardous Waste Rules is amended and now it includes use of Toxic Characteristic of Leaching Procedure.

The Indian Policies at present are generic for e- waste and has restricted the inclusion of potentially harmful materials in electrical products. However, this rule is applicable for household appliances only but not for solar

photovoltaic modules (Mani & Singh, 2016). An e- waste recycling facility following this policy already exist but covers only residential appliances and not solar photovoltaic panels.

In 2015, 20GW by 2022 of solar PV grid connected system was proposed which was later revised to 100GW (Hairat & Ghosh, 2017). Even though it could be delayed due to the pandemic, the huge amount of PV waste generation in future is inevitable. Even though India at present does not have a proper policy regarding PV panel disposal, increasing growth in PV waste is likely to make the policy makers to draft one in future.

**Linear PV Lifecycle**

The current lifecycle of solar PV panels in India follows the traditional take-make-dispose model. At the end of its life span, when panels fail, fall below desirable performance or wear out in their natural life time then they are retired from operation and it is sent for disposal (Arup, 2020) These are mostly sent to glass recyclers where valuable materials like silver are not extracted. Even though silver is present in small quantities, it represents a significant share in global consumption. The value of silver constitutes approximately 50% of the total material value followed by aluminium which holds approximately 25% of the material value (Wong, n.d.).

In Linear PV Lifecycle even though it is destined to reach recycling units for disposal, considerable amount of panels often end up in landfills and dump yards which leads to leaching of harmful chemicals into groundwater thus affects the whole surrounding.

**Circular Economy**

The circular economy presents an opportunity for government, businesses and consumers to rethink the traditional take – make – dispose model of consumption and develop business models that produce better economic, social and environmental outcomes The circular economy provides a holistic approach to PV lifecycles that gives variety of benefits (Gaustad et al., 2018). Not only does it strives to achieve a reduction in waste and landfill volumes, but also towards the generation of new markets, better utilization rates, resource efficiencies, economic stimulation and better social outcomes.

Business models that are based on the circular economy enable:

• Better authority of resource streams.

• Supply chain innovation

• Increased co-operation within the supply chain.

• Creation of services that capture value

More importantly, these benefits are maximized and more likely to be simultaneously achieved when all elements of a business model are circular (Mathieux et al., 2017). With a model which focuses only on recycling is theoretically not as economically sustainable as one that focuses on a mixture of models, such as sustainable material development, sharing and reusing platforms, and recycling (Brenner & Adamovic, 2017). It is not only about dealing with waste, but about reducing its total demand and increasing overall efficiency and impact.

Circular economy for PV panels can be broadly classified into 3 categories –

**Circular Design**

It is important that circular products are designed with the end-of-life in mind, as well as the potential for repair, upgrade and part removal during their life. Common strategies to achieve more circular designs include standardization and modularization.

Standardization would mean a more harmonious method of assembling panels across the PV industry. In such case potential recyclers would have to use lesser techniques to recycle different panel types (Gallagher et al., 2019) Modularization for the PV panel industry is probably less applicable as the nature of PV systems – being made of PV panels – means the systems are already in fact modular at least at a high level. Therefore, focusing on ensuring the panels are designed for deconstruction will be key, in order to facilitate an efficient recovery process (H. Kim & Park, 2018).

Over the years there has not been a significant change in material mix of solar photovoltaic panels. But over these years considerable saving on the materials have been attained with better efficiency of metals and resources. Researchers over the years have tried to reduce the hazardous substances like cadmium and polymers through various other alternatives (Fthenakis, 2018). Some research were focussed on cost reduction techniques of solar photovoltaic panels in order to cut the manufacturing cost (Lesniewska, 2017). As the usage of valuable and rare material will also increase along with the solar PV panel market, cost and availability of material will be of key concern which in turn will drive towards alternate materials. The other materials present in photovoltaic panels is not of major concern and only valuable materials might have limitation in future (Wadia et al., 2009). Moreover, the hike in price could help improve the feasibility of recycling activities as of now the extraction of material is not economical.

**Barriers in Circular Design**

It generally requires a level of standardization and collaboration among companies. Every company might have their own design and their own reason to use them hence to achieve a common platform for all could be an issue.

Many countries like India, Australia, and import manufactured solar PV panels and only assembling is done within country. To achieve standardization among countries will be critical.

Lower market acceptance or understanding of reused or recycled products among consumers is a key issue to address and significant upfront investment required is required.

Moreover data about its performance, life span and operational costs is uncertain. Most importantly there is a gap between designers and recyclers (Arup, 2020)

**Circular Use**

The people living in apartments might not have their own roofs but a common and shared roof. Sharing platforms can be created for people who do not control their roof, find it difficult, or impossible to place solar PV on their buildings. By enabling these groups, solar PV with high utilization rates due to sharing between building users could be achieved (B. Kim et al., 2019). This has the extended benefit of expanding the accessibility of solar to more of the community. Solar gardens provide the opportunity to share solar PV, especially for renters or people with shaded roofs.

Another way of Circular use is through leasing of solar PV setup. Through leasing, consumers commit to paying a certain amount of money for the use of the panels. This involves delivering performance rather than products, where the ownership is retained by the service provider (Liu et al., 2014; Rai et al., 2016) The service provider is well placed, and has scale, to more efficiently manage and maintain the asset than the consumer.

**Barriers in Circular Use**

A shift from upfront investment to ongoing payments has potential implications for operating capital and taxation.

The Payback period is often greater, and this influences the kinds of loans required.

Consumer preference for new, individual products, rather than shared or service based products.

Restrictive rules that prevent renters, apartment owners or other community members from installing and sharing PV

Long term commitment and not suitable for frequently migrating tenants (Salim et al., 2019; Svatikova et al., 2015)

**Circular Recovery**

During the early stage usage of solar PV panels, if a defect is detected, customers may claim guarantee or warranty for replacement or repair accordingly. In order to claim it sometimes insurance companies are also involved to compensate for it. Eventually, most of the defective panels end up back to the manufacturer for repair and inspection. Most defective panels are hence typically returned to the producer itself for inspection and repair. (Duflou et al., 2018; Goe et al., 2015)

These defective panels mostly have issues that could be resolved and can achieve performance almost similar to a new PV panel. Such refurbished solar PV panels are sold back in market at a reduced price for replacement or also available in second hand market. With the increase in volume of solar photovoltaic panels throughout the country, such second hand panels and its constituents are also increasing, thus creating its own market. According to the forecast for solar PV panels efficiency, a considerable amount of installed panel are in good condition for usage even after its lifetime (Le Guen et al., 2017). Hence if a solar photovoltaic panel is dismantled after its usable lifetime, these panels can be refurbished and used if it passes the defined standards which in turn makes way to a huge scope for second hand PV panel's service/repair jobs.

At present, low volume of solar photovoltaic panel exist in waste market and is not sufficient enough to make advanced recycling feasible. Thus, these solar PV panels end up at existing glass and metal recyclers who treat them similar to any other e – waste. The separation of major constituents through mechanical process is main focus over here. Almost 80% of the material by weight is recovered but the valuable materials present are not recovered in this process (Berger et al., 2010). At present, there is no regulation or policy mandating the use of dedicated advanced recycling plant but in future constructing advanced recycling plants is necessary to maximize the profit by recovering valuable material like silver.

Some things to keep in mind before designing a advanced recycling unit are –

To minimize the damage during collection, transportation or dismantling.

Economic Feasibility to operate the plant by recovering valuable material

Labelling to identify the refurbished panels from new ones.

Recycle friendly PV module design (Choi & Fthenakis, 2010; Tao & Yu, 2015)

**Barriers in Circular Recovery**

Lack of regulatory or producer responsibility schemes for disposal hence it usually ends up in landfills.

High investment is required to develop appropriate infrastructure recycling facilities throughout the country and depending on the quality of design, ability to disassemble the panels varies

It is not clear who should bear the cost for these PV panels recycling and when one should pay for the same

Recycled materials are often of lower quality and slightly lesser efficient than new materials.

Distinguishing between working second-hand panels and e-waste is a key issue and determining the condition and performance of used panels is critical.

To produce high purity recycled products, a combination of mechanical, thermal and chemical processing steps is often required

Cost of logistics and lack of standardization for waste collection, regulation, hazardous materials and approvals (Salim et al., 2019)

**Scope of New Industries and Jobs in PV**

There are many stakeholder in waste management industry like waste treatment companies, manufacturers, dealers, municipalities, governments, importers and consumers. A stable relation and co-operation among all such stakeholders is the need of the hour to ensure a proper solar photovoltaic panel waste management. A proper end-of-life management of solar panels has the key to unlock a new industry and offer job opportunities related to various stakeholders (Petter Jelle et al., 2012). Thus, an emerging industry will require a skilled and unskilled labour force to carry out the work. Basic education and training regarding solar PV waste recycling would become an essential constituent for non - conventional energy which would help deliver appropriate skillsets in order to incorporate the solar photovoltaic sector, a part of circular economy and part of 3R (Contreras-Lisperguer et al., 2017)

Research and Development organisations would have an vital part to execute, in order to attain a significant material reduction by increasing efficiency, and to suggest a better recycling process available for solar PV modules (Tyagi et al., 2013). The main focus being the cost reduction of solar photovoltaic panels, many manufacturers have set up their own R&D to increase panel's efficiency. The conventional method has always focussed on the production rather than disposal (end-of-life) (Deng et al., 2019). The recent significant growth in this industry validates the previous statement and increasing waste volume will be an eye opener to the industry.

The private entities are believed to be the forerunners in future repair and service sector of solar PV panels. Huge scope in case of employment opportunity will rise for manufacturers and installation companies. At the same time the solar photovoltaic waste collectors and e - waste recycling companies are expected to expand their business (Arup, 2020; Tsanakas et al., 2020; Weckend et al., 2016).

Waste management is usually regulated by government all over the world. Except European Union, all over the world solar PV panels are treated as a regular e-waste. There is no proper advanced recycling plant set up established due to the concern of feasibility. Even then many companies are looking into innovative ways to identify a business model regarding solar PV waste management (Mo & Kim, 2020).

**Case study model for PV recycling**

The only solar PV specific policy and regulation available is European Union directive. Under this, PV Cycle a nonprofit organization was established which offers specific waste management service according to the existing rules and regulation of that member country. The member countries are mostly those under the EU directive and other than those countries they offer a consultancy based service. They have set up collection points at various places and if the number of panels are less than 40, the customer is supposed to take them to these collection points and in case of more than 40 panels, they can schedule a pickup. It has laid out an efficient supply chain from collection point to the recycling plant. Being an nonprofit organization it acts a platform for connecting various retail manufacturers, dealers and consumers. The extra money or the profit is kept for future expansion and expenditure.

A dedicated solar PV recycling plant was set up in March 2017 in France by Veolia with the help of PV cycle, France. It was the first of its kind in Europe with a unique technology which helped recover 1800 tonnes of material which would be injected back into the value chain. Instead of specifically manufacturing PV panels

again with the secondary raw materials, they are sent to their respective industries. The PV panel has a glass content of around 70% which is sent back to the glass manufacturers and the aluminum frame and other plastics constitutes about 10% is used as construction works while valuable materials like silicon goes back to various other industry needs. The cables and other connecting wires are crushed and sold as copper shot .Veolia and PV Cycle France is successfully running this plant in compliance with EU – WEEE

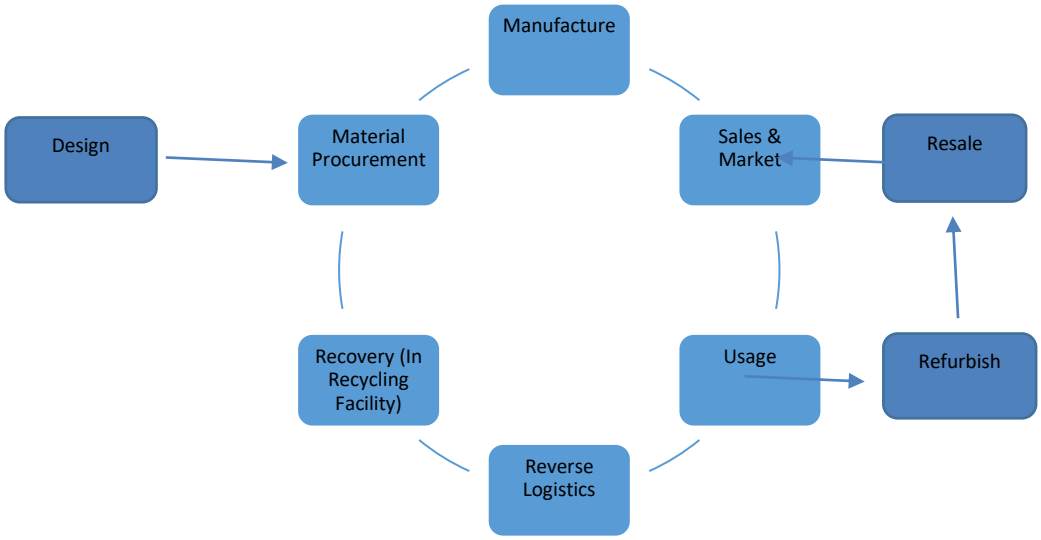


Figure 1 - Circular Economy

**Findings and Recommendations**

The solar photovoltaic waste is growing at a rapid rate and India as a country needs to be ready to support the growth. The EU directive is the only available regulation for solar PV waste and acts as a benchmark. Its efficient approach in providing expected result in regards of disposal is quite commendable. The rules and regulation for solar PV waste should be tightened over a period of time. The Government of India should take quick action regarding existing policy and regulation in place. Already existing e-waste rules lays down the basic foundation for solar PV end of life management. A change in regulation by policy makers and involvement of private players will ensure a long term growth of this sector. Solar PV end of life management suggestions for India -

**Regulatory and Government Policy for solar PV end-of-life management.** The PSUs and private stakeholders are required to take an effective and well informed decision on recycling and management opportunities for a sustainable waste management of PV panels. At present, European Union is the only one to put a proper regulation for solar PV waste disposal in place while other countries are still at planning stage. (E.g. China, Japan). To ensure a good end of life management of PV panels and to enhance decision making, a monitoring system for PV waste is recommended to oversee the process. The policy should clearly define the roles and responsibilities of all the stakeholders. This policy must be included into national and regional regulations and must be strictly followed nation wide

**Research and Development for design and socio- technical system implementation.** The need for R&D is critical as it would help suggest better way to recycle or improve the efficiency of solar panels significantly. Such innovations and recommendation of technologies can help recover valuable materials like silver and specifically some hazardous materials like polymers which could help improve socio – economic benefit. The amalgamation of manufacturers and recyclers will help cost cutting by reusing the valuable materials through enhanced recycling techniques.. More importantly, R&D must be combined with environmental and techno – commercial analysis so as to maximise the socio-economic benefits. Such extensive study requires access to wide range of fields like science, finance, commerce, business and engineering. Moreover, Skill development

and training programmes is essential for solar PV producers for future opportunities in reuse and repair for solar photovoltaic panels which has failed its average life time usage.

**Strengthening infrastructure and developing of local solar PV recycling industries.** With increased capacity addition throughout the country, new market and demand will emerge. This will create better job opportunities for local recyclers. The focus should be on the ability to procure locally sourced material which could be possible by developing a good advanced recycling plants which will help recover valuable materials and also potentially hazardous materials. The idea of circular economy must be considered where solar PV manufacturer and recycler co-exist. The material availability and recycling feasibility both are met at a satisfactory level.

**Financing feasibility and schemes of investments for solar PV panels.** The recycling feasibility is the major concern prevailing all over the world. It is equally important that all stakeholders are considered before responsibility allocation for recycling. Past experience in progressed market has indicated that pressurizing residential consumer to recycle is not practical as they do not have the expertise to dismantle or carry them to a solar PV panel collection centre. On the other hand voluntary approach has also failed due to the customer's financial implication. The most successful practice over the past years state that extended producer-responsibility schemes proves to be effective. This includes pay-as-you-go service and several liability approaches where the manufacturer is responsible for solar photovoltaic panel collection and disposal. The cost required for such proper disposal and recycling can be included in the manufacturing stage itself.

The national approach regarding solar PV panels should address a sustainable end of life management along with a feasible recycling. A rigid policy in place will help recover valuable materials like silver and potentially hazardous material like polymers, thus making advanced recycling feasible and socio-economical.

**Conclusion**

It is essential that we identify and address the key barriers so that we are ready for future hurdles, in order to achieve a circular PV industry in India. With a proper policy and regulation in India, the rapid growth of solar PV industries especially the recycling and refurbishment of older solar photovoltaic modules will help create a sustainable and economical industry in long run.

**Regulatory framework**, Mandatory usage of environmentally safer materials while manufacturing solar photovoltaic module and creating a design which is easy for dismantling will help end-of-life management to be carried out efficiently. The roles and responsibilities of each stakeholders should be clearly specified. A standard procedure for solar photovoltaic waste collection, treatment and recycling should be laid out to help form a fail proof policy. The Producer Responsibility Organisations (PRO) should be strengthened in order to make them self-sufficient for collecting and end-of-life management. Use of sustainable materials in PV panels must be promoted and PV module design which has considered end-of-life management must be given preference by the government during bidding process.

**Standardization** is need of the hour as we need a common platform for all manufacturers and recyclers. This will enable designers to design a product with its end of life taken into account and similarly the recyclers will give back the manufacturers with extracted valuable materials from scrap, thus bringing down the operating cost for both.

**Financing,** proposing extended producer responsibility along with Pay as you go (PAYG) would be a step towards feasible recycling. Moreover, encouraging a holistic circular economy where every stakeholder benefits from one another or proposing a concept where the cost of recycling at end of life could be included in the manufacturing stage itself.

**Businesses and investors** can demonstrate leadership in the space through feasibility studies and pilot projects, especially through collaborations. A whole new sector could be formed and with proper initiative by big investors, companies can revolutionize the solar PV panel market.

**Operational infrastructure**, Identifying locations and technical requirements for setting up of advanced recycling plants throughout the country. Focus on efficient recovery of valuable and hazardous material to make this infrastructure feasible. PPP model between government and private players could be established.

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