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A Review of Recycling Processes for Photovoltaic Modules

Marina Monteiro Lunardi,
Juan Pablo Alvarez-Gaitan, José I. Bilbao and
Richard Corkish

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Abstract

The installations of photovoltaic (PV) solar modules are growing extremely fast. As a result of the increase, the volume of modules that reach the end of their life will grow at the same rate in the near future. It is expected that by 2050 that figure will increase to 5.5–6 million tons. Consequently, methods for recycling solar modules are being developed worldwide to reduce the environmental impact of PV waste and to recover some of the value from old modules. Current recycling methods can recover just a portion of the materials, so there is plenty of room for progress in this area. Currently, Europe is the only jurisdiction that has a strong and clear regulatory framework to support the PV recycling process. This review presents a summary of possible PV recycling processes for solar modules, including c-Si and thin-film technologies as well as an overview of the global legislation. So far, recycling processes of c-Si modules are unprofitable but are likely to be mandated in more jurisdictions. There is potential to develop new pathways for PV waste management industry development and offer employment and prospects for both public and private sector investors.

Keywords: recycling, life-cycle, photovoltaic, waste, end-of-life

1. Introduction

Photovoltaic (PV) solar modules are designed to produce renewable and clean energy for approximately 25 years. The first substantial PV installations happened in the early 1990s and since early 2000s solar PV electricity distribution has grown extremely fast [1].

The cumulative worldwide PV generation capacity reached 302 GW in the end of 2016 [2] and the predominant technology (90% of the market) is crystalline silicon (c-Si) cells [3]. Also, during the last years there were several advances on renewable energy in general, including significant price decline and a constant increase in attention to environmental impacts from energy sources [4, 5]. Furthermore, the International Technology Roadmap for Photovoltaic (ITRPV) prediction for the installed PV capacity in 2050 is 4500 gigawatts [6].

As a result of the increase in the global market for PV energy, the volume of modules that reach the end of their life will grow at the same rate in the near future. At the end of 2016, the cumulative global PV waste reached 250,000 metric tons, while it is expected that by 2050 that figure will increase to 5.5–6 million tons [7].

Much PV waste currently ends up in landfill. Given heavy metals present in PV modules, e.g. lead and tin, this can result in significant environmental pollution issues. Furthermore, valuable metals like silver and copper are also present, which represents a value opportunity if they can be recovered. Hence, the landfill option creates additional costs and it does not recover the intrinsic values of the materials present in the PV modules.

Hence, methods for recycling solar modules are being developed worldwide to reduce the environmental impact of end-of-life modules and to recover some of the value from old PV modules. However, current recycling methods are mostly based on downcycling processes, recovering only a portion of the materials and value, so there is plenty of room for progress in this area. Moreover, currently only Europe has a strong regulatory framework in place to support recycling, but other countries are starting to build specific frameworks related to PV waste. It's clear that sustainable development of the PV industry should be supported by regulatory frameworks and institutions across the globe, which is not the case at the moment. There must be adequate management policies for photovoltaic modules when they reach their end-of-life (EoL) or when they are not able to produce electricity any longer.

As mentioned above, the European Union (EU) provides a legislative framework for extended producer responsibility of PV modules in European scale through the Waste Electrical and Electronic Equipment (WEEE) Directive 2012/19/EU [8]. The main objectives of this policy are to preserve, protect and improve the quality of the environment, to protect human health and to utilize natural resources prudently and rationally. Since February 2014, the collection, transport and recycling of PV modules that reached their EoL is regulated in every EU country [8].

On the other hand, countries with fast expanding PV markets such as China [9], Japan [10], India [11], Australia [12] and USA [13] still lack specific regulations for EoL PV modules. These countries treat PV waste under a general regulatory framework for hazardous and non-hazardous solid waste or WEEE. However, there are some exceptions.

In 2012 the Japanese government introduced a “feed-in tariff” [14] that guaranteed the rate for electricity generated from renewable energy and exported to the grid, which supported rapid growth of solar module installation in the country. Once all the installed capacity starts reaching EoL (within 20–30 years) they will create a significant waste problem for Japan. In late 2017, the Japan Photovoltaic Energy Association (JPEA) has published voluntary guidelines on how to properly dispose of EoL photovoltaic modules. Also, manufacturers, importers

and distributors of photovoltaic modules have been invited to provide information on the chemical substances contained in the product and to inform the waste disposal companies. JPEA strongly recommend that industry follow the guidelines [15].

In USA, some states go beyond the Resource Conservation and Recovery Act which regulates hazardous and non-hazardous waste management [13]. California, for example, has additional threshold limits for hazardous materials classification based on the Senate Bill 489 that categorizes end-of-life PV modules as Universal Waste (facilitating easy transport). This bill is currently pending United States Environmental Protection Agency approval [16].

In Australia, governments have recognized the significance of guaranteeing that regulations are in place to deal with the PV waste issue. Ministers agreed that the state of Victoria would lead innovative programs that seek to reduce the environmental impacts caused throughout the lifecycle of photovoltaic systems. These efforts are part of an industry-led voluntary product management arrangement to address the potential emerging risks of PV systems and their waste. PV modules are listed under the National Product Administration Act to signal the intention to consider a scheme to deal with such waste [17].

The non-inclusion of PV residues in waste legislation in some countries is due to different reasons. Solar modules have a lifespan of up to 25–30 years [18] and so there has been limited interest in investigating the aspects of EoL so far. Moreover, the quantity of this type of waste is still considered insignificant compared to the quantity of other WEEE [19], which currently makes setting up specific recycling plants for solar modules uneconomical. In addition, the definition of mandatory requirements for EoL treatment could still be an obstacle to the effective acceptance of these recycling processes [20]. Because of that, there should be a continuous focus on scientific evidences on the potential impacts and benefits related to the treatment of photovoltaic residues.

Furthermore, recycling processes for all the different PV technologies are not yet well developed. The processes are well developed for mono or multicrystalline silicon. FirstSolar [21] has an established recycling process for CdTe, but for other thin films there are still room for improvements. and are being tested and for generation 3 (new materials [22]) the recycling technologies are not well developed yet.

Only about 10% of PV modules are recycled worldwide. The main reason for that is the lack of regulation. Actually, it has been shown that, for the current recycling technologies, silicon-based modules do not have enough valuable materials to be recovered and the cost of the recycling process is always higher than the landfill option (not considering the externalities), making recycling an economically unfavorable option [23]. However, the prediction for 2050 is that the recoverable value could cumulatively exceed 15 billion US dollars (equivalent to 2 billion modules, or 630 GW) [7]. In addition, the recycling of solar PV modules can ensure the sustainability of the long-term supply chain [24], thereby increasing the recovery of energy and embedded materials and, also, reducing CO₂ emissions and energy payback time (EPBT) related to this industry.

For years, the PV industry and researchers have worked intensively in search of different types of efficient and cost-effective materials to manufacture solar PV modules and specific ways of

keeping them adequately bonded to withstand several years of outdoor exposure. The modules are made to minimize the amount of moisture that can come in contact with the solar cells and their contacts while keeping manufacturing costs down. The current standard c-Si module is bonded using two layers of EVA to bond the layers together. Because of that, recycling solar modules is a relatively complex task, since these materials need to be separated. Once the materials/layers of a solar module can be separated, metals such as lead, copper, gallium, cadmium, aluminum and silicon can be recovered and reused in new products.

Originally created by PV CYCLE in 2007 and commercially available in Europe, the process of recycling mono or multicrystalline silicon modules begins with the separation of the aluminum frame and the junction boxes and then a mechanical process is used for the extraction of the remaining materials of the module (a process similar to recycling of glass or electronic waste). The problems with this process are that the value of the material recovered is low (as it is a downcycling process) and that the maximum amount of recovered materials is about 80%, which is not sufficient for future requirements, and the value of recovered materials is smaller than the original [25]. Thin film processes are under development or near implementation in Italy, Japan and South Korea but costs are not yet competitive. Even up to 90% recovery of materials is not sufficient when compared to production costs [26]. Lastly for recycling processes aiming to generate new materials, the aim is to keep the materials intact for reuse or direct recycling, recovering the frame, glass, tabbing and solar cells without breakages and in good condition. The recovery rates can achieve up to 95% and the materials recovered have higher commercial value. However, these processes are complex and are currently just at laboratory scale, being studied by a few research groups [27].

Even with the difficulty of recovering rare, toxic and valuable materials from solar modules, the recycling process has a remarkable environmental advantage [28]. Nevertheless, the need to recycle this type of waste is imminent. The better knowledge of these technologies and growth on the waste amounts that could generate profitable outcomes has supported the development of the first PV recycling plants. Hence, PV manufacturing companies (e.g. First Solar, Pilkington, Sharp Solar, and Siemens Solar) are investing in the research on solar modules at EoL [29].

The challenges to design the ideal PV recycling process are many. The focus should be on the avoidance of damage to the PV cells and module materials, economic feasibility, and high recovery rate of materials that have some monetary value or are scarce or are hazardous, that can be reused in the supply chain. Finally, the next step for the industry and researchers is to create module designs that are “recycling-friendly” [29].

2. Photovoltaic technologies

2.1. Crystalline silicon technology

Crystalline Si (c-Si) technologies dominate the current market share of PV modules (more than 90%). The aluminum back surface field (Al-BSF) [30] is the current industry standard technology

but the passivated emitter and rear cell (PERC) [31] is gaining importance in the world market and is expected to replace the Al-BSF technology in the future [3]. The heterojunction (HIT) cells are also expected to gain some space with predictions of 15% of the total market share by 2027 [7]. Besides that, Si-based tandem solar technologies are expected to appear in mass production after 2019 [7].

There are different cell structures for crystalline silicon-based PV cells [32]. The cells are electrically interconnected (with tabbing), creating a string of cells in series (60 or 72 cells are standard numbers used) and assembled into modules to generate electricity (**Figure 1**).

A typical crystalline silicon (c-Si) PV module contains approximately 75% of the total weight is from the module surface (glass), 10% polymer (encapsulant and backsheet foil), 8% aluminum (mostly the frame), 5% silicon (solar cells), 1% copper (interconnectors) and less than 0.1% silver (contact lines) and other metals (mostly tin and lead) [33]. The rest of the components have a small percentages of the module weight [29, 34].

The EU directive [8] established recycling targets in terms of module weight and also expresses the intention to increase the collection rates to allow the progressive recycling of more material and less to be landfilled. Even with targets aiming for 65% recycling product weight, some of the current studied recycling processes can recycle over 80% of the weight of a PV module (**Figure 2**). However there is still incentive to improve, considering that most of the weight is from glass and frame, which are relatively easy to remove, depending on the recycling process.

2.2. Thin-film technologies

Thin-films represent less than 10% of the total PV industry [3]. The currently dominant technologies are cadmium telluride (CdTe), copper indium gallium selenide (CIGS) and amorphous silicon (a-Si) with, approximately, 65%, 25% and 10% of the total thin-film market share, respectively [35].

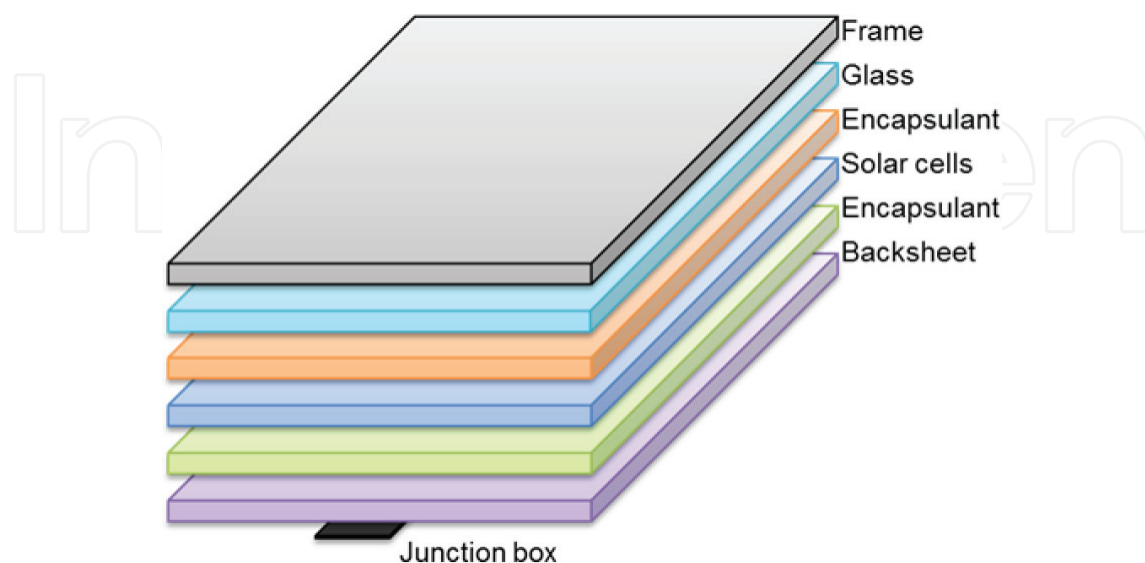


Figure 1. Silicon solar module basic structure [32].

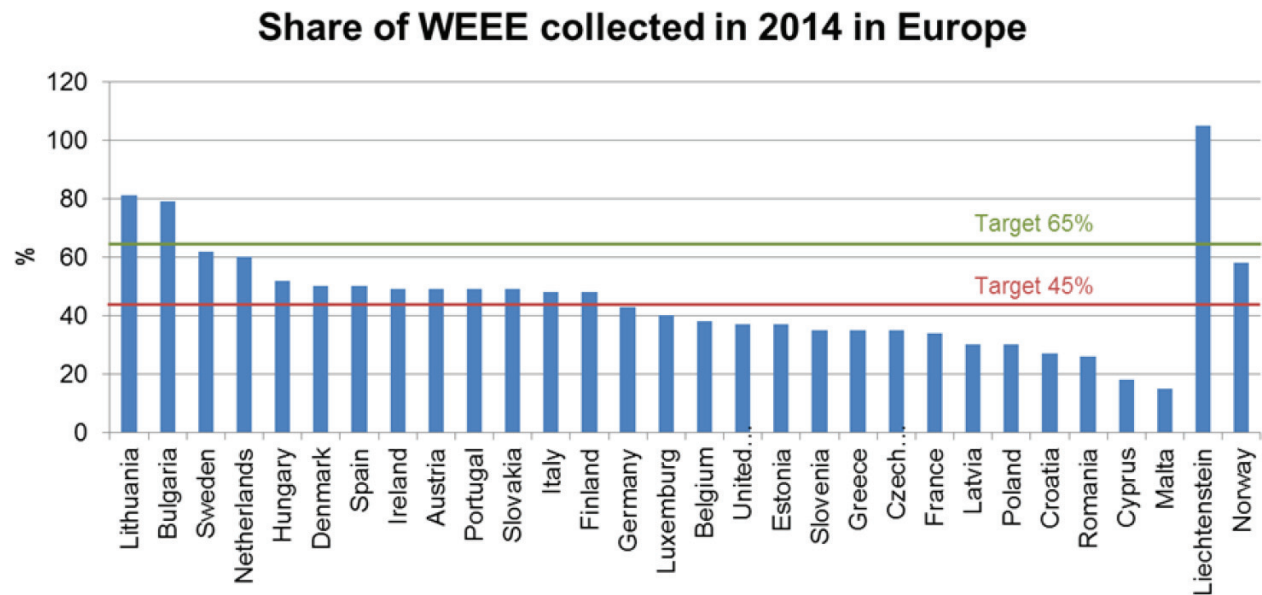


Figure 2. Total collection rate for WEEE in 2014 as a percentage of the average weight of EEE put on the market in the three preceding years (2011–2013) [8].

Thin-film solar cells were developed with the aim of providing low cost and flexible geometries, using relatively small material quantities. CdTe, CIGS and a-Si are the main technologies for thin-film PV modules [36]. CdTe is the most widely used thin-film technology. It contains significant amounts of cadmium (Cd), an element with relative toxicity, which presents an environmental problem that has been studied worldwide [37, 38]. CIGS has a very high optical absorption coefficient because it is a direct band gap material (can be tuned between 1.0 and 2.4 eV by varying the In/Ga and Se/S ratios [39]) and efficiency of approximately $15.7 \pm 0.5\%$ for high bandgap [40]. A-Si has low toxicity and cost but also low durability and it is less efficient compared with the other thin-film technologies [41]. Current projections expect the a-Si module market to disappear in the near future, since they cannot compete on costs or efficiency [3].

Basically, thin-film modules consist of thin layers of semiconducting material (CdTe, CIGS or a-Si) deposited on a substrate (glass, polymer or metal) (**Figure 3**).

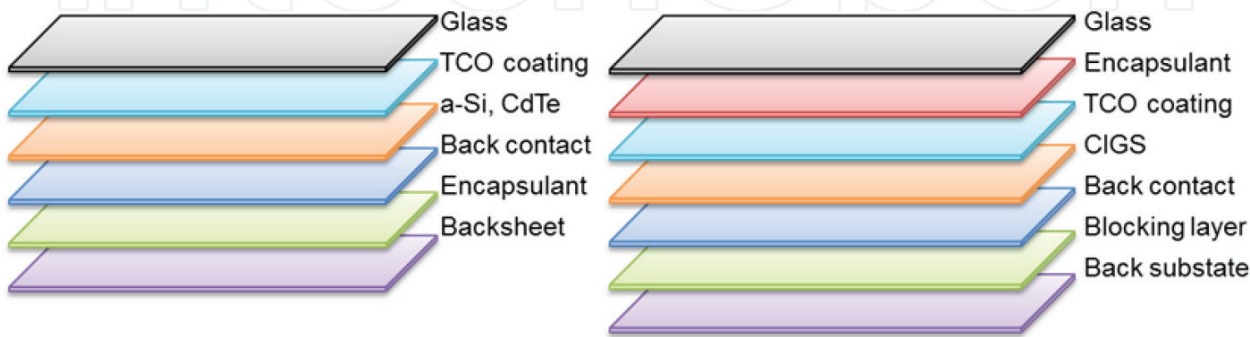


Figure 3. Thin-film solar module basic structures [36].

3. Photovoltaic recycling technologies

PV modules are largely recyclable. Materials such as glass, aluminum and semiconductors can, theoretically, be recovered and reused. Hence it is vital that consumers, industry and PV producers take responsibility for the EoL of these modules. So far, the most common methods for recycling c-Si PV modules are based on mechanical, thermal and chemical processes.

Although thin-film solar cells use far less material than c-Si cells, there are concerns about the availability and toxicity of materials such as tellurium (Te), indium (In), and cadmium (Cd), for example. Furthermore, the production processes also generates greenhouse gases emissions during some reactor-cleaning operations. Because of these issues, it is very important to focus on the recycling of PV modules for all the technologies.

PV Cycle is a not-for-profit organization which goal is to manage PV waste through their waste management programme for solar PV technologies [42]. PV Cycle was the first to establish a PV recycling process and PV waste logistics throughout the EU. In 2016 their process of recycling PV achieved a record recycling rate of 96% for c-Si PV modules (fraction of solid recycled) [25], which is a percentage that surpasses the current European WEEE standards. The process begins with the removal of the cables, junction box and frame from the PV module. Then, the module is shredded, sorted and separated. The separation of the materials allows them to be sent to specific recycling processes associated with each material. The summary of this process is shown in **Figure 4**.

FirstSolar [21] developed a recycling process for CdTe modules. The company manages the collection and transportation of EoL modules to the recycling centre; however, the recycling process itself must be financed. This is made by setting aside funds by the company itself at the time of the module sale, which also happens with WEEE. The summary of this process is shown in **Figure 5**.

The recycling process starts with the shredding of the modules into large pieces and subsequently in to small fragments (5 mm or less) by a hammer mill. During the next 4–6 h the semiconductor films are removed in a slow leaching drum. The remaining glass is exposed to a mixture of sulfuric acid and hydrogen peroxide aiming, to reach an optimal solid–liquid ratio. After that process, the glass is separated again. The next step is to separate the glass from the larger ethylene vinyl acetate (EVA) pieces, via a vibrating screen. The glass is cleaned and sent to recycling. Sodium hydroxide is used to precipitate the metal compounds, after which they are sent to another company where they can be processed to semiconductor grade raw materials for use in new solar modules. This process recovers 90% of the glass for use in new products and 95% of the semiconductor materials for use in new solar modules [21].



Figure 4. Summary of PV cycle recycling process for c-Si modules [25].

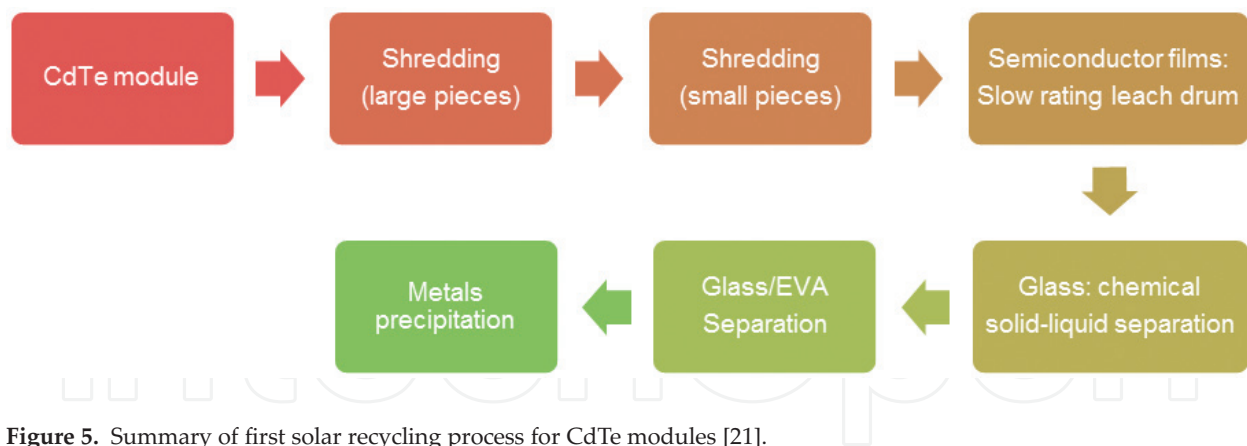


Figure 5. Summary of first solar recycling process for CdTe modules [21].

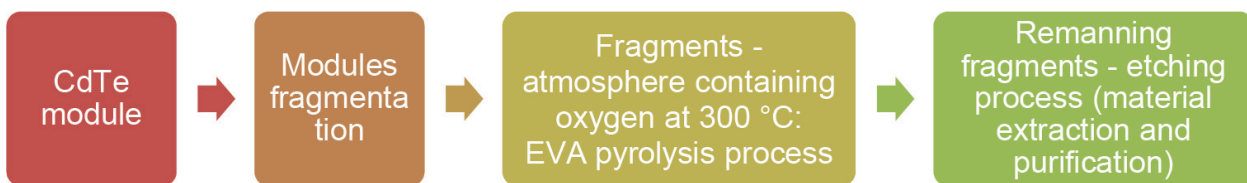


Figure 6. Summary of ANTEC solar GmbH recycling process for CdTe modules [43].

Also, for recycling CdTe modules, ANTEC Solar GmbH designed a pilot plant with a similar technology to the First Solar process. It starts with a physical fragmentation of the modules. After that, these small pieces are exposed to an atmosphere containing oxygen at 300°C. These conditions result in the delamination of the EVA. Subsequently, these fragments are taken to a 400°C atmosphere containing chlorine gas which causes an etching process. This step of the process generates CdCl_2 and TeCl_4 that are condensed and precipitated afterwards [43]. The summary of this process is shown in **Figure 6**.

A company that has a well established c-Si recycling process is the SolarWorld [44]. This company started recycling in 2003 with a pilot plant using a thermal process. Today, the take-back of modules is organized via a “bring-in” system [44]. Their process is based on a thermal process, which starts by pyrolysing the modules. During this process, the plastic components are burnt at 600°C. The solar cells, glass and metals are separated manually after that. The glass and some metals are sent to other companies for recycling and the solar cells can be turned into wafers again. The outcomes of this process are the recovery of more than 84% of the module weight, being 90% of the glass and 95% of the semiconductor materials [44]. This process can recover up to 98% unbroken cells depending on the conditions of the module and the thickness of the cells. The summary of this process is shown in **Figure 7**.

A pilot project was funded by the Japanese Government via the New Energy and Industrial Technology Development Organization (NEDO). The recycling process for Si or CIS is based on pyrolysis of the polymers in a furnace. The process starts with the removal of the frames and the backsheet foil before the thermal process begins. After that, for CIS only, the EVA resin

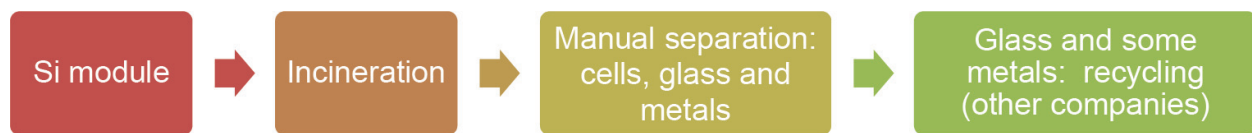


Figure 7. Summary of SolarWorld recycling process for Si modules [44].



Figure 8. Summary of NEDO recycling process for Si modules (pilot project).



Figure 9. Summary of “hot knife” recycling process for PV modules [46].

is burned and the CIS layer is grated. For the c-Si modules, the semiconductor materials are recovered as well as the glass cullet [45]. The summary of these processes is shown in **Figure 8**.

In 2014 the Environment Ministry of Japan, through NEDO, together with private companies, began working on new technologies to pry the PV modules apart. The new technology appeared to solve a clear problem, the firm attachment of the glass and the cells to the EVA, and the consequent difficulty to separate them simply by smashing them to pieces and sorting them out [46].

NPC incorporated is one of the companies that make solar module recycling equipment. The process, called the “hot knife method”, can separate the cells of a module from the glass in about 40 seconds. It places the module between two rollers, which move it along and hold it steady until it runs into a 1 meter-long steel blade (“hot knife”) that is heated to 180–200°C and slices the cell and the glass apart (**Figure 9**) [46].

In Japan, the scrap glass can be sold for 0.5–1 Yen/kg. At that price, the 10–15 kg of glass in a solar module is worth about 15 Yen (approximately 0.14 US D). Their goal was to develop a recycling technology that can cost less than 5 yen/watt (1000 yen for a 200-watt module, not including transportation cost) by the end of April 2018, which they already did by January 2018 [46].

Furthermore, some innovative treatment processes for recycling PV solar modules have been developed.

Loser Chemie has some collection points from where they gather several types of photovoltaic systems (c-Si, CdTe, CIGS and GaAs). The company has developed and patented original



Figure 10. Summary of loser Chemie recycling process for PV modules (pilot project).

processes using mechanical and chemical treatment to recycle solar cells [47]. The first step is to crush and separate the materials mechanically. In the next stage, they use chemical treatment to recover the semiconductor metals. After that, the aluminum metallisation is also recovered and can be used for producing wastewater treatment chemicals as aluminum oxide [47]. The summary of these processes is shown in **Figure 10**.

Reclaim PV has teamed up with major solar module manufacturers who distribute in Australia and is refining its processes. The company is developing a process of reclaiming efficient cells from damaged solar modules. Their cell recycling system is able to extract efficient components (but not unbroken cells) from end-of-life solar modules in order to develop new green products or be reintroduced into the PV industry as new solar modules [48].

4. Photovoltaic recycling technologies studied worldwide

Table 1 summarizes the recycling possibilities for silicon solar modules, as well as the advantages and disadvantages of each process.

Studies show that the impurity levels are an important issue during the recycling processes. For example, high temperature thermal processes and mechanical processes can create impurities. Also, low temperature processes that are used with specific mechanical or chemical steps can generate impurities as well. Hence, the ideal outcome can only be achieved with a combination of thermal, chemical or metallurgical steps [29, 61]. Once materials can be recovered without impurities, then they will have a higher market value, which is one of the main obstacles to the growth of the PV recycling industry with the current technologies.

An overview of possible thin-film recycling processes is shown in **Table 2**.

The large-scale recycling of thin-film PV modules is well advanced and, as well as the Si solar cells, thin-film PV modules are currently processed and recycled using a combination of mechanical and chemical treatments to achieve meaningful outcomes.

Process	Advantages	Disadvantages	Status	Ref.
Organic solvent dissolution	<ul style="list-style-type: none"> • Easy access to the EVA • Less cell damage • Recovery of glass 	<ul style="list-style-type: none"> • Delamination time depends on area • Harmful emissions and wastes 	Research	[49]
Organic solvent and ultrasonic irradiation	<ul style="list-style-type: none"> • More efficient than solvent dissolution process • Easy access to the EVA 	<ul style="list-style-type: none"> • Expensive equipment • Harmful emissions and wastes 	Research	[50]
Electro-thermal heating	<ul style="list-style-type: none"> • Easy removal of glass 	<ul style="list-style-type: none"> • Slow process 	Research	[51]
Mechanical separation by hotwire cutting	<ul style="list-style-type: none"> • Low cell damage • Recovery of glass 	<ul style="list-style-type: none"> • Other separation processes required for full removal of EVA 	Research	[52]
Pyrolysis (conveyer belt furnace and fluidised bed reactor)	<ul style="list-style-type: none"> • Separate 80% of wafers and almost 100% of the glass sheets • Cost-effective industrial recycling process 	<ul style="list-style-type: none"> • Slightly worse texturisation (damage to cell surface) 	Research (pilot)	[53]
Solvent (Nitric acid) dissolution	<ul style="list-style-type: none"> • Complete removal of EVA and metal coating on the wafer • It is possible to recover intact cells 	<ul style="list-style-type: none"> • It can cause cell defects due to inorganic acid • Generates harmful emissions and wastes 	Research (pilot)	[54]
Physical disintegration	<ul style="list-style-type: none"> • Capable of treating waste 	<ul style="list-style-type: none"> • Other separation processes required for full EVA removal • Dusts containing heavy metals • Breakage of solar cells • Equipment corrosion 	Commercial	[55]
Dry and wet mechanical process	<ul style="list-style-type: none"> • No process chemicals • Equipment widely available • Low energy requirements 	<ul style="list-style-type: none"> • No removal of dissolved solids 	Commercial	[56]
Thermal treatment (Two steps heating)	<ul style="list-style-type: none"> • Full removal of EVA • Possible recovery of intact cell • Economically feasible process 	<ul style="list-style-type: none"> • Harmful emissions • High energy requirements • Cell defects and degradation due to high temperature 	Commercial	[57]
Chemical etching	<ul style="list-style-type: none"> • Recover high purity materials • Simple and efficient process 	<ul style="list-style-type: none"> • Use of chemicals 	Commercial	[58–60]

Table 1. Silicon solar modules recycling processes.

Process	Advantages	Disadvantages	Status	Ref.
Organic solvent dissolution	<ul style="list-style-type: none">• Easy access to the encapsulant• Less cell damage• Recovery of glass	<ul style="list-style-type: none">• Time for delamination depends on area• Harmful emissions and wastes	Research	[62]
Irradiation by laser	<ul style="list-style-type: none">• Easy access to the encapsulant	<ul style="list-style-type: none">• Slow process• Very expensive equipment	Research	[63]
Mechanical separation by hotwire cutting	<ul style="list-style-type: none">• Low cell damage• Recovery of glass	<ul style="list-style-type: none">• Other separation processes required for encapsulant	Research	[52]
Vacuum blasting	<ul style="list-style-type: none">• Removal of semiconductor layers without chemicals• Recovery of clean glass	<ul style="list-style-type: none">• Relatively slow process• Emission of metals• Further chemical/mechanical treatments	Research (pilot)	[55]
Attrition	<ul style="list-style-type: none">• No usage of chemicals• Recovery of clean glass	<ul style="list-style-type: none">• Further chemical or mechanical treatments needed	Research (pilot)	[55]
Flotation	<ul style="list-style-type: none">• Relatively simple process• Low use of chemicals	<ul style="list-style-type: none">• High losses of valuables during rinsing and sieving process• Flotation process required	Research (pilot)	[55]
Dry etching	<ul style="list-style-type: none">• Simple process	<ul style="list-style-type: none">• High energy demand• High effort for purification	Commercial	[43]
Physical disintegration	<ul style="list-style-type: none">• Capable of treating waste	<ul style="list-style-type: none">• Other separation processes required for encapsulant• Dusts containing heavy metals• Breakage of solar cells• Equipment corrosion	Commercial	[55]
Dry and wet mechanical process	<ul style="list-style-type: none">• No process chemicals• Equipment widely available• Low energy requirements	<ul style="list-style-type: none">• No removal of dissolved solids	Commercial	[56]
Chemical etching	<ul style="list-style-type: none">• High purity materials• Simple and efficient process	<ul style="list-style-type: none">• Use of chemicals	Commercial	[58–60]
Thermal treatment	<ul style="list-style-type: none">• Full removal of encapsulant• Recovery of intact cell• Simple and economical	<ul style="list-style-type: none">• Harmful emissions• High energy requirements• Cell defects and degradation	Commercial	[55]
Leaching	<ul style="list-style-type: none">• Complete removal of metals	<ul style="list-style-type: none">• High use of chemicals• Generation of acidic fumes• Complex control of chemicals	Commercial	[64]

Table 2. Thin-film solar modules recycling processes.

5. Environmental aspects

Several studies have analyzed the impacts of recycling processes for PV modules on the environment. There are advantages and disadvantages of the different methods, considering all the stages, from the collection of the PV modules to the end of the recycling process.

An environmental study made for the European Full Recovery End-of-Life Photovoltaic (FRELPE) project showed that environmental impacts from c-Si recycling processes come from plastic incineration and some chemical and mechanical treatments (sieving, acid leaching, electrolysis, and neutralization) for the recovery of metals [65].

Additionally, before the recycled silicon from solar cells can be used again, further chemical treatment is necessary, as well as for silver and aluminum. The chemical treatments have the potential of producing environmental impacts. Besides that, it is important to note that no process can recycle 100% of recovered materials from solar modules yet [28].

Nevertheless, for the PV Cycle [25] c-Si recycling process it was shown that there is a significant decrease in Global Warming Potential impacts (up to 20% compared to the process of making cells) [66] and for CdTe modules, there is an environmental benefit from the glass and copper recycling [67].

When comparing c-Si recycling and landfill EoL scenarios it was found that the environmental impacts from the recycling process are lower than for landfill, assuming that the recycled resources go back to the PV cells and modules manufacturing. These results considered that the recycling process involving dismantling, remelting, thermal and chemical treatments [28].

It can be seen that there are opportunities and challenges related to PV recycling processes. Although it was already shown that there are environmental benefits, the recycling methods still need to improve in order to achieve better recovery rates and work on the transportation issues.

6. Economic aspects

The recovery of valuable materials during the recycling of PV modules can have great economical value. The extraction of secondary raw material from EoL PV modules, if made in an efficient way, can make them available to the market again [68].

Attention has been paid particularly to silver. PV modules that reach their EoL will build up a large stock of embodied raw materials (as mentioned previously), which can be recovered and become available for other uses or even for solar cells again. However, this will not occur before 2025, according to some forecasts [68].

The ITRPV predicts that, by 2030, the total material value recovered from PV recycling can reach USD 450 million. With this amount it is possible to produce 60 million PV modules (18 GW), which would be approximately 33% of the 2015 production [7]. Considering Si, up to 30,000 t of silicon can theoretically be recovered in 2030 [7], which is the amount of silicon needed to produce approximately 45 million new modules. Considering a polysilicon current prices at USD 20/kg and a recovery rate from commercial recycling processes of 70% this is equivalent to USD 380 million [7].

7. Conclusions

The current study presented an overview of possible PV recycling process for solar modules, including c-Si and thin-film technologies. The motivation, legislation and current processes were discussed and possible issues were addressed.

So far, recycling processes of c-Si modules results in a net cost activity when compared to landfill (due to the avoidance of the true environmental costs and externalities for the latter) but these processes can ensure the sustainability of the supply chain in the long-term, increase the recovery of energy and embedded materials, while reducing CO₂ emissions and energy payback time (EPBT) for the whole PV industry. The unprofitability of the current methods does not mean that the recycling of PV modules should be discarded. The PV waste management has the potential to develop new pathways for industry development and offers employment prospects to investors, for both public and private sector [7].

It is well known that the recycling of EoL PV modules has positive influences on the environmental impacts. Recycling of PV modules can remove and retain potentially harmful substances (e.g. lead, cadmium, and selenium), recover rare materials (e.g. silver, tellurium and indium) and make them available for future use [8]. To achieve the best possible results at acceptable costs, it is essential that future recycling processes stay up to date on the continuous innovations in solar cells and modules technologies.

However, the current waste volumes are still low, which entails economical obstacles for the development of the existing processes. If we compare the economics of recycling electronics and telecommunications, where the profits are generated through the recovery of precious metals and parts, it is unlikely for PV solar modules to have sufficient amounts of these materials to pay for the associated costs of the steps of recycling processes [69].

It is important that specific legislation is established for PV waste management and recycling and that this step is given before the amount of waste from EoL PV modules becomes alarming, as forecast for the year 2030 [7]. Regulation will help, but it might not be the only way. The economic viability should be achieved as well. If a recycling process for PV waste that is revenue positive (i.e. a good business) can be created, then it will happen regardless of regulations.

It was shown that recycling technologies for PV wastes are extensively explored not just on labs and pilot plants, but some are also commercially available. It is also clear that a few challenges (e.g. economic feasibility, recovery of more materials, and recovery of unbroken cells), still remain in process efficiency, complexity, energy requirements and use of non-environmentally friendly materials for the treatment of some elements.

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Author details

Marina Monteiro Lunardi¹, Juan Pablo Alvarez-Gaitan², José I. Bilbao¹ and Richard Corkish^{1*}

*Address all correspondence to: r.corkish@unsw.edu.au

1 The Australian Centre for Advanced Photovoltaics (ACAP), School of Photovoltaic and Renewable Energy Engineering, University of New South Wales, Sydney, Australia

2 School of Civil and Environmental Engineering, University of New South Wales, Sydney, Australia

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