Chapter 9
Sustainable Attainment of Solar E-waste Recycling Concerning to COVID-19 Crisis: A Review

Nidhi Jariwala and Jaykumar Soni

Abstract Solar energy is looked at as a critical component to fight against increased climate change. It is seen as the green solution for the increased demand in energy, but the problems that will occur after 20–30 years when these solar panels have to be disposed of are seldom considered. Due to increased growth in the development and utilization of solar energy resources, the disposal of waste solar panels has become problematic. Photovoltaic systems are in the lead because they are cost-effective, and it has increased efficiency. All these systems are expected to produce much e-waste by the end of their life cycle. Currently, the research is focused on how to increase the efficiency of solar panels rather than focusing on the disassembling and recycling of the panels. By recycling silicon-based solar panels, valuable metals within the panels can be recovered instead of lost to the landfill. Proper disposal of many compounds is not yet discovered; hence they are landfilled without any treatment, which causes harm to the environment. The environmental policies constrict market projections for Cadmium Telluride (CdTe) Photovoltaic (PV) because Cadmium has Carcinogenic properties. This paper aims to review the present and upcoming or subsequent recycling technologies for solar panels and produce a recycling technology that is most sustainable and likely to be acquired in the coming years. Although these technologies require advanced techniques and enhanced improvement before execution, when all these progressive technologies are combined, they will provide better recycling options for the generated solar e-waste.

Keywords Solar e-waste · Solar energy systems · Solar panels · Disposal · Sustainability

N. Jariwala (✉) · J. Soni
Civil Engineering Department, L. J. Institute of Engineering and Technology, LJK University, Ahmedabad, Gujarat, India
e-mail: jariwalanidhi009@gmail.com

J. Soni
e-mail: jay.soni_ljiet@ljinstitutes.edu.in

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2021
C. Chakraborty et al. (eds.), The Impact of the COVID-19 Pandemic on Green Societies,
https://doi.org/10.1007/978-3-030-66490-9_9
9.1 Introduction

“Photovoltaic (PV) power generation is among the most promising technologies for renewable energy” [1]. “Photovoltaic (PV) modules are highly efficient solar power generators which are non-polluting. This has been attracting unceasing attention recently thanks to its potential application in alternative energy generation. Since they only use solar energy, they do not produce noise, emit no harmful gases or use material resources” [2]. Aside from positive environmental effects, the strategy of implementing renewable energy sources would lead to a rise in the waste stream from, among others, solar power plants. This could cause severe environmental problems [3].

“Five countries (China, Japan, Germany, the United States, and Italy) shared roughly 70% of world’s solar energy. End-of-life (EoL) management of photovoltaic waste modules requires alternatives to landfill and is a viable option for recycling. Technological approaches are already on the market, and literature emphasizes environmental benefits, while economic benefits are not well known” [4]. Many new photovoltaic technologies were placed on the market, and there has been further advancement of existing technologies. It is unclear whether all these advances will impact the fate of photovoltaic Eol modules. “Nonetheless, it is clear that the quantity of PV waste generated together with the substantial quantity of retirement PV modules installed over the course of several decades would need to be safely recycled” [5].

PV recycling can contribute to resource conservation by saving useful raw materials (glass, copper, aluminium, semiconductor materials, etc.) for potential use in PV modules or other new items, in addition to helping to handle significant future quantities of wastes. Upon transport to the nearest recycling plant, PV modules are recycled through a series of steps involving size reduction (shredding and milling), removal of semiconductor film, solid-liquid separation, separation and rinsing of laminate foil/glass and precipitation of semiconductors [6]. It is important to examine the role that materials play over the lifespan of the product in order to take further steps toward a sustainable closed-loop product trajectory. There are multiple kinds of solar panels but they include mainly aluminium, glass, silver and an elastic substance called ethylene vinyl acetate (EVA). A typical crystalline silicon solar panel consists of 65–75% glass, 10–15% frame aluminium, 10% plastic and just 3–5% silicon. In fact, they can contain a lot of harmful and even cancer-causing materials (carcinogenic), such as arsenic, chromium, and cadmium. The working panels are sealed off with glass and are very safe; but, if the glass is broken or the panels are damaged, there could be leakage possibilities for certain substances. This work provides a wide comprehensive view of the recycling possibilities and the fate of the photovoltaic materials [7]. “The ultimate aim is to build a structured PV recycling model that promotes different recycling technologies for different modules and controls for future planning of PV recycling infrastructures” [8].
9.1.1 Why Solar Energy?

9.1.1.1 Solar Energy Is Environmentally Friendly

The most commonly known truth about solar energy is that it provides a renewable, green source of electricity. Solar power is the best way to slash your carbon footprint. There is nothing in the solar energy that is polluting Mother Nature. Solar power does not emit greenhouse gasses and requires almost no other energy, except for having to operate a clean water supply. It is also healthy, and friendly to the community. “And there is still confusion among people as to why solar power is OK. Solar power is autonomous, and solar panel installation on your roof is a secure and easy way to contribute to a sustainable future. Starting from home is a great way to prove you care for the surroundings” [9].

9.1.1.2 Solar Power Makes the House Go off the Grid

“The decline in solar panel costs serves as a perfect example of why solar energy usage should increase. Traditional electricity depends heavily on fossil fuels including coal and natural gas. Not only are we bad for the world but we also have little resources. This translates into a dynamic market, in which energy rates adjust during the day.

Solar power is expanding your electric independence! By investing in a 4 kW solar panel, which is the most popular domestic capacity, you can easily shield yourself from unexpected spikes in power costs, and enjoy low-cost electricity all day long—the sun will never raise its rates and will provide you with energy protection. When you have solar panels on your roof, technically you’ve reached an energy-independent status. Solar battery storage systems can also help to store energy at night and on rainy days” [9].

9.1.1.3 Solar Power May Use Unused Land

We might keep asking why solar power is so. It’s becoming readily available to most of us with the growing need for solar energy. There are large lands around countries that are far from major cities or towns and are not used at all for anything. We can actually use the land with solar power, and then generate enormous value; solar energy is for all a source of electricity. “This way, we don’t need to use high-cost land that could be better suited for other purposes. You may have heard about the solar farms—panels used to store large amounts of solar energy. It perfectly shows how underexploited land is used for solar electricity. For example, a 45 acre solar farm has recently been installed in the United Kingdom, and it will fuel 2,500 homes” [9].
9.1.1.4 Solar Energy Causes Less Power Loss

“Electricity must be distributed to end-consumers through vast networks from big power plants. Long distance transmissions cause power losses. Ever wondered what solar panels are used for? They’re supposed to get energy from the sun on your roof. Because of the short reach, rooftop solar power is helpful in increasing the electricity production. The money is domestic and as a result you are in charge of your own bills and energy use. Solar power systems are also stable and therefore reduce the risk of service failure” [9].

9.1.1.5 Solar Power Increases Protection Of the Grid

“We are less at risk of experiencing blackouts or brownouts, because more of us turn to solar power. Each UK household that has solar cells built, functions as a small power station. In effect, this gives us more control over the electricity grid, particularly in terms of natural or human-caused disasters. Through the aid of solar panel grants you will still be paying out to sell electricity back to the grid” [9].

9.1.1.6 Solar Power Creates Jobs and Economic Growth

Solar power will contribute to our national economy. The more people who opt for solar, the more companies will need to install solar panels. It provides new jobs for eligible workers, and thereby keeps the economy growing. For example, the UK will become the second largest solar employer in 2015, with 35,000 workers, and the largest solar photovoltaic (PV) panel market in the continent’s installations.

9.1.1.7 Solar Power Is a Free Energy Source

“The sun gives us more energy than we will ever need and no one can monopolize the sunlight. Your solar power system will start saving money as soon as it’s turned on; however, the solar power’s long-term benefits are best seen. The longer you have your solar power system, the more you can enjoy the benefits of solar power and help for the climate. Solar energy, in addition to solar electricity, has a second application. We frequently associate solar energy with electricity acquired by photovoltaic panels, but the energy generated by the sun can be used in heating as well. This process is achieved through the installation of solar thermal systems which effectively turn the sunlight into heating solutions” [9].
9.1.2 Impact of Covid-19 on Solar Power

“Over the past two decades, solar power has experienced a tremendous rise. However, the COVID-19 crisis could drastically threaten the momentum. Governments will be crucial more than ever to addressing these problems and deciding the speed of solar energy deployment soon. Especially important would be stimulus packages that aim to get the global economy back on track. When designing these packages, policymakers should bear in mind the structural benefits that solar energy can bring not only to the power sectors but also to the health, transport, agriculture and industry sectors—particularly economical and sustainable development and job creation—while also reducing emissions and supporting technological innovation” [9].

“COVID-19 [10] has had a minimal effect on operating wind and solar power projects because it relies on natural resources, i.e., wind and sunlight that has not been disrupted while at the other end of the spectrum rooftop solar projects are most adversely affected in the renewable sector, as most of them are small-scale companies. Solar rooftops would be more affected than grid-connected networks, which are under critical utilities. The industry will have to deal with the consequences after the shutdown, as new rooftop solar is not a market requirement. With users grappling with numerous financial concerns, rooftop solar would be the least priority on their list, leading to a pause in decisions about solar rooftop installation. Solar implementation projects have suffered the greatest impact of the COVID-19 pandemic since solar cells and modules have been mainly imported from China, which has lockdown since December 2019” [11].

9.1.3 The Working of Solar Panels

“Solar panels capture some sort of clean energy from renewable sources in the form of sunlight and transform the light into electricity which can then be used to supply large amounts of electric charges. In contrast to common opinion, solar panels simply consist of several usually individual solar cells that actually consist of silicon, phosphorus (which provides the negative charge) and boron (which provides the positive charge) layers. Solar panels actually absorb the photons and thereby produce a essentially current of electricity, usually contrary to common opinion. The resulting energy produced by photons touching the surface of the solar panel causes electrons to actually be kicked out of their atomic orbits and released into the solar-induced electric field, which then subtly draws these very free electrons into a directional current. The very whole kind of process is indirectly called the Photovoltaic Effect. Specifically, a relatively average home has reasonably more than enough roof area for the necessary number of solar panels to generate sufficient solar energy to supply all of its power needs mostly excess energy generated goes to the main power grid, paying off in particular nighttime electricity use” [12].
In a well-balanced grid-connected network, a solar array generates power during the day which is then used in the home at night, which is especially important. Net metering systems effectively allow solar generator proprietors to be charged if their unit produces more power than is actually needed at home, which is generally very important. A battery bank, charge controller and, in most situations, in a subtle way, in off-grid solar applications, an inverter are kind of necessary components. The solar array transmits some kind of direct current (DC) electricity through the charge controller to the battery bank. The power is then essentially drawn from the battery bank to the inverter which essentially converts the DC current into an alternating real current (AC) which can be used for non-DC devices. Supported by an inverter, in reality, arrays of solar panels can be built to meet the most demanding electric charge requirements in an essentially large way. The AC current can be used in a large way for driving loads in homes or particularly commercial buildings, recreational vehicles and boats, remote cabins, cottages or houses, remote traffic controls, telecommunications equipment, oil and gas flow monitoring, RTU, SCADA and quite a lot more” [13].

9.1.4 Photovoltaic Effect

Electricity can be produced directly from sunlight, through a process called the photovoltaic effect, which is characterized as the generation of an electromotive force as a result of ionizing radiation absorption. The photovoltaic effect can be observed in virtually any junction of material with various electrical characteristics, but the best performance to date has been from Silicon solar cells (Fig. 9.1).

9.1.5 Advantages and Disadvantages of Using Solar Panels

9.1.5.1 Advantages

Some advantages of using solar panels are: Solar Panel fuel supply is direct and endless so no external fuel is needed, it is sunlight-cost-free, solar modules unlimited life, quick response, and high reliability, can work in open and under high temperatures, short circuit inherently protected and safe under any conditions of load, free from pollution, low maintenance, freelance job, simple operation, and no electro-chemical reaction, and no liquid media, noise-free, because moving parts are not present, no losses of AC to DC conversion because DC is directly generated, no loss of transmission, as installed near the load, fits central, isolated and hilly areas, suitable for loads/objects traveling. Since it is modular, there is provision for future capacity expansion. It is capable of generating power from mili-watts to several megawatts. From small electronic devices to large-scale MW power generation stations, it can
be used almost anywhere and it can be easily assembled and placed with minimal cost.

9.1.5.2 Disadvantages

There are a few disadvantages of using solar panels such as: Initial expense is huge, depends on the weather, extra expense for battery backup, the output is affected by climatic condition, location, latitude, longitude, altitude, angle of tilt, ageing, denting, bird dropping, etc., it does not have the capacity for self storage, machine manufacturing is very complex and wide area for solar panel installation is required.

9.1.6 Types of Solar Cells

9.1.6.1 Monocrystalline Silicon Solar Cells

“Solar cells made of monocrystalline silicon (mono-Si), also known as single-crystalline silicon (single-crystal-Si), are readily identifiable by their shading and uniform appearance on the outside, suggesting high silicon purity. Monocrystalline
solar cells consist of cylindrical shaped silicon ingots. To improve the implementation and lower price of a single monocrystalline photovoltaic cell, four sides are cut off from the cylindrical ingots in such a way that they render silicon wafers, which is what gives their usual look to monocrystalline solar panels” [14].

“Monocrystalline PV panels have the best level of potency because they are made from the highest quality silicon. These are space-efficient and have the longest possible life, too. The costliest are the monocrystalline solar panels. A large amount of the original silicone ends up in these panels as a waste product” [15].

9.1.6.2 Polycrystalline Silicon Solar Cells

“In 1981, the first polycrystalline silicon-based solar panels, also known as polysilicon (p-Si) and multicrystalline silicon (mc-Si), were introduced onto the market. Raw silicon is melted and casted into a square frame, which when cooled down is cut into perfectly square wafers [15].

The method followed to produce polycrystalline silicon is simpler and more cost-effective. Compared to monocrystalline, the amount of waste silicone produced is lower. Polycrystalline solar panels tend to be significantly less heat resistant than monocrystalline solar photovoltaic panels” [14].

9.1.6.3 Thin-Film Solar Cells (TFSC)

“The main idea for the production of thin film cells is to deposit one or many thin layers of photovoltaic material onto a substrate. They’re also recognized as thin-film photovoltaic cells (TFPV). The various types of thin-film solar cells can be classified into different groups by depositing photovoltaic material onto the substrate:

- Amorphous silicon (a-Si)
- Cadmium telluride (CdTe)
- Copper indium gallium Selenide (CIS/CIGS)
- Organic photovoltaic cells (OPC) [14].”

“Thin film solar panels are easy to mass-produce. But in most residential environments they are usually not very useful. They are economic but they need a large amount of space as well. PV panels based on amorphous silicon, cadmium telluride and copper indium gallium selenide are currently the only commercially viable thin-film technologies on the market” [15].

9.2 Materials

The power produced by a single cell is low and thus, in series/parallel combination, multiple cells are interconnected to get the necessary voltage and current. When the multiple solar cells are connected to a common voltage in series, the
unit thus created is called the solar module. SPV module is mainly used for charging batteries. Thus 36 cells are usually joined in series to form a regular module capable of charging 12 V battery. A terminal box for external connections is installed on the rear side of the board. A photovoltaic system’s basic building block is the solar cell, a semiconductor device which has a simple p-n junction and produces DC electricity when exposed to sunlight. The solar cell is made of “Semi-Conducor” materials that are processed to make the photovoltaic system. The solar-cell is made of silicon single crystal, polycrystalline, and silicon amorphous with an area of a few sq. centimeters to 200 cm² and even more (Figs. 9.2 and 9.3).

“The effect of photovoltaic (PV) is the basis for transforming light into electricity in photovoltaic, or solar, cells. It is therefore common for PV modules to be classified basically by the form of light-absorbing materials used. In addition, the categorization of PV modules by manufacturing technologies is rational. The Silicon wafer based PV module is the most common type of solar cell produced worldwide. This was also the dominant one for delivering power modules into photovoltaic applications. The commercially available multicrystalline silicon solar cells are about 14–19% effective” [16].

All the components and materials of PV module are described in Tables 9.1 and 9.2.

“Solar panels use toxic materials including lead and polymers, and compounds. If discarded in an unregulated manner, the possible end-of-life disposal of such
**Figure 9.3** Actual photovoltaic module

**Table 9.1** Description of components of PV module

| Sr. no. | Components/materials | Description |
|---------|-----------------------|-------------|
| 1       | Frame                 | It is made up of Aluminium |
| 2       | Glass                 | Low iron solar textured glass of 3.2 mm or 4.0 mm are used. It comprises of 70% of weight of solar panel |
| 3       | Solar cells           | Front (−ve): Padded silver bus bar (0.8 ± 0.05 mm) with fine textured surface anti-reflective silicon nitride (blue/light blue) Rear (+ve): Maximum aluminium surface Back surface layer, 1.8 ± 0.2 mm long (silver/aluminium) discontinuous solder pads in 5 busbars |
| 4       | EVA                   | Ethyl Vinyl Acetate (EVA) Encapsulant is matt from inside and embossed from outside |
| 5       | Backsheet             | It is 365 μm thick and is a fluoro-based UV and weather stable. It has extremely low moisture permission |
| 6       | Sealant and adhesive  | It is a one-part, non-corrosive neutral-curing silicon adhesive. It combines mechanical strength with high elongation |
| 7       | Solder wire           | It is manufactured from virgin metals (Sn63/Pb3) and flux cored. The post solder residues are non-corrosive |
| 8       | Junction Box          | A junction box has bypass diodes allowing power flowing in one direction and preventing it from feeding back into the panels. Internal wires connect to diodes, offering an convenient way to link panels |
Table 9.2  PV module components and their weight percentages [25]

| Name of the material | Component in PV module | Percentage by weight (%) |
|----------------------|-------------------------|---------------------------|
| Glass                | Cover of PV              | 70.00                     |
| Aluminium            | PV frame                 | 18.00                     |
| Adhesive (polymer based) | Encapsulation layer | 5.10                      |
| Silicon metal        | Solar cell               | 3.65                      |
| Polyvinyl fluoride   | Back sheet layer         | 1.50                      |
| Copper and polymers  | Cables                   | 1.00                      |
| Aluminium            | Conductor                | 0.53                      |
| Copper               | Conductor                | 0.11                      |
| Silver               |                         | 0.053                     |
| Tin and lead         |                         | 0.053                     |
| Total                |                         | 100”                      |

Toxic materials may have adverse environmental consequences, as well as serious health effects. Leaching lead has an immense environmental impact, such as habitat destruction, reduced flora and fauna growth and regenerative levels, and a few other health hazards, such as adverse reaction to kidney function, nervous, immune, reproductive and cardiovascular systems. Cadmium is a highly toxic carcinogen and has high potential for human accumulation” [17] (Fig. 9.4).

Fig. 9.4 Classification of the mass share of material contained in PV module in t
9.2.1 Solar Panels

“A Solar Panel consists of a variety of solar panels, most of which are connected in series and quite parallel arrangement to provide certainly similar voltage and kind of current for charging a battery, which kind of is very important. A diode particularly is connected on the +ve terminal of really such string in forward bias, really contrary to popular belief. This really is called Blocking diode, kind of contrary to popular belief. This diode essentially is provided so that in daytime current can flow from module to battery, but at night or in cloudy day current should not flow back from battery to module or from one string to another string” [18].

9.2.2 Causes of Degradation of Solar Panels

“While crystalline solar panels are often sold with real lifetime promises of 25–30 years, those 30-year-old modules will not work as well as they did on Day 1, or so they thought for the most part. Performance decreases as solar cells actually undergo degradation fairly due to conditions that for the most part are inevitable sort of such as UV exposure and weather cycles in a definitely big way. Manufacturers know this mostly, and solar panels come with a guarantee of power generation or efficiency that usually guarantees an 80% 25-year yield.

Because of a 2012 NREL study (Jordan and Kurtz 2013) that for the most part found solar panels degrade 0.5–3% per year, panel companies basically are only sort of comfortable providing this guarantee, barring some issues with the equipment. And the panels immediately degrade; that’s built into their guarantees of performance, or so they assumed for all intents and ends. There are also external causes that can potentially contribute to a plate’s degradation and genuinely possible failure, or so they thought precisely. In particular, we spoke with Sarah Kurtz, NREL research fellow and co-author of the widely cited 2012 study on how development and manufacturing changes, along with implementation practices, greatly influence the rate of degradation.

Modules can actually fail generally due to unavoidable elements such as thermal cycling, actually damp heat, humidity freeze and UV exposure, according to NREL, which for all intents and purposes is fairly significant. Thermal cycling can cause failures in sort of solder bonds and cracks in solar cells in a subtle way. Damp heat was associated with encapsulant delamination and cell corrosion in a basically big way. Freezing of the moisture can cause adhesion to the junction box to really fail. Exposure to UV particularly leads to discoloration and deterioration of the back layer. Such issues essentially are just happening and it definitely is impossible to predict how fairly bad the deterioration is going to be, kind of contrary to popular belief.
9.2.2.1 New Inverters, Higher Voltages and PID

PID occurs when different components in the same system have different voltage potential (such as frame and solar cell) which can cause electrical current to leak and modules to lose peak output. Sometimes, grounding a system effectively removes the PID problem negatively, but fewer inverter transformers are ungrounded. Based on if the system is grounded, the sodium ions in the glass migrate through the solar cell or frame as the electrical current escapes. There’s also a problem with the whole industry switching to higher voltages, as higher voltages make the current pull stronger, and sodium ions can easily pass over top solar cells, reducing their production.

9.2.2.2 Cheaper Panels and Less Material

NREL surveyed installers in New York back in 2015, and specifically noticed that basically many generally had the same issues with new solar panels, sort of contrary to popular belief. As module companies sought to generally lower their costs, their frames definitely were made thinner to definitely reduce the aluminium, pretty contrary to popular belief. Bent frames can strain the whole panel type, and this can be especially bad as the panels are relatively smaller and less mechanically stable, especially contrary to popular belief.

9.2.2.3 More, Thinner Busbars

Solar panels often fail because of bond faults in the soldering busbar. You’d think solder bond failures are more likely, with the trend towards more busbars on solar cells. That is not entirely true. The risk of solder bond failure is higher, with more busbars and more solder bonds. But, as there are more busbars to take up the slack, the value of one solder bond failure goes down. Further busbars will also decrease the risk of complete cell breakage across a solar cell.

9.2.2.4 Flexible Panels and Installation

Since module companies are definitely reducing their costs, they can switch to ultra-thin solar cells which use less silicon in a subtle way for all intents and purposes. Thinner solar panels literally are fairly more flexible than pretty much older models which specifically make installation a delicate process and not as rigid as pretty much older models, contrary to popular belief. Hand-to-hand transport can affect a module specifically, particularly if the installer mainly subtly carries modules on the top of its hardhats in general. That bending and jumping up and down can actually lead to very real toll and micro cracks in the cells, which really is quite significant. The same with dropping a module, standing or walking on sort of top of solar modules is literally the biggest no in a major way” [19].
9.3 Methodology

PV modules have a long working life (on an average 30 years) and have been installed predominantly in large-scale (>1 MW) systems in most counterparts, particularly since the mid 2000s. “As these long-lived PV systems mature, it is anticipated that large quantities of PV modulus waste will be produced by the year 2030. End-of-life management with resource recovery is preferable to recycling as a way of managing end-of-life PV systems with respect to environmental impacts and energy use” [20]. Recycling not only eliminates waste and waste-related pollution when recycling processes themselves are successful, but also provides the ability to minimize the energy usage and pollution associated with the processing of virgin materials. “This may be particularly important for raw materials with high levels of impurity (e.g., semi-conductor precursor material), which often require an energy-intensive pretreatment to achieve the required levels of purity. Recycling is also important for the long-term management of resource-constrained metals used in PV modules” [21].

Till date, aging or damaged solar panels have typically been recycled in all-purpose glass processing plants, where only their glass and aluminium frames are recovered, and their specialist glass combined with other glasses. Typically the left over is then burned in cement stoves. So are solar panels completely recyclable? The short and simple answer is “yes.” “Essentially, silicon PV modules are made of glass, plastic, and aluminium: three materials that can be recycled in massive quantities. Given the recyclability of the PV modules, the process of separating materials may be tedious and involves modern machinery and technology” [22].

Below are the four basic steps for efficient recycling of a silicon module:

1. The aluminium frame (100% reusable) could be removed.
2. Separating the glass by means of a conveyor belt (reusable 95%).
3. Thermal treatment with temperature of 500 °C. It allows the tiny plastic components to evaporate which allows for quick separation of the cells.
4. Etching away and smelting silicon wafers into reusable slabs (reusable 85%).

“A variety of methods are currently being developed for extracting useful metal components from PV wastes. Several process steps need to be incorporated to remove the metal frame, back panel, EVA resins and protective tempered glass coating before recovery of the PV modules” [23]. “The most successful recycling method to date for c-Si PV modules is focused on mechanical, thermal and chemical processes” [17]. “The new state-of-the-art recycling process aims to recycle more than 80% of the PV module by weight. For the recovery of value-added components or products, EoL products or scraps collected under various schemes are shipped to the consolidation sites” [8].

The method flow starts with aluminium frame disassembly and junction box disassembly. Since the size, profiles, and frame fastening vary from one maker to another, frame disassembly is often performed manually. Then shredded, sorted, and separated after frame. The materials isolation allows them to be sent through different
recycling processes relating to each item. “The frameless PV module consists of the active silicon cell contained in an EVA polymer layer that allows the cell to be laminated onto the back sheets of hard polymer and onto the front sheet of glass” [7].

“Recycling of solar cells requires placing the components in a smelter or acid bath to recover the elements, including selenium (Se), indium (In), and gallium (Ga). The glass is cleaned and collected by thermal decomposition; dissolution of solvent or acid to eliminate any residual PV layers” [24]. “With the aid of a hammer mill, the recycling process begins with the shredding of the PV modules into large parts and then into small fragments (5 mm or less). The semiconductor films are then removed over the next 4–6 h in a slow leaching drum. The remaining glass is exposed to a combination of sulfuric acid (H₂SO₄) and hydrogen peroxide (H₂O₂) for optimal solid-liquid ratio. Following that, the isolation from the glass is repeated. A vibrating screen is used in the next step to isolate the glass from the larger pieces of ethylene vinyl acetate (EVA), via. After cleaning it the glass is sent for recycling. Sodium hydroxide is used to deposit the metal compounds, after which they are transported to another industry where they can be processed into raw materials of semiconductor quality for use in the modern solar PV modules. This entire process recovers 90% of the glass used in the manufacture of new products, and 95% of the semiconductor materials and metals used in new solar PV modules” [21] (Fig. 9.5).

9.3.1 Advanced Recycling Technologies

“Advanced or specialized PV recycling uses a combination of mechanical, thermal, and chemical processes to recover most materials including glass, aluminium, copper, silicon, silver, lead, and tin. The polymer fraction remains unrecoverable, 8-10 per cent by weight, and must be landfilled and incinerated” [17].

Various chemical, thermal, and a mix of mechanical methods or processes of advanced or specialized levels for PV recycling to recover most material, including metals, are used. Even then, the polymer fraction has to be landfilled and incinerated, 8–10% by weight, is unrecoverable.

The advanced recycling method consists of three processes:

1. Thermal Process: Here, the components are passed through the combustion chamber and through the process of pyrolysis (thermal decomposition in an inert atmosphere), etching (the process of cutting metal into unprotected pieces by using strong acid or mordant), the recovered metals from PV cells are sent to metal refinery for metal recovery.

2. Mechanical Process: In the mechanical process, the crushing or grinding method is used to sort the waste by size and magnetism, which goes to waste along with glass if the waste is nonmagnetic. Other processes scrape and cut the encapsulation layer for the solvent treatment of components so that metal components obtain can be sent to the metal refinery for metal purification processes.
(3) Chemical process: The chemical process identifies and separates the metal fraction and glass & plastic fraction through solvent treatment. The glass and plastic are discarded separately, and metal fractions are sent to the metal refinery for recovery of metals.

In all the three processes, the silicon metal recovered is separated and further converted into silicon wafers, also called slice or substrate (A slice of silicon semiconductor mainly used for fabrication of integrated circuits). Pyrometallurgical and hydrometallurgical techniques are used in the metal refinery for the purification of metals and to obtain metals such as silver, aluminium, copper from the supplied waste. These metals can be further used in many domains depending upon the availability and degree of purity.

Other processes that could be used in the recycling process are given in the Table 9.3.
### Table 9.3 PV module waste recycling technologies [16, 22]

| Technology                                      | Advantages                                                                 | Disadvantages                                                                 |
|-------------------------------------------------|----------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| Filtration                                      | 1. Efficient 2. Able to filter particles with minimal inclusions           | 1. In industrial practice, pollution from the container must be reduced before filtration can be used |
| Centrifugation                                  | 1. High purity of Silicon Recovered                                        | 1. Uses toxic heavy liquid 2. Process is slow 3. Unable to extract c-Si particles from submicron |
| Phase-transfer separation                       | 1. Strong purity and reclaimed silicon yield 2. No heavy toxic substance used 3. Simple and cost–effective | –                                                                               |
| Electrophoresis and gravitational settling      | 1. High efficiency of separating Si/Al₂O₃                                   | 1. Contamination of Al in silicon recycled                                      |
| Electrical field                                | 1. High efficiency of separating Si/SiC 2. No hard, poisonous liquid used   | 1. Metal impurity removal pretreatment needed                                    |
| Al–Si alloying                                  | 1. Complete omission of SiC                                                 | 1. The Process is complicated                                                    |
| Hydrobromination                                | 1. High-purity Si recovery without SiC extracted first                     | –                                                                               |
| Supercritical water                             | 1. High-purity Si recovery from oily silicon ingot cutting wastes           | –                                                                               |
| Sedimentation and leaching                      | 1. Separation of Si and SiC by physical approaches 2. Less complicated operation and simpler to produce | –                                                                               |
| Czochralski mono c-Si process                   | 1. Low power consumption                                                   | 1. Recovery of c-Si Mono 2. Lowering the boron concentration to increase cell performance |
| Electrokinetic separation                       | 1. High efficiency of removal of iron particles in slurry wastes 2. Does not use additives | –                                                                               |
| Hydrometallurgy: oxidation, evaporation, reduction by inorganic reducing agents | 1. Recovery of high pure selenium which can be used directly in new solar cells | –                                                                               |
Table 9.3  (continued)

| Technology                                    | Advantages                                                                 | Disadvantages                                                                 |
|-----------------------------------------------|----------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Hydrometallurgy: dissolution, filtration,    | 1. CIS mixed waste recycling                                               | 1. Further refining of the processes needed                                   |
| liquid–liquid extraction, stripping,         | 2. Application of normal hydrometallurgic and chemical processes            |                                                                              |
| precipitation electroplating                  | 3. Recovers pure indium                                                    |                                                                              |
| Organic solvent dissolution                   | 1. The EVA is easy to access                                               | 1. Delamination period is calculated by area                                  |
|                                               | 2. Minimum damage to cells                                                 | 2. Noxious Pollution and waste                                                |
|                                               | 3. Receiving of glass                                                     |                                                                              |
| Organic solvent and ultrasonic irradiation   | 1. More effective than dissolving solvent                                   | 1. Expensive equipment                                                        |
|                                               | 2. Easy EVA Access                                                        | 2. Harmful emissions and wastes                                               |
| Electro-thermal heating                       | 1. Easy glass removal                                                      | 1. Time taking process                                                        |
| Mechanical separation by hotwire cutting     | 1. Minimum cell damage                                                     | 1. Other separation processes needed to eliminate EVA entirely                |
|                                               | 2. Glass recovery                                                          |                                                                              |
| Pyrolysis (conveyor belt furnace and fluidized bed reactor) | 1. Separate 80% of wafers, and nearly 100% of glass sheets                  | 1. Texturization marginally worse (damage to cell surface)                    |
|                                               | 2. Cost-effective method for industrial recycling                          |                                                                              |
| Solvent (Nitric acid) dissolution            | 1. Full removal of EVA and metal wafer coating                              | 1. The inorganic acid can cause cell defects                                  |
|                                               | 2. The recovery of intact cells is possible                                | 2. Produces polluting emissions and waste                                     |
| Physical disintegration                       | 1. Able to handle waste                                                    | 1. Other separation processes needed for complete elimination of EVA          |
|                                               |                                                                           | 2. Dusts which contain heavy metals                                          |
|                                               |                                                                           | 3. Solar Cell Breakage                                                       |
|                                               |                                                                           | 4. Corrosion of equipment                                                    |
| Dry and wet mechanical process                | 1. No chemical processes                                                   | 1. Dissolved solids not removed                                               |
|                                               | 2. Made readily available equipment                                        |                                                                              |
|                                               | 3. Low energy demands                                                      |                                                                              |
| Thermal treatment (two steps heating)         | 1. To complete elimination of EVA                                          | 1. Toxic emissions                                                            |
|                                               | 2. Possible recuperation of intact cells                                   | 2. High energy demands                                                       |
|                                               | 3. Measurably viable cycle                                                 | 3. Cell defects and high-temperature degradation                             |
| Chemical etching                              | 1. To recover products of high purity                                      | 1. Chemicals are used                                                         |
|                                               | 2. Process is quick and efficient                                          |                                                                              |
9.4 Result and Discussion

9.4.1 Economic Benefits of Recycling

“A research carried out in 2016 by the International Renewable Energy Agency (IRENA) along with the International Energy Agency (IEA) found that the recycling panel would represent an opportunity of approximately $15 billion by 2050 [20] (Fig. 9.6).

IRENA has projected that global PV panel waste could reach as high as 78 million tons in just about three decades. This waste, which consists primarily of glass, may be a goldmine for recovery of raw materials. Recycling has the ability to generate thousands of jobs for employees, in addition to the economic value of the content and people included in the process, and also for the new industries focused on utilizing...

Fig. 9.6 Potential value creation of materials in the coming decades’
Table 9.4 Expected economic values for the weight content of a waste PV module for aluminium, copper, silver, and waste glass

| Name of element of PV waste module | Percentages by weight (%) | Component weights for a single PV module (kg) | Unit prices forecast for products in 2040–2050 (USD/kg) | 2040–2050 Gross economic prices (USD) of recycled materials for a unit module |
|-----------------------------------|---------------------------|---------------------------------------------|-----------------------------------------------------|--------------------------------------------------------------------------------|
| Glass                             | 70                        | 14.53                                       | –                                                   | –                                                                              |
| Aluminium (frame)                 | 18                        | 3.74                                        | 2.35                                                | 8.78                                                                           |
| Aluminium (conductor)             | 0.53                      | 0.11                                        | 2.35                                                | 0.26                                                                           |
| Copper                            | 0.11                      | 0.02                                        | 7.5                                                 | 0.17                                                                           |
| Silver                            | 0.053                     | 0.01                                        | 495.2                                               | 5.45                                                                           |

recovered materials. “The recovery of metals for use in the modern manufacturing sectors is a way to minimize costs, which directly affects prices and thus motivates the productivity power of the country. Being a resource supplier nation, lowering prices could be a tremendous merit in lowering manufacturing expenses to compete with other resource suppliers on the market and thus dominating the market as a strong resource supplier. In short, they all give rise to the country’s cash inflow, and thus motivate the creation and become a strong candidate” [25]. All this plays an important part for the economy of the country.

“World Bank estimates for copper, aluminium and silver prices for the year 2030 are USD 7000 t⁻¹, USD 2200 t⁻¹, and USD 514.47 kg⁻¹, respectively” [26]. “Although the aluminium and copper prices have gone up, the estimates for silver have declined. Under these conditions, copper, aluminium and silver prices are expected to be on average as USD 7,500 t⁻¹, USD 2350 t⁻¹, and USD 495, 18 kg⁻¹ between 2040 and 2050. In this regard, the economic revenue from PV waste is shown in Table 9.4, showing waste PV module metals (silver, aluminium and copper), weights, unit prices and estimated economic values for a single module” [25].

9.4.2 Environmental Benefits of Recycling

“Many studies have analyzed the influence of recycling processes for PV modules upon the environment. There are advantages as well as drawbacks of various methods, considering all the stages, from gathering of the PV modules till the end of the recycling process” [27, 28].
9.4.2.1 Water

Intact waste in open dump sites gives rise to a risk to water sources, from leachate going into the ground and surface water resources, causing contamination and health hazard.

9.4.2.2 Air and Soil

Waste is burned in open places to decrease build-up, reduce hazards from disease point of view, and expose the market of materials that could be sold—which is especially relevant for e-waste. In general, uncontrolled and haphazard burning of e-waste generates airborne particle emissions which may be inhaled. This is a vital source of PM10 generation in regions that implements it frequently. The more broadly known environmental pollutants from majority of e-waste are from compounds that are exposed during (often crude) dismantling of the PV panels: heavy metals, polychlorinated biphenyls, and brominated flame retardants. Regardless of that, heating of plastics (including polyvinyl chloride wire casings), and circuit boards produces another variety of pollutants which includes chlorinated and brominated dioxin-related products. Human and environment is exposed to the burning of this e-waste in a considerable amount. Burning activities also rises up the amount of inhaled particulate matter which is toxic in nature, in addition to enlarging their geographical scale of influence.

9.4.2.3 Health

Batteries aside, the amount of hazardous materials in off-grid PV devices are present in very little quantity. But, the East African region has a huge, informal recycling module which uses discarded waste materials as a source of income generation by dismantling or burning of products to extract metals that could be sold. The vast majority of the informal recycling quarter which is involved in this material extraction does it with very little to almost no safety equipments. Although hazardous materials constitutes of a small part of solar products, the close propinquity and high frequency of exposure causes increase in the concentration and rate of inflow of these materials into the body. The transfer of particles from the skin and clothing of a person to family members is a secondary effect of exposure to these materials in the informal recycling sector. Even a little concentration of certain materials could cause harm to human health and it is especially prejudicial to the growth of children.
9.4.3 Ecological Impact and Cost Analysis

A life cycle analysis is conducted using a module of 125 × 125 mm multicrystalline silicon cells. Compared to a module using recycled wafers, a standard module results in a reduced energy consumption of 40 percent per kWh produced. For 20 years the generation of electricity is assumed in a sunny region resulting in a total generation of 33 kWh/Wp or 71.9 kWh/waf. The reuse of recycled silicon wafer for a second lifetime with high energy content significantly increases the carbon payback rate. With the small additional energy consumption for recycling solar cell and module cycle, we can again produce the same amount of energy for sunny regions, namely 165 kWh/Wp and 86 kWh/Wp for continental regions [29].

9.5 Conclusion

Traditional approaches to solar e-waste recycling don’t have all the solutions to this growing crisis. Such approaches are energy-intensive, inefficient, and unsustainable and pose both environmental and safety hazards. This review presents existing and potential off-grid photovoltaic recycling systems. This paper analyzes the structure of c-Si PV modules and discusses the status and trends of the treatment methods used to recycle the silicon PV module. We have developed recycling process for the waste photovoltaic module through this research. We recycle tempered glass using organic solvent. And, the EVA had been discarded with thermal decomposition. The silicon was eventually obtained by chemical etching process by removing metal impurities on the recovered surface of the PV cells. In particular, we were able to achieve a high yield of silicon by using a surfactant that may be useful to researchers interested in recycling the PV components. This work sheds new light on air conservation and on the successful use of the human-friendly waste materials. Recycling of photovoltaic modules is not currently feasible, experts claim, since the volume of waste produced is still too limited to be economically viable for recycling. However, by 2030 the waste generated from PV modules is expected to exceed 130,000 tpa, the volume that is sustainable for its recycling, according to the European PV modules recovery association. It is also found that while studies have shown that photovoltaic waste recycling and end-of-life recycling modules have significant positive effects on the reduction of environmental loads, the economic feasibility of photovoltaic module recycling remains unfavorable and policies are required to promote producers’ accountability not only in the photovoltaic sector, but also in the energy sector.

There will be a need for recycling technology soon as the waste generated from solar panels is increasing rapidly. The methods for recycling of solar panels are described in detail in this paper. However, the quality of recycled materials is yet to be known. Research on how to use the recovered materials can be performed, which form the future scope regarding the enhancement of this work.
References

1. Bergera W, Simona F-G, Weimanna K, EAA (n.d.) A novel approach for the recycling of thin film photovoltaic modules
2. Kang S, Yoo S, Le J, Boo B, HR (n.d.) Experimental investigations for recycling of silicon and glass from waste photovoltaic modules
3. Bogacka M, Pikon K, ML (n.d.) Environmental impact of PV cell waste scenario
4. Adamo ID, Miliacca M, Rosa P (2017) Economic feasibility for recycling of waste crystalline silicon photovoltaic modules 1–7
5. Choi J, Ph D, Fthenakis V, Ph D (2013) AC SC. J Clean Prod. https://doi.org/10.1016/j.jclepro.2013.11.022
6. Sinha P, Solar F, Cossette M, Menard J (2012) End-of-life CdTe PV recycling with semiconductor refining 27–28. https://doi.org/10.4229/27thEUPVSEC2012-6CV.4.9
7. Olson C, Geerligs B, Goris M, I B, JC (2013) Current and future priorities for mass and material in silicon PV module figure 1. Schematic of state-of-the-art PV recycling process flow 2–6
8. Choi J, Fthenakis V (2010) Econ Feasibility Recycl Photovoltaic Surv Model 14(6):947–964. https://doi.org/10.1111/j.1530-9290.2010.00289.x
9. Greenmatch.co.uk—Match Quotes & Suppliers|GreenMatch. (n.d.). Retrieved 1 Aug 2020, from https://www.greenmatch.co.uk/
10. Lalit G, Emeka C, Nasser N, Chinmay C, Garg G (2020) Anonymity preserving IoT-based COVID-19 and other infectious disease contact tracing model. IEEE Access 14. https://doi.org/10.1109/access.2020.3020513
11. Impact of COVID-19 on Operational Projects and Rooftop Solar: Report (n.d.). Retrieved 3 Sept 2020, from https://www.saurenergy.com/solar-energy-news/impact-of-covid-19-on-operational-projects-and-rooftop-solar-report
12. PSB Academy|Diplomas, Degrees, Postgraduate & Other Courses (n.d.). Retrieved 1 Aug 2020, from https://www.psb-academy.edu.sg/
13. Solar Panels, Solar Panels For Sale For Your Home & Business (n.d.). Retrieved 1 Aug 2020, from https://www.mrsolar.com/
14. Home-Mana Energy (n.d.). Retrieved 1 Aug 2020, from https://mepcell.com/
15. Kim H (2018) PV waste management at the crossroads of circular economy and energy transition : the case of South Korea. https://doi.org/10.3390/su10103565
16. Jing Tao SY (n.d.) Review on feasible recycling pathways and technologies of solar photovoltaic modules
17. Suresh S, Singhvi S, Rustagi V (2019) Managing India’s PV module waste 1–32
18. Advances in Solar Photovoltaic Power PlantsMd Rabiul Islam|Springer (n.d.). Retrieved 1 Aug 2020, from https://www.springer.com/gp/book/97836625050199
19. Solar Power Installation|Development|Technology News and Features (n.d.). Retrieved 1 August 2020, from https://www.solarpowerworldonline.com/
20. Agency E, Co-operation E, Climate G (n.d.) About IEA-PVPS
21. Task IEAP, Lee J (2018) End of life management of photovoltaic panels : trends in PV Module Recycling Technologies end-of-life management of photovoltaic panels : trends in PV module recycling technologies
22. Access O (n.d.) We are IntechOpen, the world’s leading publisher of Open Access books Built by scientists, for scientists TOP 1%
23. Yi YK, Kim HS, Tran T, Hong SK, Kim MJ (2014) Recovering valuable metals from recycled photovoltaic modules. J Air Waste Manag Assoc 64(7):797–807. https://doi.org/10.1080/10962247.2014.891540
24. McDonald NC, IMP (n.d.) Producer responsibility and recycling solar photovoltaic modules
25. Gönen Ç, Kaplanoğlu E (2019) Environmental and economic evaluation of solar panel wastes recycling. Waste Manage Res 37(4):412–418. https://doi.org/10.1177/0734242X19826331
26. World Bank (2017) The World Bank—Annual Report 2017. 80. Retrieved from http://pubdocs.worldbank.org/en/908481507403754670/Annual-Report-2017-WBG.pdf
27. A Review of Recycling Processes for Photovoltaic Modules | IntechOpen (n.d.) Retrieved 1 Aug 2020, from https://www.intechopen.com/books/solar-panels-and-photovoltaic-materials/a-review-of-recycling-processes-for-photovoltaic-modules

28. Lunardi MM, Alvarez-Gaitan JP, Bilbao JI, Corkish R (2018) A review of recycling processes for photovoltaic modules. Solar Panels Photovoltaic Mater. https://doi.org/10.5772/intechopen.74390

29. Frisson L, Lieten K, Bruton T, Declercq K, Szlufcik J, HDM, Goris M, Benali A, OA (n.d.) Recent improvements in industrial PV module recycling