

Review

# Global Challenges and Prospects of Photovoltaic Materials Disposal and Recycling: A Comprehensive Review

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**Abstract:** The considerable amount of waste PV modules expected to emerge from recent widespread of solar photovoltaic (PV) systems is a cause of concern, especially in sustainability terms. Currently, most end-of-life (EoL) PV modules are either disposed of in landfills or bulk recycled in existing recycling facilities. Although these approaches are easier in execution as less efforts are directed at sustainable management of these modules, they can potentially cause environmental issues including loss of valuable resources and leakage of toxic materials. Hence, high-value closed-loop recycling is much preferred for its environmental merits, although its implementation brings forward challenges that this paper attempts to shed light on. This review paper aims to provide an overview of the EoL management of PV modules, concentrating on the challenges faced in PV recycling. Additionally, PV waste-related regulatory frameworks implemented in different countries are discussed. Recommendations to improve the EoL management of PV modules and trade-offs arising from conflicting solutions are proposed. To establish a sustainable PV waste management framework, legislations promoting the extended producer responsibility (EPR) principle, presence of suitable infrastructure, research and development (R&D) and cooperation of various governmental and private bodies are highly needed.

**Keywords:** end-of-life (EoL) PV modules; PV waste management; PV recycling; PV waste challenges; high-value recycling; sustainability



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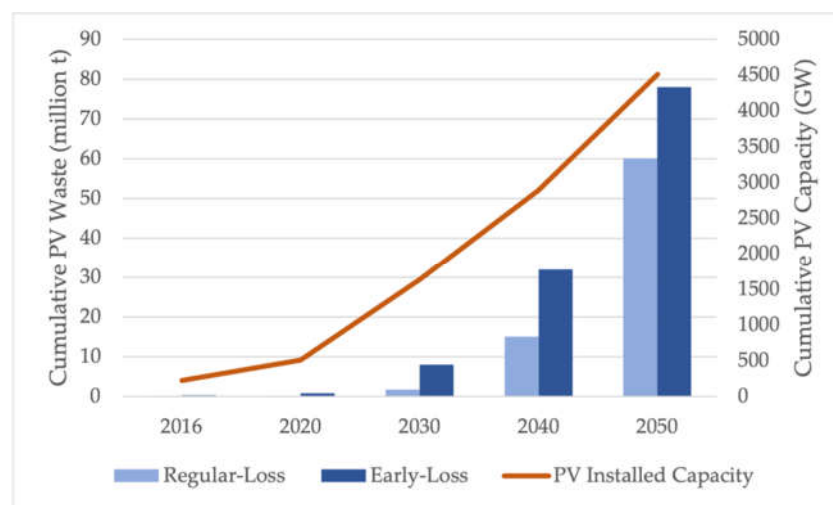
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## 1. Introduction

The uptake of solar photovoltaic (PV) systems globally has recently seen massive increase, especially with the rise in the construction of solar farms, PV installations and building-integrated photovoltaics (BIPV) [1]. According to a report by the International Energy Agency (IEA) [2], at least 175 GW had been installed around the world by 2021, totaling the worldwide cumulative installed PV capacity to 942 GW. The growth of installed PV capacity is expected to further amplify, as many countries are moving towards decarbonizing their energy systems [3]. However, the proliferation of PV installations has led to a concern over the rising amount of PV modules produced and their end-of-life (EoL) phase. PV modules are designed to last for 20 to 30 years, and since large-scale PV installations have occurred since around the 2000s in most developed countries, a remarkable amount of PV waste is expected to emerge after the year 2030 [4,5]. Furthermore, the International Renewable Energy Agency (IRENA) [4] has predicted that there will be 1.7 to 8 million t of PV waste in 2030 and 60 to 78 million t of PV waste in 2050 (Figure 1). The significant amount of PV waste that surges after 2030 is a result of the time lag between installations and the EoL stage of PV modules [6–8].



**Figure 1.** Estimated cumulative global waste volumes (million t) of EoL PV modules [4].

Unfortunately, the actual PV waste is expected to be greater than what is projected due to the actual cumulative installed PV capacity in 2020 (760.4 GW) being higher than the capacity used in the projection (511 GW) (Figure 1) [9]. Furthermore, some PV modules can enter the waste stream earlier due to other factors aside from spent lifetime, such as manufacturing defects [10], damages during transportation and installations, component degradation, damages caused by external environmental factors [11–13], or replacement of old PV modules by owners [8,14]. Therefore, the actual quantity of PV waste might be higher than projected and the waste may emerge earlier than expected.

Consequently, a sustainable EoL management option for handling the PV waste surfacing in next few years is imperative [15]. There are different methods available to manage the waste PV modules, such as through reduction, refurbishing, recycling, incineration and disposal [16,17]. Globally, waste PV modules are either incinerated or disposed of in landfill, similar to the management of most waste. However, these options promote environmental degradation and the loss of valuable materials. Hence, researchers are focusing on the more sustainable option of recycling, which is already available in the market, albeit in a smaller scale and only present in few countries [8,18]. The slow uptake for the sustainable management options of PV modules in many countries is due to the presence of numerous technological, financial and environmental challenges.

There are several recent papers that have explored the similar topic of PV module recycling and its challenges [1,8,11,15,18–22]. However, there are limited papers providing a broad and extensive compilation of the different types of challenges (technological, financial and environmental) that arose during the recycling of various types of PV modules. Most papers were focused on either one aspect of the challenges (especially technical or technological) or only on one type of PV module. Furthermore, to the authors' knowledge, there are also no similar papers that have organized and aggregated the solutions to remediate the emerging challenges.

Therefore, this paper aims to provide a review of the challenges and solutions pertaining to PV waste handling with the following discussions:

- (1) The available treatment methods for PV waste, with emphasis on recycling technologies as they are the most researched topics. The principles of high-value and closed-loop recycling are introduced and applied in the discussed technologies, since these principles represent best-practices in favor of environmental preservation;
- (2) Technological, financial and environmental challenges, which are commonly expected and brought up in parts of the literature;
- (3) Current policies and regulations complementing the establishment of a sustainable PV waste management industry worldwide, providing a reference for countries aiming

to establish similar legal instruments and infrastructure for EoL management of PV modules;

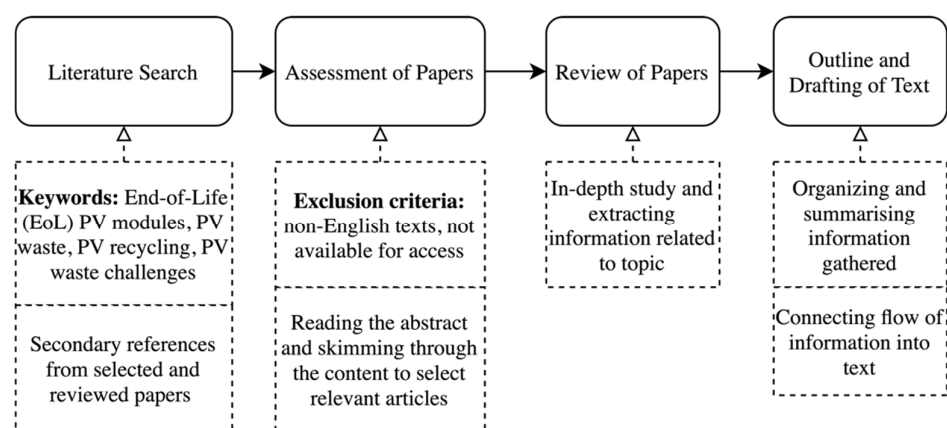
- (4) Discussions and recommendations to improve the EoL management of PV modules. The contradictions and trade-offs arise from conflicting solutions are discussed, offering critical aspects for policymakers or organizations to consider when selecting appropriate treatment types for EoL modules.

Hence, this review paper serves as a comprehensive guide to aid the discovery of issues and opportunities in PV waste recycling for interested researchers and support decision making for policymakers venturing into developing an EoL PV management industry.

## 2. Methodology

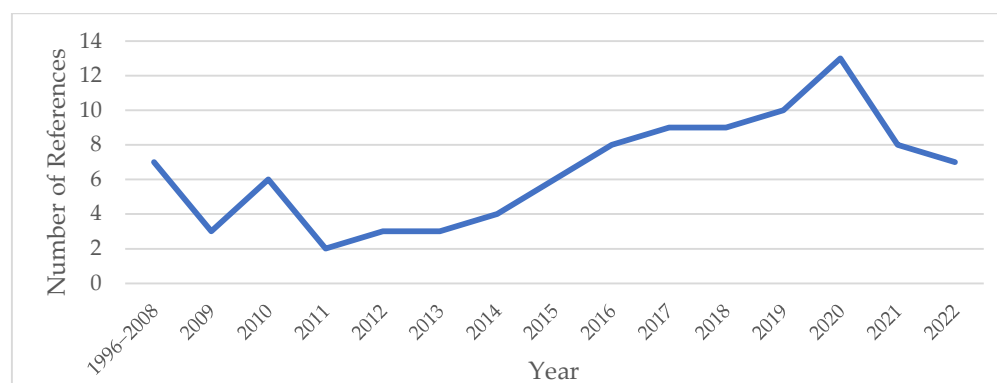
This paper is constructed as a form of narrative review of the topic of challenges and solutions associated with recycling PV waste modules. Therefore, the research questions developed are: (1) ‘What are the current recycling technologies for PV modules?’; (2) ‘What challenges have emerged from recycling PV modules that lead to its slow uptake?’; (3) ‘Are there examples of PV waste management and relevant policies being implemented worldwide?’; and (4) ‘What are the available solutions and other sustainable management options to remediate the challenges?’.

The methodology for writing this narrative review paper is shown in Figure 2. The studies gathered for writing this review paper are mainly acquired through scientific databases such as Scopus and Google Scholar. The search terms used to discover relevant papers include End-of-Life (EoL) PV modules, PV waste, PV recycling, and PV waste challenges. Besides this, there are also papers obtained through secondary references of a reviewed paper. The secondary references are studied as they provide deeper understanding of the topic and linkage to other related studies. Furthermore, papers, articles and reports from international agencies, recycling companies and collaborative projects are also examined to complement the information presented in this review paper. The papers that resulted from the search are assessed by checking whether they are in the English language and have full-access options. The relevancy of the papers is also determined by skimming through the abstract and content of each. Then, an in-depth study is conducted on the selected papers to extract related information for drafting the paper. The information gathered from these sources is organized, structured and summarized into various subsections, as presented in this paper.



**Figure 2.** Methodology used in this study.

The number of references used in this paper related to the topic of PV waste management is presented in Figure 3. It can be seen from the figure that the number of PV waste management-related references is on the rise, displaying the growing interest in researching approaches to handling the increasing PV waste.



**Figure 3.** Number of PV waste management-related references used in this paper.

### 3. Prospects of PV Materials Recycling and Disposal

#### 3.1. PV Modules

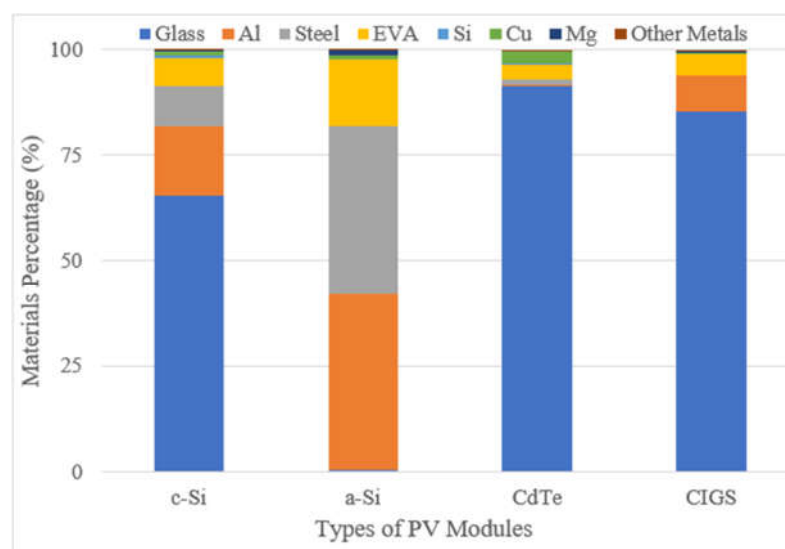
The components of a PV system can be divided into 2 main categories: PV modules and balance of system (BOS), the latter of which are the remaining components that support and complement the PV system [23,24]. To restrict the scope of the study, the discussion of recycling PV materials in this paper is focused on PV modules only, as BOS components are usually treated separately from the modules [25]. Generally, the modules are divided into three groups, which are the wafer-based silicon modules, thin-film modules and emerging technologies [23,26]. The wafer-based silicon technologies, also known as first generation technologies, include monocrystalline (mono-Si), multi- or polycrystalline (poly-Si) and ribbon silicon modules. The second generation thin-film modules include cadmium telluride (CdTe), copper indium gallium (di)selenide (CIGS) and amorphous silicon (a-Si) modules. Some examples of third generation emerging technologies are organic PV (OPV), dye-sensitised cells, copper zinc tin sulphide (CZTS), perovskite and concentrating PV technologies (CPV) [4,26].

In terms of market share, c-Si PV modules have always dominated with a percentage share of between 80% to 90% [1,27], with thin-film modules technologies following behind at around 7% to 10%. Meanwhile, the market share of emerging technologies is still minimal (~1%) [4]. Hence, this review focuses on discussing first and second generation technologies, as there is limited information on the recycling of emerging technologies [28,29].

The recycling of PV materials requires a thorough understanding of the composition of materials in the PV modules in order to better adopt a suitable recycling technology. Domínguez and Geyer [5,23] presented a detailed analysis of the metal inventory of four different types of PV modules (Figure 4). Although present in the figure, the composition and recycling of a-Si modules are not discussed in this paper, since this type of modules has low efficiency ratios and has been discontinued in recent years [4].

As can be seen from Figure 4, the majority of the composition of PV modules is made up of glass, as it is a low-cost material to be used as front glass or substrate. Aluminium, (Al) being the second largest component, is utilised as frames for PV modules. CdTe modules are generally frameless, thus Al is not present in a large quantity in this type of module. Ethylene vinyl-acetate (EVA) is a type of polymer usually used as encapsulant and back sheet in PV modules. Copper (Cu) is also prevalent in PV modules as it is used as interconnectors. Meanwhile, silicon (Si) and other semiconductor metals such as Cd, Te, indium (In), gallium (Ga) and selenium (Se) are present in small quantities in their respective PV modules [23]. However, these materials compositions vary as new technologies become available [4].

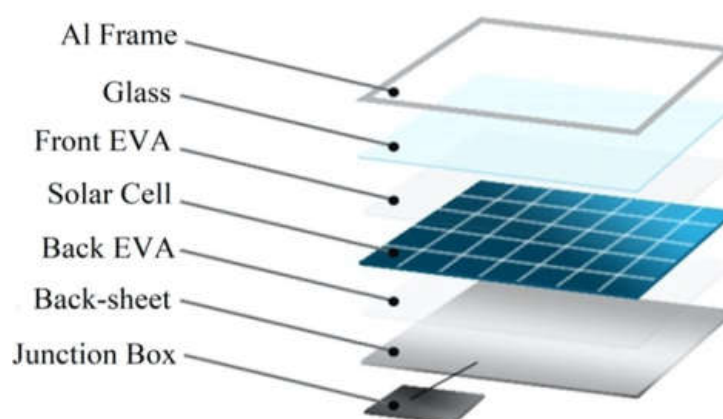
In the following subsections, the components of c-Si PV modules and CdTe as representative for thin-film modules are elaborated further, as these types of modules will constitute a larger percentage of market share and bulk of the PV waste modules in the near future [30].



**Figure 4.** Average material composition of four different types of PV modules. Adapted with permission from ref. [23] 2017 Domínguez and Geyer.

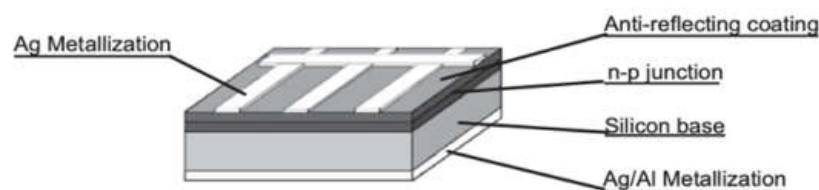
### 3.1.1. Crystalline Silicon (c-Si) Modules

Figure 5 shows the composition of crystalline silicon PV modules, which are made up of glass, EVA laminating layer, silicon solar cells, plastic back sheet (usually made from Tedlar), junction box and an aluminium frame [1,31]. The silicon solar cell is the key component in the module that converts solar radiation into electricity [27,32] and thus requires protection from mechanical damage and atmospheric elements, which is provided by the front glass, EVA and plastic back sheet [19].



**Figure 5.** Components of a c-Si PV module. Adapted with permission from ref. [33] 2022 Li et al.

The silicon solar cell is also coated with various layers such as n-p junction, anti-reflective coating (ARC) and metal electrodes (as shown in Figure 6) to ensure its optimum function and reduce its efficiency losses [34,35].

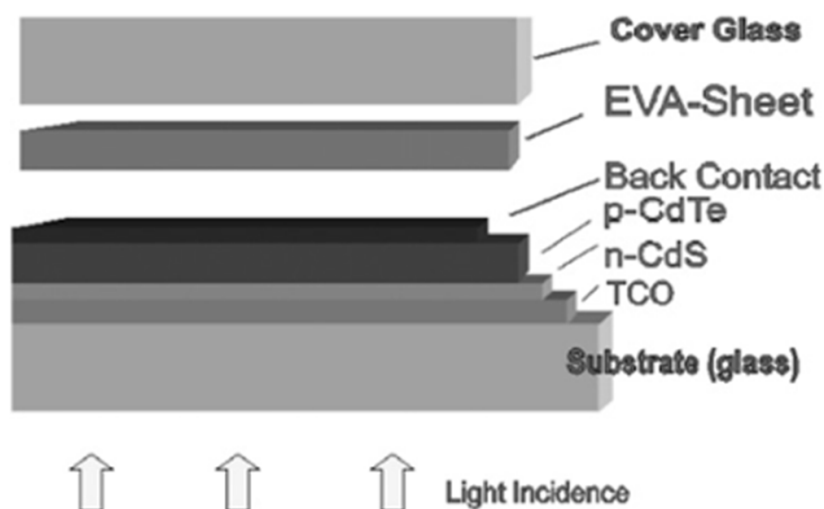


**Figure 6.** Layers of materials used on a silicon solar cell. Adapted with permission from ref. [35] 2010 Klugmann-Radziemska and Ostrowski.

Compared to the other life cycle stages, the manufacturing stage of c-Si PV modules generates the most significant environmental impacts [36,37]. In a life cycle analysis (LCA) study of a mono-Si PV system, the manufacturing of PV modules accounted for 81% of the life cycle energy use considering three phases of construction, operation and decommissioning [7]. There are also many publications that stated that the production of high-purity silicon feedstock is the most environmentally impactful process in a solar PV system [30,38–41]. This is due to the significant energy usage that occurs during the production process, requiring usage of fossil fuel sources and hence giving rise to GHG emissions [39,42]. Furthermore, this energy-intensive process causes c-Si PV modules to be relatively more expensive than thin-film modules [43].

### 3.1.2. CdTe and Other Thin-Film Modules

Thin-film modules such as CdTe and CIGS modules are produced via the low-cost process of depositing thin-films of photoactive materials on inexpensive substrates. Figure 7 shows the different material layers present in a CdTe PV module, which consists of the glass substrate, transparent conductive oxide (TCO) layer, cadmium sulphide (CdS) layer, CdTe layer, back contact layer, EVA and cover glass [44].



**Figure 7.** Components of a CdTe module. Adapted with permission from ref. [40] 2007 Rauegi et al.

Compared to c-Si modules, thin-film modules generate fewer environmental impacts and can be manufactured at lower production costs [45]. This is due to greater reduction of semiconductor material usage [24,30], lower energy used during manufacturing, elimination of aluminium frame and smaller amounts of consumables required compared to c-Si PV modules [39,46]. These studies have proven that, despite the lower efficiency presented by thin-film PV modules, they have much lower carbon footprint and better energy return performance than c-Si PV modules.

### 3.2. Disposal of PV Materials

Currently, the treatment methods of EoL PV modules include disposal, incineration and recycling. Repairing and refurbishing are also viable methods for treating EoL modules, but they are still in the earlier stages of research compared to recycling [8,47].

Globally, EoL PV materials are mostly disposed of in landfills or incinerated [1,21]. This is due to the limited waste stream of EoL PV modules currently present in most countries, which does not spark significant concern or financial justification to establish a sustainable PV materials recycling system in the country [48]. Depending on the country's policies, PV modules can be classified as either hazardous waste (HW) or non-hazardous waste (non-HW) [4,49].



Although the disposal of PV modules may be regulated, there are several negative environmental impacts that heavily discourage the landfill disposal of EoL PV modules. One of the main issues is the leaching of hazardous substances from the PV modules. The hazardous compounds present in the modules, such as Pb and Ag from c-Si PV modules and Cd and Se from thin-film modules, can induce both acute toxicity in humans and animals, as well as external environmental costs of air, water and soil pollution [21,50]. An LCA study has shown that the environmental impacts of disposing of poly-Si modules were always greater than recycling [37]. Similarly, another study has also discovered that the landfill disposal of silicon and wafer waste from the manufacturing of PV modules contributed up to 95% of the human toxicity potential (HTP) [51].

Secondly, landfill disposal of PV materials also leads to loss of potentially reusable resources such as glass, Al and other rare metals (Ag, In, Ga and Se). These resources are essentially wasted as they are not recoverable from landfills, and thus economic loss would be incurred [18,52]. An LCA study has shown that among the environmental impacts caused by landfilling c-Si PV modules, the greatest impact was present in the metal depletion category as valuable materials are lost [53]. The primary production of Cu, Ag, Al and Si are highly energy-intensive and environmentally burdensome, thus when these materials are lost, the same energy-intensive production has to be employed again to produce the same amount of materials [53].

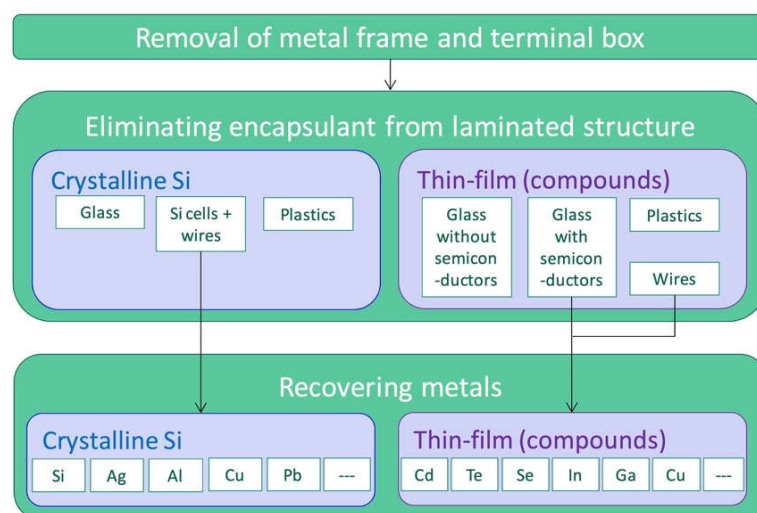
As evidenced from the negative environmental impacts, landfill disposal is not a preferred option to manage EoL PV modules. There are still potential consequences that need to be addressed even though PV modules have been disposed of responsibly.

### 3.3. Recycling of PV Materials

The recycling of PV materials can be differentiated into open-loop recycling and closed-loop recycling [1]. Open-loop recycling is where the materials are recovered in lower quality, while closed-loop recycling emphasises recovering secondary materials that are of equal quality to the original PV materials. In comparison, it is more preferable to carry out closed-loop recycling, as high-quality secondary materials can be directly fed into the supply chain to remanufacture into new PV modules [1,54]. Closed-loop recycling is also heavily associated with high-value recycling, where instead of only bulk components such as glass, Al and Cu are recycled (bulk recycling) and semiconductors and rare metals are recovered, with a focus on higher recovery rates as well [19]. The combination of these two is essential in shaping a circular economy within the PV industry, as almost every material within an EoL PV module can be reclaimed and reused, thereby minimising the depletion of resources [8,55]. As a consequence, there would be significant reduction of valuable materials being sent to landfill, and materials can be conserved for large-scale application of PV in the near future [45].

Unfortunately, the current situation in most countries is that only those high value materials present in sufficient concentrations to be economically extracted are recycled [43]. Therefore, the bulk recycling of PV modules is still the current industrial norm, whereby the modules are recycled within existing general recycling plants to reclaim the major components [4,11]. This approach is most common as it is relatively low-cost, but it is not sustainable in the long term when the environmental impacts of re-processing the raw materials are taken into consideration [1].

The recycling processes of c-Si modules and thin-film CdTe modules are different due to the differences in their module structure and metal composition. However, they are similar in terms of the necessities required to eliminate the encapsulant and to recover the materials contained within the modules (Figure 8). In both types of modules, the degree of glass–EVA separation heavily determines the value of the recovered glass [11], and the polymeric material needs to be completely removed in order for the glass to be used as cullets in soda-lime glass manufacturing of flat glass [56].



**Figure 8.** Separation process for recycling of PV modules [57].

### 3.3.1. Recycling of c-Si Modules

Currently, c-Si modules are mainly treated in bulk recycling plants designed for treating laminated glass, electronic waste and metals. In these facilities, a mechanical approach of crushing and sorting is employed to recover only bulk materials such as glass, Al frames and Cu [11,25]. Meanwhile, the remaining silicon cells and other materials including plastics are incinerated or disposed. According to IRENA [4], the cumulative recovery yields of these bulk materials can achieve more than 85% by panel mass just through mechanical separation. However, the treatment capacity of these facilities is low and the glass recovered is recycled as low-grade product [57]. Thus, in order to accomplish high-value recycling with greater recovery yields, further treatment of thermal, chemical or metallurgical methods are needed to recover the semiconductor materials [4].

The first step of recycling c-Si PV modules is to separate the major components, which are the Al frames, junction boxes, wiring and laminated glass [22,35]. This can be done through manual separation, thermal treatment or automatic separation [25,35,58]. Next, the EVA encapsulant layer sealing the silicon cells has to be removed through thermal, chemical or mechanical treatment. These studies have shown that thermal treatment of the EVA layer is more preferable compared to chemical treatment which requires usage of expensive and toxic reagents [35,59]. Besides, the effectiveness chemically treating the EVA layer is quite low, as the time duration needed to delaminate the glass is too long. Additionally, thermal treatment is usually able to recover glass and the silicon cells without breakage compared to most of the mechanical processes [19,57]. The heating condition or requirement of a pretreatment during thermal treatment is fairly important so as to avoid damaging the silicon cells, which can fetch a higher price in an unbroken state [50,60].

After removing the EVA layer, the next step is to recover the silicon wafer from the silicon cells. Conventionally, this process is carried out via chemical etching, which utilises acidic or basic solutions to sequentially remove the metal electrodes, ARC and n-p junction on the surface of the silicon cells [35,61]. However, there also exists laser treatment for removing the coating on the silicon cells, as demonstrated by this study [59]; however, the cost of employing this method is high and its effectiveness is low compared to chemical etching. In addition, a study [62] proposed a combination of chemical and mechanical treatment to remove the silicon cell coatings in an effort to reduce the use of hazardous chemicals such as hydrogen fluoride (HF), nitric acid (HNO<sub>3</sub>) and phosphoric acid (H<sub>3</sub>PO<sub>4</sub>).

The processes discussed above are general treatment methods for a complete recycling of c-Si PV modules. As summarised in Table 1, there are variations in the methods used depending on the studies and corporations.



**Table 1.** Recycling processes of c-Si and CdTe modules from different literature and corporations. The symbol ‘✓’ represents the presence of the type of treatment process.

PV Module	Recycling Processes							Yield of Materials	Suitable for Broken Modules	References
	Disassembly and Delamination				Recovery of Materials					
	Mechanical Treatment	Thermal Treatment	Chemical Treatment	Optical Treatment	Mechanical Treatment	Chemical Treatment	Laser Treatment			
c-Si		✓				✓		Silicon powder /sheets	Yes	[35]
c-Si		✓	✓			✓	✓	Pure silicon cells	Yes	[59]
c-Si		✓			✓	✓		Ag Al Silicon wafers	Not specified	[62]
c-Si		✓				✓		Al: 94% Glass Si: 80% Cu: 79% Ag: 90% Pb: 93%	Not specified but chemical etching is applicable to broken cells	[50]
c-Si, a-Si and CdTe	✓	✓						Glass: 80–85%	Not specified but broken modules can be treated together during crushing	[56]
c-Si (LGRF)	✓				✓			Glass: 92% Cu: 41% Al: 74%	Not specified but broken modules can be treated together during crushing	[25,53]
c-Si (FRELP)	✓	✓			✓	✓		Glass: 99% Cu: 69% Al: 99% Si: 95% Ag: 95%	Not specified	[53,58]
c-Si (Deutsche Solar AG)		✓				✓		Glass Al Cu Si Wafers	Yes	[63]
c-Si (YingLi Solar)	✓				✓			Glass Al EVA Si Ag Tedlar	Not specified but broken modules can be treated together during smashing	[8,64]

Table 1. Cont.

PV Module	Recycling Processes							Yield of Materials	Suitable for Broken Modules	References
	Disassembly and Delamination				Recovery of Materials					
	Mechanical Treatment	Thermal Treatment	Chemical Treatment	Optical Treatment	Mechanical Treatment	Chemical Treatment	Laser Treatment			
c-Si (Veolia)	✓				✓			Glass Al Plastic Si Metals	Not specified	[8,65]
c-Si (NPC Group)	✓	✓						Glass Al EVA Solar cells	Not specified	[8,66]
CdTe (Solar Cells Inc., currently First Solar)	✓	✓			✓	✓		Glass Te sludge: 80% Back metals: 93% Cd: 85%	Yes for chemical treatment but not suitable for water blasting	[67]
CdTe (First Solar)	✓					✓		Glass: 90% Cu Unrefined CdTe semiconductor: 95%	Yes	[25,68,69]
CdTe and CdS (ANTEC Solar)	✓	✓				✓		Glass CdCl <sub>2</sub> TeCl <sub>4</sub>	Not specified but broken modules can be treated together during milling	[8,44]
CdTe and CIS (RESOLVED)	✓	✓			✓	✓		Glass Cd Te In	Yes	[45]
CdTe and CIGS (Loser Chemie)				✓		✓		Al Glass with EVA layer Glass Metals	Yes	[57]

The recycling processes provided by Granata et al. [56], the laminated glass recycling facility (LGRF) [25,53], YingLi Solar [64] and NPC group [66] are considered to be bulk recycling as semiconductor materials and precious metals are not recovered. On the other hand, the studies by Jung et al. [50], Park et al. [62] and the industrial pilot-scale project (Full-Recovery End of Life Photovoltaics (FRELPP)) [58] are examples of high-value recycling where both bulk materials and semiconductor materials are reclaimed. The other treatment processes [35,59,65] are considered as semi-high-value recycling, as some of them recover only silicon wafer but no other precious metals. Meanwhile, the Deutsche Solar AG recycling process is closed-loop recycling which integrates reclaimed cells back into a standard PV module production line [34,63].

With the environmental impacts from the production of virgin silicon cells in mind, it is highly recommended to employ high-value and closed-loop recycling processes to recover silicon wafer, especially in an unbroken state [57,61]. This is because even if the cells have damage such as microcracks or edge chipping, they cannot be recycled into a whole wafer and have to be crushed into powder form to be used for silicon ingot production again [57,62]. Besides, high-value recycling processes have lower environmental impacts due to the displacement of primary production from the increased yields and greater profits from the higher quality of the materials recovered [53,70].

Although most of the recycling processes are carried out on intact c-Si PV modules, some processes, such as those from Klugmann-Radziemska and Ostrowski [35] as well as Deutsche Solar, are applicable for broken or damaged PV modules. After the removal of external major components and initial thermal delamination treatment, the modules are usually crushed for further treatment; thus, broken modules can still be recycled [67] but the broken wafers cannot be remade into new wafers.

### 3.3.2. Recycling of CdTe Thin-Film Modules

In a study by IEA [57], most patents on thin-film modules recycling indicated a focus on high-value recycling and the patent assignees for thin-film modules recycling were mostly corporations (95% of patents for thin-film modules recycling), suggesting that thin-film modules recycling patents are more likely to be commercialised [57]. Furthermore, in thin-film modules recycling, the recovery of semiconductor materials, despite being in very small quantities, is more important than the recovery of glass due to the scarcity of semiconductor materials [30]. Hence, CdTe thin-film modules are more commonly recycled in dedicated recycling plants instead of being bulk recycled in existing recycling plants [25].

Similar to c-Si PV modules, the first step of recycling CdTe thin-film modules is to remove the junction box. Next, the encapsulant sealing the semiconductors between the cover glass and glass substrate has to be removed, mainly through mechanical or thermal means. However, there is a study by Palitzsch (as cited by [57]) that used an optical approach to separate the glass layers in thin-film modules. Then, the semiconductor materials on the glass substrate are stripped off, usually by chemical etching; however, the mechanical method of stripping semiconductors off the glass is also being investigated [45,67]. The various recycling processes for CdTe thin-film modules are presented in Table 1.

These studies [67–69,71] presented the recycling processes of CdTe modules by First Solar, a commercial CdTe thin-film module manufacturer. These studies have displayed the evolution of First Solar recycling processes, although a high-value recycling principle has been applied since the first study. Through First Solar's recycling processes, approximately 90% of the weight of a CdTe module can be recovered, consisting mainly of glass which can be reused in new glass product [68].

ANTEC Solar has developed a patented process for recycling CdTe and CdS thin-film PV modules by treating the modules in a gaseous environment [44]; this proves is distinct from the other chemical etching processes where wet chemicals are used. Meanwhile, Berger et al. [45] have examined the feasibility of the wet-mechanical process in recovering metals from thin-film modules. The advantage of the wet-mechanical process is its lack

of chemical usage; however, there are considerable losses of valuables, resulting in low efficiency compared to conventional chemical etching [45].

For thin-film modules, as there are no materials requiring to be intact during recycling (as in Si cell), the mechanical approach to delaminating thin-films modules is not discouraged. Furthermore, crushing the modules into smaller particles enhances the performance of the subsequent chemical etching process [57], hence even broken modules can be treated in the same processes. Aside from that, most processes are not just applicable to CdTe and can be suitable for other thin-film modules as well. For instance, First Solar recycling process is applicable to CIS thin-film modules, albeit with the recovery chemistry for indium requiring further investigation [71].

### 3.3.3. Benefits of Recycling

Recycling EoL PV modules provides numerous benefits, especially to the environment. The environmental performance of recycling can be analysed via the approach of LCA, which has been carried out by many studies, as summarised in [22]. The main benefit of recycling PV modules is the reduction of the energy use and emissions associated with raw material production and the usage of secondary materials. In contrast to its zero emissions operational stage, the EoL recycling stage of PV modules consumes energy and release emissions due to the usage of fossil fuel in the recycling processes. However, a few studies have shown that the environmental impacts from recycling are very little compared to those of the production of the PV modules [25,36,69,70,72]. In addition, the recovery of materials from recycling to produce secondary resources offsets the energy use and emissions related to virgin material production, as shown by several LCA studies studies [16,25,41,53,63,69,73–75]. A recent LCA study has demonstrated that the environmental impacts of producing c-Si cells from recycled materials were 58% lower than production of cells from virgin materials. The results were mainly due to decreased energy consumption from processing raw silicon [61]. Furthermore, a study has shown that the supply of semiconductor materials, including In, Ga, Se and Te, will have their reserves depleted in 5 to 50 years at the current rate of extraction [76]. Therefore, there are greater motivations to recycle PV modules, including the recovery of the valuable materials contained within them to prevent the deficit of raw materials [20,29] and the reduction of the environmental impacts caused by the processing of raw materials.

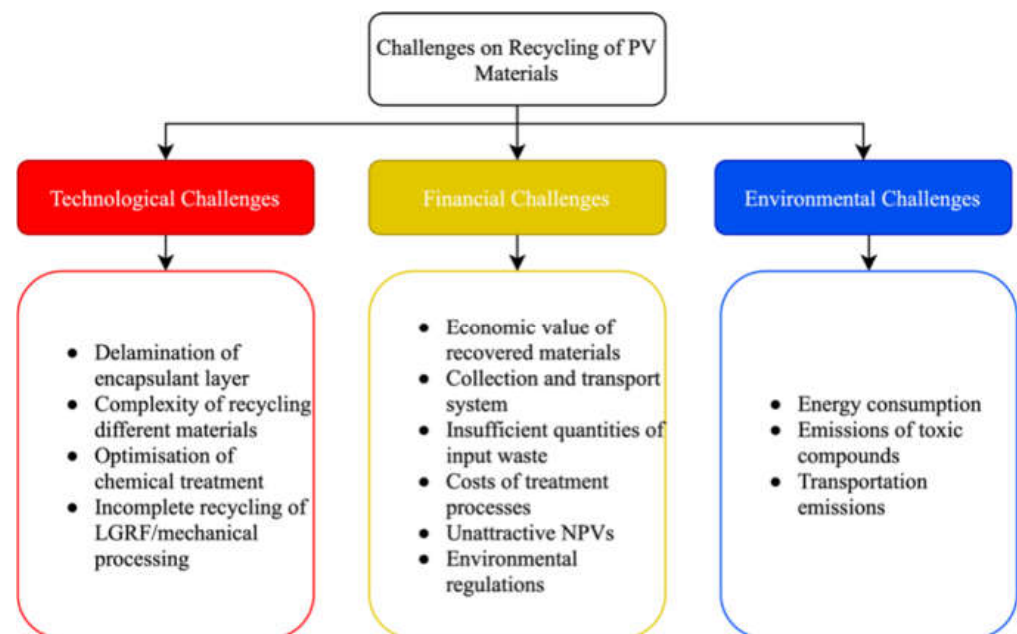
Compared to a landfill disposal scenario, the recycling of PV modules is able to reduce the amount of waste and waste-related emissions [4,77]. According to Vellini et al. [37], the recycling of poly-Si modules was able to reduce the terrestrial eco-toxicity potential (TETP) by 73.58%, fresh water aquatic eco-toxicity potential (FAETP) by 67.4% and acidification potential (AP) by 37.48% compared to EoL without recycling scenario. Furthermore, environmental credits are given when energy recovery is established during thermal treatment or incineration of PV modules, leading to significant reduction in terms of ozone layer depletion potential (OLDP) (27%), ionising radiation human health (25%) and freshwater eutrophication (18%), as evidence by this LCA study [58].

In addition to environmental benefits, recycling PV modules also brings about economical profitability. IRENA has estimated that the material value of material that can be recovered from recycling PV modules by 2030 and 2050 amounts to USD 450 million and 15 billion, respectively [4]. These impressive economic values are obtained from the secondary materials embodied within the EoL PV modules, which are locked away when PV modules are manufactured and cannot be accessed until the lifetime of a PV module is over [78]. Recycling PV modules recovers these materials, and reselling them into the global market helps stimulate a market for secondary raw materials [4]. Besides this, these secondary materials can help keep the costs of PV materials low due to their lower pricing [77]. Furthermore, the establishment of new PV EoL industries can yield new employment opportunities such as waste collectors, pre-treatment companies, producers and installation companies [4,23], hence providing economic growth to the country.

Additionally, setting up proper recycling infrastructure for PV modules further reinforces the ‘clean’ image of the solar PV system. Proper recycling can answer public concerns about the toxicity of hazardous materials present in PV modules by demonstrating that those materials can be recovered instead of being disposed in an unregulated way [71,79]. This can assist the large-scale penetration of PV in the market [72] due to the assurance offered by the proper management of EoL PV modules.

#### 4. Challenges of Recycling PV Materials

The studies on recycling PV materials have been going on for decades, but not all technologies are entirely commercialised or have achieved high levels of material recovery [57]. This is due to certain technological, financial and environmental challenges that influence the recycling rate of PV materials and are discussed in the following sections (Figure 9).



**Figure 9.** Technological, financial and environmental challenges to recycling PV materials.

##### 4.1. Technological Challenges

The delamination of encapsulant layers (mainly EVA) has always posed a significant technological challenge in the recycling of PV materials [4,20]. This is due to the protective function of EVA, which requires it to be extremely durable to protect PV cells from external elements and damage [1,80]. Hence, EVA poses considerable difficulties for recycling processes to fully eliminate the encapsulant from the glass [20]. There is a great deal of research focusing on using different approaches, often thermal or aggressive chemical treatments [1,57]. In addition, due to the duroplastic properties of the encapsulants (and also back sheet foils), these materials cannot be dissolved or melted without decomposition. Consequently, these materials are not recoverable for recycling and usually decompose into harmful emissions during treatment [4].

The next challenge is the complexity of recycling different types of materials present in a PV module. The sealed sandwich-like structure of a PV module complicates the recycling processes of PV modules [19,20], requiring multiple stages of treatment to remove each layer of materials. Materials such as Al, Cu and iron, which are present at the exterior of the PV modules, can be easily recovered through manual or automatic disassembling. However, the other metals contained within the PV modules, including Si, Ag, Cd, and Te, require additional and more advanced recovery processes [4,23,79]. Furthermore, due to the motivation to reduce the cost of PV technology, PV manufacturers choose to decrease the concentration of valuable materials in the PV modules, leading to an increase in the



number of “earth-abundant” materials used in the modules [43]. The authors observed a higher complexity of recycling these new types of modules due to the multi-element design approach. Additionally, the lower amount of valuable materials reduces the EoL values of these modules, leading to decreased likelihood of recycling [43]. These technological advances change the material composition of PV modules, thus affecting the types of recycling treatment required [5,29]. Besides, the various types of PV modules existing on the market have different dimensions, cell types and module structures, necessitating specific recycling processes to be tailored to allow for proper treatment. This issue further complicates the setting up of PV recycling infrastructure [6,11].

Similar to the previous challenge, chemical treatment reagents and processes vary depending on the composition and types of the PV modules. In terms of stripping off semiconductor materials, the challenge lies in choosing an etching solution with suitable composition and concentration, along with optimising temperature range for the chemical treatment [35]. As an example, the etching temperature and time have to be precise to avoid thinning the silicon cells too much, which can affect its mechanical strength when the cells are remanufactured as new cells [35]. After stripping off the metals, the recovery of metals from the etchant solution also requires optimisation to be fully effective [79]. For example, the recovery chemistry for CIS thin-film modules is different from CdTe modules and requires further experimentation for optimisation, even though the same chemical etching processes can be employed [71].

As mentioned, the most common method of recycling c-Si PV modules is bulk recycling [25,53], which yields only bulk components and lower quality products compared to the original components. For instance, silicon cells are crushed into particle sizes which are less valuable compared to silicon in wafer form. This also disregards the energy used to manufacture and refine the silicon wafer itself in the first place [1]. Although a major percentage by weight of the PV module can be recovered through mechanical processing alone, it is not a preferred method if a sustainable PV recycling industry with high-value, closed-loop recycling is to be established.

#### 4.2. Financial Challenges

Financial challenges constitute a large part of the overall challenges of recycling PV modules. The decision to recycle a material comes from the results of the trade-offs between costs and benefits [81], i.e., whether it would bring profits or losses. Unless there are mandated regulations and incentives from governmental organisations, financing most likely dictates the success of establishing a PV materials recycling facility.

Due to the current recycling processes not being fully developed, the materials recovered from recycling PV modules cannot always achieve 100% purity level or their maximum potential value [1,11]. Adding to the challenge is the volatility of market prices of these recovered materials, which heavily influences the resale value of the recovered materials and increases the uncertainty of the profitability [25]. Furthermore, the masses of valuable materials present in the PV modules also affect the overall economic profits. There are a few studies stating that the larger mass of glass in CdTe modules is what causes the unattractive economic recovery of thin-film modules, as glass recycling is not very profitable [25,79]. This, coupled with the lower concentration of valuable recoverable materials such as Cu, Cd, Te, In, and Se present in thin-film modules, makes recycling these modules even more economically unattractive. The recovered amounts of valuable materials may not be sufficient to finance the associated costs of collecting and recycling PV modules [79], and may deter recyclers from taking in EoL PV modules [21]. Contrastingly, the recycling of Al has positive economics [19]; however, the benefit is not shared by CdTe modules, as they are generally frameless [81]. Unfortunately, even though c-Si PV modules contain Al which can fetch higher market prices, these modules do not contain any other critical and valuable materials with high reclaim value [19,82]. Adding to the pessimistic financial situation, a study has shown that even if the economic values of recovered materials are increased considerably (by 20%), the overall economic result of a PV recycling plant could not become

profitable due to the impossibility of achieving critical mass of valuable materials in PV modules [83].

Another financial challenge posed by recycling PV materials is the collection and transport system for EoL PV modules. The collection stage of EoL PV modules presents a huge issue, especially when PV installations are highly dispersed across a large geographic area and situated far away from the storage or recycling centre [84]. The costs of collecting and transporting these PV modules are substantial, as massive coverage is needed [4,49]. Setting up suitable collection networks hence entails proper decision making concerning, for example, the parties involved in the reverse-logistics network and the location and capacity of the relevant facilities. Thus, there is also the added challenge of optimising the location of the collection and recycling centres in order to maximise the benefit of logistics while minimising its costs [6,14]. Moreover, coordination between the different PV waste management companies involved in the collection and transport system may also pose a challenge to PV recycling [5].

Due to the long lifetime of PV modules, a large amount of EoL PV modules can only be expected in the 2030s. As a result, only moderate quantities of PV waste exist on the market for most countries [4]. In order for a dedicated PV recycling facility to operate at the optimal level to warrant economic benefits [48], at least 8000 tons per year of waste flows are needed [53,58]. According to IRENA projections [4], only a few countries, such as Germany, China and Japan, have the potential of achieving the sufficient PV waste flows required to feasibly construct a dedicated PV recycling facility. Consequently, most countries face a challenge to achieve an optimal level of PV waste inputs, instead resorting to recycling PV waste in existing recycling plants for other materials because financial costs are a constraint [14,25].

Aside from that, one of the financial challenges arises from the cost of treatment processes used during the recycling of PV modules [11,85]. Deng et al. [19] and Cui et al. [86] have pinpointed the financial obstacle of increased process costs associated with the objective of attaining higher purity level of materials, which involves investment of more complicated treatment procedures. The revenue from selling the higher quality materials was not able to offset the increased processing costs. Moreover, tetrahydrofuran (THF), the chemical used to delaminate c-Si modules, incurs significant cost, especially taking into account its required quantity and disposal costs [59]. The etching solution used during recycling PV modules also contains great quantities of toxic nitrogen oxides, fluorides and different silicon species, requiring proper disposal measures that lead to higher treatment costs [35,62].

The financial challenges above, either individually or combined, could subsequently lead to the unattractive economic situation faced by the PV recycling industry. The financial methodologies that are usually used to assess the profitability of investments are the Net Present Value (NPV) and Discounted Payback Period (DPBP). The profitability is ensured when the NPV is positive and the DPBP is as short as possible [87]. Unfortunately, a few financial analyses carried out on a PV recycling plant showed non-profitability [83,88], with negative NPVs and DPBP of more than the assumed duration of the plant's useful life. Both studies showed that the cash outflow was dominated by process costs, followed by collection costs which increase as a plant's capacity increases due to greater unitary collection cost [83,88]. Another financial analysis investigating the profitability of LGRF and FRELP treating 8000 tons/yr of c-Si PV waste also resulted in negative NPVs [53]. The only profitable scenarios analysed in the study utilised LGRF processing at 16,000 tons/yr and raised the values of recovered metals by 20%, which could result in positive NPVs for FRELP [53]. Therefore, the profitability of a PV recycling plant greatly depends on several factors: the economic value of recovered materials, collection and transport system, costs of treatment processes and quantities of input PV waste.

Besides, environmental regulations also play a role in posing financial challenges in which lack of mandated regulations to recycle PV modules results in lower recycling rates [23]. Moreover, if the PV modules are characterised as HW under regulations, the

special requirements for the handling, recording and reporting of the hazardous PV modules also elevate the costs of collection and transport system [79], affecting the economics of recycling.

#### 4.3. Environmental Challenges

Compared to landfill disposal of PV modules, recycling can potentially incur greater environmental impacts due to the energy consumed during treatment processes [63,72]. Vellini et al. [37] demonstrated that the recycling of CdTe modules could lead to a slight increase of a few environmental impact indicators including GWP (4.71%), abiotic depletion fossil potential (4.19%) and OLDP (3.42%). The increase of these indicators was mainly attributed to increased fossil source use in providing energy to the recycling processes. Furthermore, another LCA study has shown that the innovative recycling process of CIGS modules-encompassing metal recovery treatment incurred greater environmental impact in terms of AP compared to both conventional recycling of CIGS and landfilling [73]. This is mainly due to the higher requirement for energy and raw materials during the metal recovery step in high-value recycling compared to bulk recycling [73]. Among the different types of treatments, thermal treatment or pyrolysis has a greater energy requirement compared to chemical and mechanical treatment due to the attainment of higher temperatures to successfully delaminate the EVA encapsulant [55,57].

The emissions of toxic compounds mainly come from the chemical treatment and thermal delamination of EVA. During chemical treatment, the etching solutions often contain hazardous compounds such as nitric acid which can potentially lead to the generation of toxic fumes. These fumes can bring about environmental issues including acid rain, as well as harmful effects to human health if the fumes are not properly treated [18,62]. Stolz et al. [25] found out that the human toxicity cancer effects caused by usage of hydrogen peroxide during the recycling of CdTe PV modules were not outweighed by the avoided environmental burdens of recovered materials. As a result, these chemical wastes require proper collection and disposal procedures to prevent further environmental degradation and human health risks [18,57]. Next, the thermal treatment of delamination, despite offering the benefit of no chemical usage, does emit hazardous gaseous compounds which require proper treatment [18,89]. The emission of gas is caused by the thermal degradation of EVA polymer, which releases compounds such as acetic acid, propene, ethane and hexene-1 [62,90,91]. Besides this, the polymer back sheet of c-Si PV module, Tedlar, releases fluorine-containing compounds such as HF during thermal decomposition [11,20].

Transportation emissions are also another source of environmental impacts occurring during the recycling of PV modules. According to Latunussa et al. [58], transporting PV waste to the recycling site constitutes a huge proportion of several environmental impact categories, including abiotic depletion potential (ADP), cumulative energy demand and OLDP. Similarly, Stolz et al. [25], Celik et al. [72] and Mahmoudi et al. [74] also discovered that transport of PV modules for recycling contributed significantly to the environmental impacts of recycling PV modules. Meanwhile, Farrell et al. [1] discouraged the practice of downcycling the components of PV modules into lower quality recycles, as this requires the additional transportation of these components into other facilities for further processing. This is also opposed to a circular economy where recovered components can be directly integrated back into production line, reducing transportation needs to various facilities [1].

### 5. Current Policies of PV Materials Disposal and Recycling

This section discusses the current management approaches to handling EoL PV modules and examples of related regulations being implemented in different countries.

#### 5.1. Waste Management Approaches to End-of-Life PV Modules

There are different types of EoL PV waste management approaches which are shown in Table 2. In the following subsections, the examples from public-private and regulatory approaches are further discussed.

**Table 2.** Different types of waste management approaches to handle EoL PV modules [4,15].

Waste Management Approaches		Examples
Voluntary	<ul style="list-style-type: none"> <li>• Rely on voluntary actions by producers to hold responsibility for EoL of PV modules</li> <li>• Usually established through internal environmental management systems</li> <li>• Can be directly managed by manufacturers through providing their own recycling operations, or indirectly managed through third parties (contracted service providers, other producers, or government entities) to collect and recycle waste PV modules</li> </ul>	<ul style="list-style-type: none"> <li>• ISO 14000</li> <li>• Individual voluntary take back programmes</li> <li>• First Solar Collection and Recycling Programme</li> </ul>
Public-private	<ul style="list-style-type: none"> <li>• A public-private partnership between PV industries and regulators</li> <li>• Leading PV manufacturers establish an association which finances the collection and recycling of PV modules</li> <li>• Increased coverage area of PV collection and recycling system</li> </ul>	PV CYCLE
Regulatory	<ul style="list-style-type: none"> <li>• Specific regulations and policies are developed to handle the EoL PV modules</li> <li>• Mandates the collection and recycling of PV modules by PV producers</li> </ul>	European Union WEEE Directive

#### 5.1.1. PV CYCLE

PV CYCLE is a non-profit organization founded by PV manufacturers in July 2007 as an effort to address the increasing volume of waste of PV modules. It is a member-based organization where the members are obligated to finance the collection and recycling of PV modules through annual financing and a variable fee, which is based on the market share of PV modules placed by each of the manufacturers in the previous year [29,92].

The main purpose of PV CYCLE is to implement an industry-wide take back and recycling system for EoL PV modules. It does this by mapping the EoL PV modules and ensuring the materials within the PV modules are properly managed through recycling and recovery. PV CYCLE itself is mainly responsible for the collection and transport of the modules, whilst the other operating steps of recycling and recovery are outsourced to third parties [29,92]. Due to its members mostly being PV manufacturers themselves, PV CYCLE is a convenient platform for them to realise the EPR principle by cooperating with each other in the EoL management of PV modules.

PV CYCLE has also collaborated with other partners in several R&D projects facilitating the technological progress in PV waste treatment services, including FRELP, PV-MOREDE, CU-PV, ReSolar, CABRISS and CIRCUSOL [93]. The FRELP, PV-MOREDE and CIRCUSOL projects have been mentioned in the previous sections. Cradle-to-cradle Sustainable PV modules (CU-PV) is a project aimed at incorporating the DfR principle by reducing the usage of Ag and Pb in c-Si PV modules [48,83]. ReSolar is a joint project made up of Belgium companies, waste officials and research institutes which aims to improve cooperation and communication between waste recyclers and materials processors [93]. Lastly, the purpose of CABRISS is to promote a circular economy within the PV industry; this would be similar to CIRCUSOL, but with a focus on reusing recycled waste materials recovered from PV modules, such as Si, In and Ag. The recovered materials can be reused in manufacturing new PV cells or provided as feedstock to other industries to develop industrial symbiosis [93,94]. Currently, only the CIRCUSOL project is still in progress, while the other projects have completed and closed [93].

### 5.1.2. EU WEEE Directive

After witnessing the exponential growth of electric and electronic equipment (EEE), the European Union has developed WEEE Directives 2002/96/EC and 2002/95/EC to combat the emerging waste. It was not until 2012 that the original WEEE Directive 2002/96/EC was revised to Directive 2012/19/EU, to include PV modules in the lists of WEEE. As the directive is drafted based on the EPR principle, any PV producers intending to market their products in the EU member states are legally bound to the responsible EoL management of their PV modules [30,95].

The PV producers are expected to fulfil their reporting and information responsibilities in addition to the financial obligations of setting up the collection and recycling of their EoL modules. Besides, producers are required to provide comprehensive information to both buyers and waste treatment companies on the correct EoL management procedures of their PV modules to avoid improper disposal of PV modules, its associated risks of hazardous material leakage and occupational risks [4,95].

Additionally, the WEEE Directive also establishes annual collection and recovery targets for e-waste including PV modules. Currently, the latest annual collection targets (from 2018 and onwards) are 65% (by mass) of all equipment placed on the market or 85% of waste generated. Meanwhile, the latest annual recycling and recovery targets are 85% recovery and 80% recycling [4,14].

The high target for recycling and recovery of e-waste, coupled with mandatory handling of collection and recycling operations by producers, can eventually push towards the implementation of high-value recycling. Therefore, as an approach to support this, the European Committee for Electrotechnical Standardization (CENELEC) has developed standards and technical specifications detailing the requirements for collection, logistics and treatment of WEEE, including PV modules, under the request of the European Commission. The standard EN50625-2-4 describes the specifications in terms of administrative, organisational and technical requirements in the handling of EoL PV waste [57,96].

Furthermore, the directive has also included the financing framework for collecting and recycling EoL PV modules depending on the types of transactions, whether it is a B2C or business-to-business (B2B) transaction. Overall, the WEEE Directive has given a certain amount of flexibility to each of the EU member states in determining the financial obligations, as well as incorporating more stringent requirements in the EoL management of PV modules [4].

### 5.2. Policies for Management of End-of-Life PV Modules in Different Countries

Different countries have their own waste management regulatory framework regarding the disposal of EoL PV modules, which are shown in Table 3.

**Table 3.** Regulations and policies for EoL management of PV modules in various countries.

Countries	Expected PV Panel Waste Volumes by 2050 (Million Tonnes)	PV Waste-Specific Regulations and/or Other Similar Policies and Programmes	References
Australia	0.9–0.95	<ul style="list-style-type: none"> <li>• No PV waste-specific regulations</li> <li>• Victorian Government has banned e-waste from landfill since 2014</li> <li>• Solar PV components are listed under Minister's Priority List 2021–2022</li> <li>• A PV industry-led product stewardship arrangement is in development which will be finalized by June 2022</li> </ul>	[4,15,97,98]



Table 3. Cont.

Countries	Expected PV Panel Waste Volumes by 2050 (Million Tonnes)	PV Waste-Specific Regulations and/or Other Similar Policies and Programmes	References
China	13.5–19.9	<ul style="list-style-type: none"> <li>No PV waste-specific regulations</li> <li>China's National High-tech R&amp;D Programme PV Recycling and Safety Disposal Research, which proposes suggestions for policy and technology R&amp;D</li> <li>China's 13th 5-Year Plan includes directions for EoL management of PV modules, focusing on developing large-scale, low-cost and low-energy recycling processes for c-Si PV modules</li> <li>Issuance of general technical requirements for recycling and reuse of c-Si PV modules in 2017 and thin-film modules in 2021 (expected) by China Photovoltaic Industry Association</li> </ul>	[4,57,84]
Germany	4.3–4.4	<ul style="list-style-type: none"> <li>Transposed EU WEEE Directive into German Law through a revision of the Electrical and Electronic Equipment Act (ElektroG)</li> <li>Regulated through National Register for Waste Electrical Equipment (Stiftung EAR)</li> </ul>	[4,99]
India	4.4–7.5	<ul style="list-style-type: none"> <li>No PV waste-specific regulations</li> <li>Waste PV panels are covered by general waste regulations and managed under the 2016 Solid Waste Management Rules and the Hazardous and Other Waste (Management and Transboundary Movement) Rules</li> </ul>	[4,100]
Italy	2.1–8.2	<ul style="list-style-type: none"> <li>Legislative Decree No.49 implementing the EU WEEE Directive</li> <li>Italian National Institute for Environmental Protection and Research (ISPRA) is responsible for monitoring the achievement relating to the Decree</li> <li>Guarantor of Electric Services (GSE) is responsible for managing all PV modules installed after the entry date of Legislative Decree 49/2014</li> </ul>	[4,29,30]
Japan	6.5–7.6	<ul style="list-style-type: none"> <li>No PV waste-specific regulations</li> <li>PV waste is treated under the general waste management regulatory framework: the Waste Management and Public Cleansing Act</li> <li>Ministry of Economy, Trade and Industry (METI) and Ministry of Environment (MOE) has jointly produced a roadmap and guideline promoting proper EoL management of renewable energy equipment</li> <li>Ongoing technological R&amp;D programmes carried out by local companies and in cooperation with international companies</li> </ul>	[4,18,101,102]

Table 3. Cont.

Countries	Expected PV Panel Waste Volumes by 2050 (Million Tonnes)	PV Waste-Specific Regulations and/or Other Similar Policies and Programmes	References
Korea	1.5–2.3	<ul style="list-style-type: none"> <li>• No PV waste-specific regulations</li> <li>• New PV waste legislation incorporating EPR scheme is in development</li> <li>• Inclusion of PV waste as industrial waste in Article 4.2 of South Korea’s Enforcement Rule of Wastes Control Act (Act No. 14783)</li> <li>• R&amp;D project to demonstrate recycling technology and a non-R&amp;D project to establish a PV recycling centre</li> </ul>	[4,57,103–105]
Mexico	0.63–1.5	<ul style="list-style-type: none"> <li>• No PV waste-specific regulations</li> <li>• Legal instruments that could contribute to PV waste management</li> <li>• Political Constitution of the US of Mexico</li> <li>• The General Law for Ecological Balance and Environmental Protection (LGEEPA)</li> <li>• The General Law for Prevention and Comprehensive Management of Waste (LGPGIR)</li> </ul>	[4,23,41]
UK	1–1.2	<ul style="list-style-type: none"> <li>• Revised EU WEEE Directive was transposed into UK regulations</li> <li>• All PV producers must register under the producer compliance scheme and all installers must join a distributor take back scheme</li> <li>• First-level treatment of PV modules must take place within UK</li> </ul>	[4,106]
US	7.5–10	<ul style="list-style-type: none"> <li>• No PV waste-specific regulations</li> <li>• PV modules are disposed based on Resource Conservation and Recovery Act (RCRA)</li> <li>• Senate Bill 489 in California authorises the change of classification of EoL solar PV panels from HW to universal waste</li> <li>• Solar Incentives Job Bill 5939 in Washington state requires PV manufacturers to provide take back and recycling programme for PV modules</li> <li>• A National PV Recycling Program has been launched by US Solar Energy Industries Association (SEIA), which facilitates the PV recycling operations by aggregating services from recycling vendors and PV manufacturers</li> </ul>	[4,5,57,107,108]

As of now, most countries do not have PV waste-specific regulations that mandate the collection and recycling of EoL PV modules, except for EU member states and certain states in the US [108]. However, some countries such as Australia, China, Japan, Korea, and the US are proactively undergoing R&D programmes to develop cost-effective and sustainable PV waste recycling technologies, as well as establish suitable infrastructures to prepare for the emergence of large quantities of PV waste.

According to Latunussa et al. [58], there are several factors leading to the late inclusion of PV waste within waste management legislation, such as the long lifetime of PV modules, low amount of PV waste, concern that mandating EoL management of PV modules may act as obstacles for country-wide PV penetration, and lack of scientific evidence regarding the

benefits and impacts of PV waste treatment to policymakers. Lack of relevant regulations, environmental legislation and infrastructure relating to handling of PV waste can be of great concern because these countries may consider exportation of PV waste. Exporting PV waste could be a feasible option if the waste-generating and -receiving countries have achieved consensus through a shared treatment programme. On the other hand, if the system is not well coordinated, the negative impacts can be more detrimental compared to landfill, as the waste might be disposed of in the ocean or illegally discarded along the transportation route [1,14].

## 6. Discussions and Recommendations

### 6.1. Recycling of PV Modules

The different types of modules require different treatment for optimum results. Thermal treatment is encouraged for delaminating c-Si PV modules so that both silicon cells and glass can be recovered intact. On the other hand, the mechanical approach of CdTe and other thin-film modules is a preferred method for thin-film modules unless unbroken glass is to be recovered, in which case the thermal and mechanical scraping approach can be considered. Chemical etching is still the most common and effective method to remove coatings on silicon cells (for c-Si modules) and semiconductor materials from the substrate glass (for thin-film modules). Besides, the recycling processes can be tailored for different types of EoL PV modules, including intact modules, broken modules and manufacturing scraps as well as modules that do not fulfil the quality requirements [35,44]. Despite that, the design of the recycling process requires considerations of the advantages and disadvantages of the respective treatment, which can be found compiled by [15,78].

There is another thing to be noted concerning incineration being present in both the landfill disposal and recycling of PV modules. The difference is that incineration in recycling typically only applies to waste plastics and polymeric materials as these materials cannot be recovered for reuse. Thus, the recycling of PV modules is still the superior option as valuable materials can be recovered, and only those materials that are unrecoverable (in a considerable smaller proportion compared to entire module being landfilled) are incinerated.

To compare the environmental impacts and economic feasibility between recycling c-Si and thin-film modules, Table 4 has been drafted to summarise the findings.

As shown in Table 4, most studies compared the environmental impacts of recycling between c-Si modules and thin-film modules, but there are limited studies explicitly comparing the economic feasibility of recycling these two types of modules. In terms of environmental impacts of recycling alone, the studies showed inconclusive results regarding which type of modules generated greater impacts, mainly due to the different research methodologies and approaches in comparison. Vellini et al. [37] found that CdTe modules generated overall lower impacts compared to c-Si modules. However, there is no direct comparison of EoL impacts of recycling alone, aside from the EPBT calculation, where the EPBT was reduced significantly when recycling of c-Si modules was implemented. Comparing the impacts of recycling alone, Vellini et al. [37] and Celik et al. [72] indicated that the recycling of c-Si modules is more environmentally preferable than the recycling of thin-film modules. In contrast to this, Maani et al. [109] discovered that the recycling of c-Si modules generated higher impacts than CdTe modules, especially for chemical treatment, due to usage of greater amounts of chemicals. Economics-wise, the study by McDonald and Pearce has shown that the recycling of CIGS modules is the only scenario where there was profitability. There are also many studies affirming the infeasibility of c-Si recycling [83,88] and CdTe modules recycling [110,111] unless higher input PV waste is present [53,74]. Even though some modules might have less profitable or environmentally impactful recycling processes, they should still be treated in view of the overall environmental benefits attained from the sustainable management of EoL modules.

**Table 4.** Summary of findings related to comparison of environmental impacts and economic feasibility between recycling c-Si and thin-film modules.

Literature Works	Findings
Vellini et al. [37]	<ul style="list-style-type: none"> <li>• LCA impacts of recycling CdTe modules were lower than c-Si modules in terms of gaseous emissions and resource depletion</li> <li>• CdTe modules generated higher LCA impacts in human, aquatic and terrestrial toxicity compared to c-Si modules</li> <li>• Recycling was able to reduce the energy payback time (EPBT) of c-Si modules from 2.6 years to 1.6 years, and increase EPBT of CdTe modules from 1.3 years to 1.34 years</li> </ul>
Celik et al. [72]	<ul style="list-style-type: none"> <li>• Costs and environmental impacts of EoL transportation were lower for c-Si modules compared to CdTe and CIGS modules</li> <li>• CIGS modules generated the highest carbon emissions in the EoL phase, followed by CdTe modules and c-Si modules</li> <li>• EoL carbon emissions of CdTe and CIGS modules made up 13% and 21% of the entire life cycle emissions respectively, compared to 5.6% of life cycle emissions made up by EoL emissions of c-Si modules</li> </ul>
Maani et al. [109]	<ul style="list-style-type: none"> <li>• Bulk recycling of c-Si modules and CdTe modules produced greater impacts than extraction of virgin materials (recovery of metals were not included in the scope of comparison with virgin material extraction)</li> <li>• Recovery of Ag from c-Si PV modules had the highest cost reduction and environmental impact relief in relation to obtaining virgin Ag, compared to Cu, Te, and tin (Sn) from CdTe modules</li> <li>• CdTe modules generated lesser impacts than c-Si modules in chemical delamination and material recovery</li> </ul>
McDonald and Pearce [110]	<ul style="list-style-type: none"> <li>• Recycling of CIGS modules was the only scenario incurring profits, while the recycling of other types of modules such as CdTe and c-Si modules incurred losses</li> </ul>

As c-Si modules have been the dominant PV technology since the 2000s [5,57], the focus on recycling in the current term should be concentrated on its waste streams which are expected to be generated in near future [6,84]. Since the high-value recycling processes for c-Si modules are not yet commercialised and still of laboratory scale, the direction of R&D should be reoriented to increase the cost-effectiveness of these recycling processes for industrial-scale application. The establishment of dedicated high-value recycling plants for c-Si modules is imperative, as bulk recycling is still widely employed worldwide.

In addition, the recycling of thin-film module manufacturing scraps and EoL thin-film modules should be considered, as they are the second largest PV market share and are projected to increase in the future [6,18]. However, as there exists dedicated recycling plants for thin-film modules such as CdTe treatment plant by First Solar, the commercialisation of recycling processes for this type of modules should have no significant issue [110].

## 6.2. Potential Solutions and Future Research

The challenges elaborated in Section 4 may hinder the development of PV recycling industries to a certain degree. However, there are potential solutions and ongoing research that can remediate the above challenges to make PV recycling more favourable in terms of technology, finance, and environment.

### 6.2.1. Technological Challenges

The technological challenges in recycling PV materials presented can be usually remediated via technological breakthroughs in the research and development sector, which are shown in Table 5.

**Table 5.** Potential solutions to remediate the technological challenges in recycling of PV modules.

Challenges	Solutions
Delamination of encapsulant layer	R&D to effectively delaminate EVA layer including methods of organic solvent, pyrolysis, and ultrasonic radiation Substitution of EVA layer with thermoplastics Elimination of encapsulant use **
Complexity of recycling different materials	New PV modules designed for recycling ** Development of combined recycling process to recycle mixed PV waste or integrated facility with several recycling technologies for different modules ** Extensive R&D to effectively separate different materials
Optimisation of chemical treatment	Extensive R&D to investigate optimised chemical treatment processes
Incomplete recycling of LGRF/mechanical processing	Incorporation of comprehensive recycling processes including thermal and chemical treatments **

\*\* Possibly lead to contradictions and require trade-off.

Established research has already been carried out to delaminate the EVA layer from PV modules, including through thermal treatment, mechanical crushing, vacuum blasting and optical treatment, as shown in Table 1. However, further research and development (R&D) can be beneficial in reducing both the costs and difficulty in removing the encapsulant layer. For example, Farrell et al. [1] recommended that further research ought to focus on pyrolysis as this does not promote chemical oxidation to the other components of the PV module, which is what happens with the burning or combustion thermal method. Lesser amounts of carbon dioxide would be emitted, whilst the heat recovered during pyrolysis can be used to further delaminate other modules, contributing to the sustainability of recycling PV modules [1]. Another option is to substitute the EVA layer with thermoplastic material, offering advantages such as faster manufacturing time, higher resistance to potential induced degradation, better utilisation of the UV spectrum and no emission of acetic acid [80]. Thermoplastics are capable of melting instead of decomposing like EVA at higher temperature, offering easier separation and reclamation during recycling. Consequently, thermoplastic encapsulant can reduce the breakage of cells during the recycling process, as proven in the project by CU-PV [48,112]. Elimination of encapsulant use in PV modules altogether is also another possible approach to solving the technological challenge posed by the encapsulant itself. One of the examples is the New Industrial Cell Encapsulation (NICE) technology developed by Apollon Solar, which replaces EVA with neutral gas filling such as nitrogen or argon. NICE technology has the potential to reduce the direct production cost of a module by 50% due to the avoidance of soldering and lamination processes [8,113]. Additionally, this technology has been demonstrated to allow easier recovery of silicon wafers and glass from a simulated EoL PV module according to Einhaus et al., as cited in [20]. The elimination of encapsulant may provide the added benefit of skipping thermal treatment to decompose the EVA, and mechanical treatment only is sufficient to separate the components in the PV modules.

The presence of a variety of different materials can complicate the process of recycling the PV modules. To remediate this issue, the concept of design for recycling (DfR) should



be implemented especially for new modules. A recycling-friendly design enables easy dismantling or separation of the various components in the modules, leading to improvement in the recovery rate and purity of the recycled materials [20,114]. The selection of materials to be used in the recycling-friendly design is thus essential in determining the recyclability of the product. For instance, hazardous materials such as fluorinated back sheets should be designed out or designed to be recovered easily to reduce the associated handling costs and environmental impacts [19,20]. However, for the EoL PV modules with a current design, which are expected to emerge in large quantities in near future, extensive R&D is needed to further improve the current recycling processes with new innovative methods. The same R&D is also required to remediate the challenge of optimising chemical treatment during the recycling process, as suitable chemical composition and conditions can only be discovered via continuous experimentation. If different types of PV modules are to be recycled at the same site, one option is to utilise a combined recycling process that can recycle mixed PV waste such as the one carried out by Granata et al. [56]. Another alternative is to construct an integrated PV modules recycling facility that is able to run various recycling processes for each type of module present, but the downside is that a significantly higher capital cost is needed [6].

The disadvantages of the incomplete recycling of LGRF or mechanical processing can be alleviated by the incorporation of further treatment processes such as thermal and chemical treatment. There are a few recycling technologies available that prioritise higher recovery rates of materials by integrating multi-step processes [44,50,62,69], thereby achieving environmental benefits in terms of reduced losses of potentially usable resources. Rocchetti and Beolchini [73] also supported the utilisation of innovative recycling which involves a more comprehensive set of treatment processes that focus on high-value recovery. The study demonstrated that the innovative recycling of CdTe modules had the best environmental performance compared to all scenarios, although the innovative recycling of CIGS modules only outperformed the scenario of disposal in landfill [73].

#### 6.2.2. Financial Challenges

The remediations for the financial challenges in the recycling of PV materials (Table 6) may involve large-scale infrastructure changes and at times external support to achieve the necessary economic profitability.

For the most part, the challenge caused by the market value and critical mass of valuable components in the PV modules are nearly unavoidable and cannot be fully resolved. The components of c-Si and thin-film PV modules have been relatively unchanged for decades [20], and even if there are variations in design, there would not be a significant increase of valuable components to warrant profitable return. Therefore, the only possible changes that can be made are increasing both the recovery rate and purity level of the recovered materials. One of the solutions is to prioritise the recovery of Al frame which is of greater mass and market value than the other valuable components in PV module (especially for c-Si module) [57,75,86]. Furthermore, the dismantling process of the Al frame is generally less complex, leading to greater recovery rates. The report by IEA also highlighted the interest of major research patents in recovering components by module separation, such as Al frame, glass and solar cells, rather than recovering individual elements (Si, Ag, Cu) [57]. Therefore, this insight can be applied in which recycling technology can focus on recovering the components, rather than recovering them in elemental form. This also aids the reintegration of recovered materials back with minimum processing. Secondly, the proposed development of a pre-treatment stage by this study [73] which concentrates the valuable elements in thin-film modules before recovery takes place, is also a viable method in increasing the mass and recovery rate of materials, especially for CIGS modules. Thirdly, D'Adamo et al. [88] proposed the inclusion of thin-film modules into the input c-Si PV waste to increase the overall value of materials recovered due to the presence of higher value components in the thin-film modules. This is in contradiction with [25,79,81] where the authors are of the opinion that the valuable components in thin-film modules

are present in too little amount to result in economic profitability. Furthermore, adding thin-film modules into c-Si waste may complicate the recycling process due to mixture of different PV waste, unless a universal recycling technology is used. Lastly, further refining from the R&D side is required in developing more advanced technology that can reclaim the materials at higher quality or purity level [4,88].

**Table 6.** Potential solutions to remediate the financial challenges in recycling of PV modules.

Challenges	Solutions
Economic value of recovered materials	Prioritized recovery of Al frame Development of pre-treatment step to concentrate valuable elements Inclusion of thin-film modules among c-Si PV waste ** Extensive R&D to further refine the quality of recovered materials
Collection and transport system	Bring-in services for small-scale PV systems Pick-up services for large-scale PV systems Establishment of decentralised recycling plants ** PV industry collective operation to collect and transport waste modules
Insufficient quantities of input PV waste	Cooperation between countries with low PV waste flow through a shared treatment programme Recycling at existing general recycling plants or construction of flexible recycling plants accommodating compatible products ** Construction of decentralised low-capacity recycling plant **
Costs of treatment processes	Treatment of PV modules in gaseous environment Usage of aluminium chloride to extract Al from silicon cell Extensive R&D to reduce consumption of chemicals and costs of recycling technology
Unattractive NPVs	Utilisation of economies of scale ** Recycling at existing general recycling plants or construction of flexible recycling plants accommodating compatible products ** Proper assessment of economic benefits obtained from secondary material recovery Financial support from authorities and governmental organisations
Environmental Regulations	Government mandate on recovery of valuable and hazardous materials Showcasing effective PV recycling programme to seek regulatory relief

\*\* Possibly lead to contradictions and require trade-off.

The collection and transport system of EoL PV modules poses a significant challenge in terms of planning and finances. One of the proposed solutions is to only provide pick-up services for larger-scale PV systems and bring-in services for much smaller PV systems. The definition of small-scale PV systems can vary depending on the reverse-logistics company, but the sizes applicable for bring-in systems cited in the literature range from 2 kW to 5 kW [4,85]. If bring-in services are not viable, the collection can be carried out by either periodic pick up or through cooperation with PV installers/dismantlers [4,79]. As the dismantling of PV systems may require skilled workers, these installers/dismantlers can assist in collecting the waste PV modules and delivering them to the recycling facilities when the overall quantities are large enough to warrant a trip. However, the proper re-

sponsibilities and finances needed require consensus between the dismantlers and the reverse-logistics companies. To optimise the collection and transport system for PV waste, Choi and Fthenakis [6] found that the total expenses are the lowest in the scenario having multiple decentralised small-scale recycling facilities compared to having just one centralised large capacity recycling facility. Establishing multiple decentralised facilities reduces the distance travelled by vehicles, and subsequently the GHG emissions are minimised as well. However, the authors highlighted the need to consider the marginal capital cost and expected processing capacity of each recycling facility, which may vary depending on future amount of PV waste [6,82]. Another option is through collective action by the PV industry. Cooperation between PV manufacturers in collecting EoL modules and eventually recycling them aids their financing as the costs are shared by the members [77,81].

The challenge of currently insufficient quantities of input PV waste can be remediated by three solutions. The first solution is to establish collaboration between countries that have low PV waste to jointly recycle their PV waste together via a shared treatment programme. This programme enables the proper EoL management of these PV modules, while the economic values obtained can be returned to the respective countries, albeit with an agreement needing to be achieved [14,102]. If transboundary transport of PV waste is not possible, there are two other alternatives for solving the issue within the country. The first alternative is to process the EoL modules in existing general recycling plants or at newly constructed flexible recycling plants that can treat multiple products with a compatible recycling process [53,83]. This solution is not perfect, as elaborated before, due to its capability of only recovering bulk materials. However, it is the more financially feasible option as no additional investment is needed, while the small amount of EoL modules are still treated instead of being disposed of [53]. This solution should be used for the short- or medium-term to support the recycling of the currently low quantities of input PV waste, but the construction of dedicated recycling plant should be considered when PV waste flow increases in the future. The second solution is the same as in the previous challenge; decentralised low-capacity recycling plants can be constructed [6]. These low-capacity plants are better suited when the input PV waste is still low, and additional plants can be built when the waste flow increases. Despite that, this solution is the costlier one of the two as capital investment is needed to construct the new plants.

One potential solution to reduce the costs of treatment processes, especially at the etching stage, is to chemically treat the modules in a gaseous environment. The recycling process described by Campo et al. [44] utilised gases such as chlorine and nitrogen to etch away Cd and Te from CdTe thin-film modules. The recycling process is mentioned as being more economical compared to other etching processes, including wet-chemical, pyrometallurgical and hydrometallurgical processes. Although there is no evidence on the achievable costs savings, further research can be carried out on the gaseous method to determine its estimated costs. Another means of reducing the financial burden of chemical treatment is to utilise aluminium chloride to extract Al from silicon solar cells, as mentioned by Palitzsch and Loser [115]. The Al removal process yields poly-aluminium-hydroxide-chloride, a valuable chemical that can be employed in wastewater treatment processes. Hence, aside from achieving its original purpose of removing Al, the usage of aluminium chloride also provides economic relief from the sale of the wastewater chemical [115]. Similarly, extensive R&D is also needed to reduce the consumption of chemicals or replace them with more environmentally friendly alternatives [63], as well as to optimize the costs of recycling technology.

Aside from the solutions discussed previously, there are also general solutions that can assist in the overall economic feasibility of the PV recycling industry. The main solution that is often proposed is to utilise the benefits of economies of scale to obtain financial advantage [57,88]. Constructing a larger capacity centralised recycling plant is one of the options, which is shown by Cucchiella et al. [83] where the loss per unit of PV waste treated dropped from 4.2£/kg to 1.9£/kg when the plant capacity increased from 185 tons to 1480 tons. The results showed an economic improvement in the order of 50%. Furthermore,

a larger plant enables the implementation of automated systems, more efficient thermal and innovative chemical treatments [82,83]. These can all lead to better sales price realised by greater quality of materials recovered from the recycling of PV modules. In order for economies of scale to be utilised, the PV waste flows have to be sufficiently large to saturate the plant capacity, which is the dilemma currently faced by most countries where PV waste volumes are low. Therefore, bulk recycling is an alternative due to lower investment costs needed upfront, but at the expense of quality and value of materials recovered. Thus, this necessitates a proper assessment of economic benefits from recovered materials to determine the economic feasibility of PV waste recycling [5]. As choosing different types of recycling processes would yield different qualities of materials, an economic assessment such as presented by Tao et al. [11], is needed to quantify the benefits that can be achieved from the recoverable materials. This is useful in preventing a project from becoming financially unattractive while the values obtained from materials can be great incentives for investors. Moreover, the fiscal aspect of recycling EoL PV modules is expected to become favourable when the R&D on recycling technologies become more mature, while the landfill disposal costs are expected to rise due to land scarcity [79]. Lastly, the financial situation of the PV waste recycling industry can be supported by authorities and governmental funds [11,116]. Enactment of suitable regulations, R&D support programme and financial incentives for the investors are examples that can be implemented to increase the economic profitability of the industry [14,84].

The impact of environmental regulations on the recycling of PV modules can be beneficial when there is a mandate by governmental organisations on the recovery of certain materials. With a legislation in place, PV manufacturers or waste management companies are bound to their responsibilities to recycle the PV modules to avoid environmental pollution. If handling PV modules becomes expensive due to their classification as HW, the PV recycling industry can set up an effective recycling system to seek regulatory relief. According to Eberspacher et al. [81], the case of the lead–acid battery in the US has shown the possibility of exclusion from HW management rules by authorities when there is a highly effective recycling system in place. Thereafter, the authorities can change the classification of EoL PV modules from HW into universal waste, easing the key requirements from HW management requirements and thus improving the economics of handling the PV modules [81,107].

Although the financial challenges and proposed solutions may seem to be too complicated and could demotivate the setting up of PV recycling infrastructure, there are several examples of successful financing schemes established around the world that can be used as references. One of the examples is First Solar's pre-funded collection and recycling programme, which started in 2005 [17,68]. The programme is based on the Extended Producer Responsibility (EPR) principle, whereby First Solar as the manufacturer has itself taken up the responsibility to collect and recycle its own produced modules. The financing is pre-funded and protected by a trust structure from the insolvency of the company, thus ensuring that the costs needed for the programme are always available [68]. Another example is Germany's financing schemes under the European Union (EU) Waste Electrical and Electronic Equipment (WEEE) Directive. In Germany, for business-to-consumer (B2C) operations, producers are mandated to establish and cover the financing of a collection and recycling system for EoL PV modules, depending on their share of the PV modules placed on the market. Besides this, producers are also required to pay an annual premium for last-man-standing insurance which would cover the costs of collection and recycling if all PV market players were to disappear from the market [4].

As can be seen from the examples from both private companies and countries, a successful and organised PV collection and recycling system usually necessitates the employment of the EPR principle. This principle binds the EoL management responsibility to the producers or manufacturers, which is a justified option as this party usually has access to the relevant technology, PV waste (manufacturing scraps), finance and reverse logistics required for the recycling of EoL PV modules.

### 6.2.3. Environmental Challenges

The environmental challenges in the recycling of PV modules should be mitigated or at least reduced as much as feasible to prevent environmental degradation and the associated human health risks. The solutions proposed are as shown in Table 7.

**Table 7.** Potential solutions to remediate the environmental challenges of recycling PV modules.

Challenges	Solutions
Energy consumption	Increase in renewable energy mix in energy consumption Large-scale thermal treatment to increase the efficiency and economy ** Heat recovery from thermal treatment
Emission of toxic compounds	Replace toxic chemicals with more environmentally friendly alternatives Effective delamination, substitution or elimination of EVA encapsulant ** Elimination or reduction in usage of fluorinated polymers Treatment of gaseous emissions from recycling
Transportation emissions	Establishment of decentralised recycling plants ** PV industry collective operation to collect and transport waste modules Development of on-site pre-treatment recycling facilities

\*\* Possibly lead to contradictions and require trade-off.

Although energy consumption in recycling EoL PV modules is a necessity and justifiable by the value of recovered materials [63], efforts can still be made to lessen the associated environmental impacts. As discussed earlier, the problem with energy consumption lies with the usage of fossil fuels, which generate GHG emissions. Hence, one of the options is to increase the share of renewable energy in the energy mix to reduce the emissions from fossil-fuel-based energy. Fthenakis et al. [39] have briefly described the PV Breeder scheme, in which energy generated by solar PV is to be used back in PV production with the purpose of decreasing the life cycle emissions of PV modules. According to the evaluation, if 30% of the electricity required for PV production is supplied by onsite or nearby PV installations, approximately 12.5 to 15.8% of PV module GHG emissions can be curbed [39]. Taking note of the results, the issue of energy consumption in PV recycling may be mitigated if renewable energy produces a larger portion of the energy required by the recycling process [55]. Similarly, countries which have a higher renewable energy percentage in the national energy mix gain merit from reduced overall life cycle GHG emissions [34]. Ultimately, the employment of renewable energy such as solar PV in energy generation can lead to a positive cascade in which the downstream processes, including manufacturing, operation and EoL, benefit from lesser environmental impacts. Next, the greater energy consumption drawback from thermal treatment can be remediated by increasing its scale of treatment. Utilizing economies of scale in the thermal treatment process, aside from increasing its cost effectiveness, also raises its efficiency, leading to lower energy consumption per unit of PV module treated [57]. Moreover, the efficiency can be further enhanced by incorporating a heat recovery step, which utilises the heat contained in the gaseous by-product from the thermal treatment to be used back in heating other PV modules [1,57].

To ease the environmental impacts originating from the application of chemical compounds, the main solution is to reduce the usage of these chemicals or replace them with more environmentally friendly alternatives [55,63]. One example is the chemical solvents and treatment processes developed by Yokohama Oils and Fats Industry to delaminate PV modules. Although the treatment time may be long (approximately one day), the solvents employed were comparatively more environmentally friendly than other chemicals such as nitric acid and hydrogen peroxide [57]. Another example is demonstrated in this



study [117], where methanesulfonic acid (MSA) solution combined with an oxidising agent ( $\text{H}_2\text{O}_2$ ) are utilised to extract and recover Ag from mono-Si cells. MSA solution offers the advantages of low toxicity, high conductivity, high thermal stability, high solubility for Ag, as well as reusability which is initiated by the addition of HCl solution [117,118]. The results obtained affirmed the feasibility of using MSA solution to extract Ag, as the Ag from the cells has completely dissolved in the solution and can be recovered with 99.8% purity [117]. Next, the gaseous emissions from the thermal degradation of EVA can be mitigated by advanced and effective delamination treatment, substitution and elimination of EVA encapsulant. The elaborations on this solution can be found in previous sections, as the options for solving the technological challenges of EVA also simultaneously provide relief from the associated environmental impacts. Similarly, fluorinated polymers which are prone to releasing toxic compounds should be opted-out in the design of PV modules to simplify the treatment of its waste emissions [20,70]. Aside from that, the quantity of toxic emissions discharged to the environment can be managed by the addition of a treatment device. For instance, a condensation unit coupled with solvent refining and dewatering equipment can convert the gaseous emissions into liquid solvent [18,56], which is more easily contained and handled for further processing. Installing an abatement device such as a scrubber to capture fluorine-containing gas is also another viable treatment method [11,70].

The emissions from transportation during the collection stage of EoL PV modules can be lessened through solutions similar to the ones proposed for the financial challenges. Establishing decentralised recycling plants and cooperation between PV manufacturers can result in an optimised and planned collection and transport network. Aside from yielding costs savings, reduced repetition of routes and shortened distances also lead to decreased transportation emissions [6,77]. Another alternative is to provide on-site treatment equipment on a smaller scale to recycle EoL PV modules. One example of this is the PhotoVoltaic panels Mobile Recycling Device (PV-MOREDE) developed by La Mia Energia Scarl in Italy, which is a device that enables the universal recycling of EoL modules through mechanical treatments only [57,119]. The mechanical treatment provided by PV-MOREDE includes the removal of Al frame and junction box, reduction of volume by cutting glass into smaller pieces, and multiple processes of milling and sieving [57,119]. The NPC Group in Japan has also developed a mobile semi-automated frame and J-box separator which can be loaded onto a truck along with a generator [120]. Its purpose is to disassemble the Al frames and junction box from the PV modules on site to allow easier recovery of the components. Both PV-MOREDE and the separator from NPC Group function to reduce transportation costs [120], as several bulk components are already separated and available to be sent to other facilities for further processing [70]. This reduces the need for intermediate logistics [119] and is also beneficial for easing the environmental impacts of emissions [70].

#### 6.2.4. Contradictions among Proposed Solutions

Solving the challenges that emerge from the recycling of EoL PV modules would undoubtedly result in several contradictions and trade-offs, as presented in Table 8. These trade-offs are part of the decision-making processes in developing a sustainable and comprehensive PV waste management framework, and thus require significant considerations by relevant governmental organisations and private bodies [14].

According to Norgren et al. [20], applying DfR principles usually results in trade-offs, as substituting or removing certain materials to be used in PV modules affect the costs and performance of the PV modules. In the best case scenario, changing the material composition, i.e., swapping out a fluorinated back sheet for an F-free back sheet, improves both the recyclability and costs of the PV module. However, in most cases, there is a trade-off between recyclability and cost or performance, as shown by the elimination of encapsulant using NICE technology. Therefore, it is up to the PV manufacturers to decide on the prioritised requirement of the product, whether to focus on commercial viability or recycling target [20]. The decision to reduce quantities of rare and valuable materials in the

design of PV modules also leads to a compromise of reduced EoL value of PV modules. Hence, it is recommended for PV manufacturers to directly involve themselves in the recycling operations so that they are informed of the recyclability of their PV modules. Implementation of the DfR principle would be less complex, since they are responsible for EoL management of the PV modules themselves, and it is in their best interests to reduce the costs associated with handling EoL modules. Depending on the available recycling technology, manufacturers are able to alter the design of PV modules to ensure maximum recoverability of the materials contained within, especially when significant changes are made to the design of PV modules [20].

**Table 8.** Contradictions and trade-offs present in solving the challenges of PV recycling.

Category	Contradictions/Trade-Offs		References
Design for Recycling	Elimination of encapsulants <ul style="list-style-type: none"> <li>• Elimination of EVA resolves the difficulty in delaminating the encapsulant during recycling process</li> <li>• Example: NICE technology</li> </ul>	Performance of PV modules <ul style="list-style-type: none"> <li>• Efficiency of NICE-PV modules is decreased</li> </ul>	[8,20,113]
	Reduction in usage of valuable materials <ul style="list-style-type: none"> <li>• Materials such as Te, Ge, In, and Ag are limited in supply, and are reduced in design for new modules for resource conservation purpose</li> <li>• Frameless modules are designed to simplify recycling and reduce transportation costs</li> </ul>	Reduced resale value of module components <ul style="list-style-type: none"> <li>• Reduced concentrations of valuable materials in EoL PV modules decrease economic incentive to recycle PV modules</li> </ul>	[20,43,70,86]
Type/Scale of Recycling Operations	Dedicated PV modules recycling plant <ul style="list-style-type: none"> <li>• Specializes in recycling PV modules, more comprehensive treatment processes including thermal and chemical treatment</li> <li>• Aims for high-value and closed-loop recycling, increases fraction of materials recovered with better quality</li> <li>• Reduces loss of valuable semiconductor materials</li> <li>• Requires higher investment cost</li> <li>• Requires greater quantity of waste PV modules to be economically profitable</li> </ul>	Bulk recycling at existing general recycling plants <ul style="list-style-type: none"> <li>• EoL PV modules are recycled in laminated glass, electronic waste, or other metals recycling facilities</li> <li>• Mainly mechanical recycling processes with the purpose of recovering bulk materials such as glass, Al and Cu</li> <li>• Valuable semiconductor materials are lost</li> <li>• Requires lower investment costs as there are existing facilities</li> <li>• Suitable for locations generating low quantity of PV waste</li> </ul>	[1,4,14,25,57]
	Decentralised low-capacity PV recycling plants <ul style="list-style-type: none"> <li>• Optimize collection and transport system</li> <li>• Decrease costs of transportation due to lesser distances travelled</li> <li>• Overall system costs including treatment costs are subjected to capital cost of each plant</li> <li>• Reduce emissions from transportation</li> <li>• Suitable for locations generating low quantity of PV waste</li> </ul>	Centralised large capacity PV recycling plants <ul style="list-style-type: none"> <li>• Utilize benefits of economies of scale to increase economic efficiency</li> <li>• Enable implementation of more advanced and efficient treatment systems</li> <li>• Increases transportation emissions due to longer distance travelled</li> <li>• Require greater quantity of EoL PV modules to achieve economies of scale</li> </ul>	[6,57,58,70,83]
	PV module recycling plant dedicated to one type of PV modules <ul style="list-style-type: none"> <li>• Designed treatment processes aimed at achieving highest level of material recovery for a fixed type of PV module</li> <li>• Lower flexibility to accommodate a different type of PV module</li> </ul>	PV module recycling plant designed for mixed PV waste <ul style="list-style-type: none"> <li>• Higher flexibility to accommodate different types of PV module</li> <li>• Inability to achieve high-value recycling as the recovered materials are mixed</li> <li>• Mainly employ mechanical processes</li> </ul>	[56,119]

Next, considerations are needed for the planning of the type or scale of recycling operations to be established. Table 8 showcases the different pros and cons of each of the recycling options with regard to several factors, including the quantity of PV waste, finan-

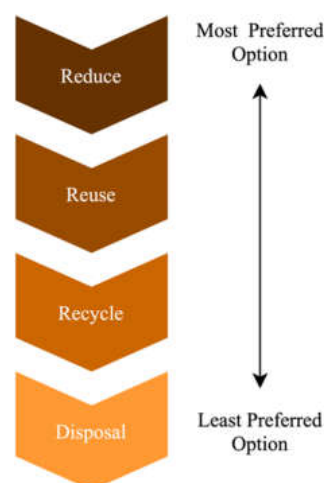
cial investment needed, types of treatment processes, quality of recovered materials and environmental emissions. The selection of the recycling options is thus highly dependent on the priorities established by the governmental or private organisations. If financial costs are concerning and the PV waste generated is too low, utilising bulk recycling plants to recycle PV waste may be the more suitable option. However, if the situation calls for decision making stemming from considerations of multi-influential factors, which is evidently quite difficult, Mahmoudi et al. [14] have suggested the use of Multi-Criteria Decision Analysis (MCA) to facilitate the decision-making process in the EoL management of PV modules. MCA is a tool that is developed to solve complex problems utilising multiple and sometimes conflicting criteria. It can assist better decision making by weighting different factors from technological, financial and environmental aspects, leading to a desired trade-off that minimises the compromises. Figure 10 depicts the various decision-making criteria suggested to be implemented in EoL PV waste management. The effectiveness of a particular factor increases the further the output of MCA is from the centre; however, it does so at the expense of sustainability [14].



**Figure 10.** Suggested decision-making criteria in MCA for EoL PV waste management. Adapted with permission from ref. [14] 2021 Mahmoudi et al.

#### 6.2.5. Prevention and Reduction in EoL PV Module Management

The selection of EoL treatment method of modules can be assisted with the waste management hierarchy, as shown in Figure 11. The higher up the treatment method is, the more environmentally favourable it is and the less effort is required to carry out the method compared to the lower treatment stages.



**Figure 11.** Waste management hierarchy of the EU member states, Adapted with permission from ref. [121] 2019 Mahmoudi et al.

Prevention or reduction of waste is the most preferable method in the hierarchy of waste management, as the absence of waste eliminates the need for its treatment, and the associated technological, financial, and environmental impacts can thus be avoided.

In terms of PV waste, prevention is nearly impossible since PV modules are always needed for solar PV installations. However, acquiring knowledge of the possible degradation and failure of PV modules is helpful in identifying counteracting solutions, and thus reduces the chance of PV modules from becoming waste. The failure of PV modules during their service life can be categorised into infant failures, constant failures and wear-out failures [122,123]. For example, infant failures resulting from transportation and installation damages can be avoided by providing extra care to the PV modules during these services [11,85]. As the modules are easily breakable due to their higher glass content, they may no longer be usable after damage. Constant failures and wear-out failures are normally caused by degradation of components such as loss of adhesion of the encapsulant layers, faulty junction box, potential induced degradation, cracking of cells and discolouration of EVA [15,124,125]. These failures can be detected immediately by a monitoring tool utilising a Geographic Information System (GIS), as presented by De Simón-Martin et al. [124]. Regular monitoring of PV module failures allows the development of preventative maintenance activities including replacement of damaged modules, cleaning procedures, load removal on modules (such as snow) and rearrangement of PV modules according to their performance [124,126]. This prevents the further degradation and worsening of modules' condition, allowing a higher chance of refurbishing the components into new modules. Aside from that, R&D is also essential in reducing the possibility of degradation. For example, potential induced degradation resistance can be improved through optimizing the ARC layer in silicon cells [127].

Another option is to reduce the materials required to manufacture PV modules, especially those that are hazardous and toxic in nature [4]. IRENA [4] has discussed the trend of reducing or substituting components present in the PV modules, including glass, Si, In and Ag. Substitution of rare materials with other materials that are more abundant in nature is essential to preventing the depletion of limited resources. Besides, to achieve materials and costs savings, significant R&D has been carried out to produce thinner and lighter modules whilst maintaining the efficiency of the PV modules [4]. The PV concentrator technologies under research is an example of effort directed at reducing the material intensity of PV technology [128], which can simultaneously bring down the costs in the near future [27,32]. Another example of emerging PV technology under research is the matrix photovoltaic solar cell (MSC), which consists of a multilayer structure made up by alternating silicon layers. The MSC possesses advantages of increased electrical efficiency, lower costs of production, exclusion of Ag usage and longer lifetime (40–50 years), especially in combination with a new encapsulation technology using two-component polysiloxane compound. If MSC is paired together with concentrator technologies, usage of high quality silicon can be conserved [32]. Hence, this emerging solar cell assists in delaying the emergence of waste due to its longer lifetime, while at the same time it also reduces the material intensity. Panchenko et al. [32] have also described solar PV roofing tiles which employ recycled materials such as polyethylene bottles, stretch films and adhesive materials. Aside from bringing down the production costs, this feature also reduces the need to use virgin materials in the production of the PV module.

#### 6.2.6. Repair and Reuse in EoL PV Module Management

The second-best alternative to waste management is to reuse the waste or prepare the waste for reuse, for example through repair or refurbishment. Reusing waste is higher in the hierarchy than recycling, as the efforts that need to be invested in this stage are still significantly lower than recycling [11].

In the case of PV waste, not all PV modules enter the EoL stage resulting from their spent lifetime; approximately 80% enter due to their being defective modules, damaged modules from transportation and installation, as well as modules that suffer from failures

at an earlier stage [4,8]. These modules typically have components that are still usable and salvageable and can be refurbished into second generation modules [11]. The collected modules require testing to examine their feasibility for repair, and then refurbishment can be carried out through replacement of frames, junction boxes, diodes, laminate layer or even solar cells [4,8]. These repaired modules can be resold on the market at a reduced price, stimulating the growth of second generation PV modules [4,54]. However, to gain public confidence in the PV repair and refurbishment industry, certification and quality standardisation for the second generation modules are necessary [4,8]. To remediate this, Tsanakas et al. [8] recommended the CIRCUSOL project, which proposes a circular business model providing consolidated services of reuse, refurbishment, remanufacturing and recycling of EoL PV modules, carried out through a product-service system (PSS). In this system, product service providers are responsible for the decision making on the optimal EoL management options of PV modules collected. The project also devises technical standards or regulatory framework that can be applied to second generation PV modules [8].

Furthermore, reuse can also be applied for PV modules nearing the end of their designated lifetime. Some PV system owners may replace their PV modules when they deem the energy generation capability of their system no longer economical, even though the PV modules are not suffering from major damage or degradation [129]. Hence, Hocine and Samira [129] proposed the utilisation of these used modules in remote areas for pumping and lighting purposes. Since the modules are still producing power, albeit at a reduced performance, a larger PV system capacity with greater number of modules has to be designed to compensate for the reduced power yield. Aside from giving PV modules a second life, selling the used modules also allows the original module owner to recoup some of the purchase cost instead of disposing the modules with no financial gain [11,129].

Both repair and reuse of PV modules after EoL are able to extend the estimated lifetime of the product to 40 to 50 years if care is given to maintain the quality of the modules. This is beneficial in reducing the need for recycling and delaying the emergence of large amounts of PV waste requiring treatment at once [1,129].

#### 6.2.7. Recycling in EoL PV Module Management

In sustainable PV waste management, a circular economy is necessary as it keeps the resources in use in the value chain for the longest feasible duration, preventing the loss of valuable materials [114]. Circular economy performs the best when reduce and reuse waste management options have been exhausted, leaving the remaining unusable PV modules to be recycled. Subsequently, in line with the concept of circular economy, PV manufacturers are encouraged to employ the recycled materials from PV waste recycling into the manufacturing of new modules to promote a closed-loop supply chain [18,20]. Several studies have demonstrated promising results of reclaimed wafer having similar efficiencies as commercial standard solar cells [60,62], reinforcing the technical feasibility of reintegrating quality recycled material into new module production. Regarding the financial competitiveness of reusing recycled materials, Deng et al. [54] have presented a comprehensive analysis of the financial implications of reusing recycled Si wafers in second-life manufacturing of PV modules in various scenarios. The authors have discussed the best possible benchmarks to make high-value and closed-loop recycling economically viable, as presented in Table 9. This demonstrated the economic feasibility and possibility of recycled material being reused in new module production, although the authors highlighted the importance of continuous improvement in the cost effectiveness and technological capabilities of recycling technologies to further reduce the pricing gap between newly produced modules and second-life modules. Even if the remanufactured modules are currently more expensive than newly produced PV modules, the trend of moving towards reusing recycled materials (either due to sustainable motivation or scarcity of resources) will eventually push towards a lower cost of remanufacturing modules due to the economies of



scale [54]. However, there has not yet been a study researching the economic viability of remanufacturing thin-film modules [47].

**Table 9.** Necessary benchmarks required to achieve economic viability in remanufacturing of EoL c-Si module [54].

Types of Remanufacturing	Benchmarks
Reuse of recycled metallurgical-grade silicon (MG-Si)	<ul style="list-style-type: none"> <li>Cost of recovering MG-Si must be lower than purchasing cost of virgin MG-Si (2.5 USD/kg)</li> </ul>
Reuse of recycled solar-grade silicon (SoG-Si)	<ul style="list-style-type: none"> <li>The efficiency of second-life cells produced from recycled SoG-Si must not be lower than the average efficiency of commercial Si cells by 2.5%<sub>abs</sub></li> <li>Cost of recovering SoG-Si must be lower than purchasing cost of virgin SoG-Si (~10 USD/kg)</li> </ul>
Reuse of recovered intact Si wafers	<ul style="list-style-type: none"> <li>If the efficiency of second-life cells produced from recovered wafers is maintained within 1%<sub>abs</sub> lower than the average efficiency of standard Si cells, the manufacturing costs would be reduced by 20%</li> </ul>

The situation becomes more favourable when the manufacturers themselves take up the responsibility of recycling their own PV modules, such as the case with First Solar. Aside from shortening the loop of supply chain with the assurance that there would be utilisation of the recovered materials, these PV manufacturers also benefit from reusing their own logistics network for the collection and recycling of EoL PV modules [18,20].

Besides, Norgren et al. [20] proposed the application of a product-as-a-service (PaaS) business model in the PV value chain, which leverages on the reusability and recyclability of the product to decrease its selling prices in order to become more competitive. One of the examples is rentable products, where the end users acquire the product at reduced costs while the manufacturers would re-acquire and recycle the product once the end users return the product. This also results in a circular economy in which the materials are kept in the loop in its entire life cycle, with the condition that the rentable products are collected effectively [20].

Incorporating circular economy into PV waste management is an important step towards enhancing the sustainability of the recycling process. Besides, coupled with research and development which employs the DfR principle, optimises the recoverability of materials and reduces the costs of recycling [4,88], the EoL management of PV modules could become increasingly favourable in terms of technology, finance and environment.

### 6.3. Policy and Infrastructural Recommendations

The growth of the PV EoL management and recycling industry is highly dependent on the available infrastructure and relevant policies that drive the motivation to handle PV waste sustainably. One of the most important policies is the EPR principle. Binding the manufacturers to the handling of their EoL product forces them to reconsider the design of the product and incentivises them to produce products that are easily recyclable in order to reduce the costs of handling difficult or hazardous waste. This principle is widely adopted in the EU through the WEEE Directive and has been implemented quite successfully in all the member states in the handling of PV waste [4,130]. The WEEE Directive is a useful reference for countries formulating legislations to manage PV waste, as it encompasses various aspects including financial accountabilities, responsibilities of involved parties and



collection and recycling targets [17]. The WEEE framework can be modified and adapted to each country subjecting to the regulatory environment. However, a regulatory framework alone is not sufficient to initiate the sustainable management of EoL PV modules [78]. Participation from producers, recyclers, consumers and waste management companies is also vital in ensuring full compliance to the PV waste legislations [131]. Similarly, the execution of high-value recycling in order to achieve the required collection and recovery targets would be impossible without relevant R&D projects and infrastructure. However, complicated administration procedure, unclear guidelines and difficult licensing requirements can deter the implementation of the PV module recycling industry [48]. Therefore, simplifying regulatory issues while creating a central office responsible for all processing related to management of PV waste are effective in establishing a well-run recycling programme [132].

After relevant regulations and policies are in place, suitable waste management infrastructure has to be established or expanded to accommodate the quantities of PV waste. It is highly advisable to develop PV recycling industries locally, providing employment opportunities to locals and minimising the exporting of PV waste to foreign countries [4]. Establishing local PV recycling industries enhances the local supply chain by supplying secondary materials which are scarce in the country and usually have to be imported to fulfil the country's demand [30]. The matter becomes more attractive when there exists a local PV manufacturing supply chain, which can be complemented by the provision of recycled PV material to be used in module production [19]. Thus, the financial motivation to recycle PV waste is justified through the abatement of the costs of importing rare materials as well as the profitable trading of valuable materials.

Another infrastructural recommendation is the incorporation of a tracking system in PV modules. One of the technologies that can be used is the radio-frequency identification (RFID) technology, which stores information such as material composition, manufacturer details, operations and maintenance service provider, as well as possible changes in components through repair or refurbishment. These details can be accessed and monitored whenever needed, and the information provided can assist the recycling companies in identifying the components in the PV modules more accurately, allowing easier recovery of these materials [8,20]. Furthermore, a comprehensive tracking system also leads to timely collection of EoL PV modules whenever they are discarded by end users, avoiding irresponsible disposal of PV modules or illegal transboundary movement of PV waste [14]. Consequently, nearly all PV modules can be accounted for, and the details recorded in the tracking system can facilitate the decision-making process on the EoL management of the PV modules, especially in the PSS model proposed by [8].

Finally, successful and sustainable PV waste management requires participation from all parties, including the public, PV manufacturers, waste management companies, research institutions as well as the authorities. It is crucial to foster awareness of the proper handling of PV waste, its environmental benefits, potential hazards, relevant legislations and the economical profits that are brought about through the recovery of valuable materials from EoL PV modules [14]. Creating awareness among the target audiences can lead to their behavioural change and increased support towards establishing a better EoL management of PV modules. For example, fostering awareness towards the value of the secondary raw materials recovered from PV waste facilitates better trading of these materials, since relevant manufacturers and end users are made aware of the availability of these materials. However, the addressing of market barriers, including absence of quality standards, concerns about low purity rate and trading difficulties, is also essential in ensuring smooth trading of recovered materials [14].

## 7. Conclusions

This study has highlighted the negative impacts of landfill disposal of EoL PV modules and emphasised the necessity to sustainably manage PV waste. High-value and closed-loop recycling should be applied to the EoL management of PV modules, as the aim is

to increase the recovery rates of materials with a focus on higher qualities, hence leading to conservation of resources. The establishment of recycling infrastructure for both c-Si and thin-film modules is imperative to accommodating the emerging waste. However, numerous technological, financial and environmental challenges have to be addressed along the way. Thankfully, there are solutions and ongoing research that may alleviate the challenges faced by the PV recycling industry, as compiled in Section 6. Nevertheless, significant efforts and future research should be allocated to prioritising approaches near the peak of the waste management hierarchy. Additionally, trade-offs arise when there are multiple and conflicting criteria influencing the decision-making processes of instituting a PV recycling industry. Hence, MCA can be employed to facilitate the decision-making process, enabling the establishment of a PV recycling industry which is best adapted to the prioritised criteria. Meanwhile, regulatory actions and policies also play important roles in shaping a sustainable PV waste management industry.

Overall, establishing a sustainable and successful PV recycling industry requires the presence of suitable infrastructure, legislation employing EPR principle, extensive R&D programme and cooperation from related parties, including PV manufacturers, consumers, governmental authorities and waste management companies. Hence, even though significant amounts of PV waste may not surface immediately, the development of the PV waste management industry should not be delayed considering the immense efforts required for comprehensively planning a framework. The time lag of the emergence of PV waste is thus a perfect opportunity to be exploited. Since solar PV has always been viewed as a green technology, its EoL management should also be carefully administered to reflect and uphold its reputation as clean energy.

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