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Review

Review on feasible recycling pathways and technologies of solar photovoltaic modules

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A R T I C L E I N F O

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A B S T R A C T

Given the rapid increase in production and installation of PV systems, recycling of PV modules is becoming more and more important. In this paper, three types of recycling pathways from perspectives of close-loop life cycle, which are manufacturing waste recycling, disposed module remanufacturing and recycling, are investigated. For each pathway, proven technologies are presented and their advantages and drawbacks are described. The results show that recycling technologies for PV manufacturing wastes and end-of-life modules are wildly explored and some are commercially available, although the challenges still remain in process efficiency, reduction in process complexity, energy requirements, and use of chemicals. Some research has been conducted on remanufacturing and reuse of PV modules. The ease-to-disassembly design may improve the reusability of valuable components. It is also found that though studies showed that PV module manufacturing waste recycling and end-of-life module recycling have significant positive impacts on the reducing environment loads, economic viability of PV module recycling is still unfavorable and policies are needed to encourage producer responsibility not only in the PV manufacturing sector but also in the entire energy industry, and an efficient collection network should be important to the economic viability of PV module recycling business.

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1. Introduction

There is an urgent need for developing clean and renewable energy technologies due to the environment deterioration and energy crisis. The PV technology is considered to be one of the greenest and most promising energy-generating technologies as it generates electricity directly from the sun and therefore avoids

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fossil energy consumption and greenhouse gases (GHG) emissions during system operation. Over the last decade, PV technology has shown the potential to become a major technology of power generation for the world – with robust and continuous growth even during times of financial and economic crisis. In 2011, more than 69 GW was installed globally and could produce 85 TWh of electricity every year. The growth rate of PV during 2011 reached almost 70%, an outstanding level among all renewable technologies [1].

However, we cannot avoid the fact that the life cycle of a photovoltaic module is not completely free of environmental impacts. The question of environmental impacts of PV system end-of-life (EoL) stage is raised because very few LCA studies have included this stage. In fact, although the production and installation of PV modules are increasing rapidly, the amount of end-of-life PV modules is relatively small. Currently, most of the collected and recycled PV modules are defects during production, damaged ones during transportation and installation, and malfunctioned ones during operation. Given that end-of-life PV products are not yet available, industrial-scale End-of-Life-Treatment (EoLT) facility for PV systems hardly exists, and sound recycling of PV products is still technically and economically challenging. However, as PV modules have a technical lifetime of 20–30 years and constructions of most of the PV installations started in the 1990s, a significant amount of disposed PV modules can be expected in the next 10–15 years and therefore EoLT of PV products is becoming more and more important.

In addition to reduction of solid wastes, recycling is also one of the solutions that contributes to the prevention of harm from hazardous substances released from disposed PV product such as metal cadmium (Cd), which can be toxic as well as carcinogenic or teratogenic, mitigation of the risk of supply shortages of semiconductor material resources, alleviation of some other environmental impacts and reduction of production costs [2–7]. According to Cyrs et al. [8], CdTe-based PV panel EoL management is still important, though landfill disposal of CdTe-based PV panels does not pose a human health hazard at current production volumes. Raugei et al. [9,10] analyzed the Cd emission in the EoL stage of PV system based on three recycling scenarios. The results showed that the stringent control of Cd-containing PV waste flows is hopefully to prevent worrisome increases in the overall cadmium emissions to the environment. According to de Castro et al. [11], mineral reserves of some scarce materials being used will also put pressure on the PV industry, because there is also a trade-off between solar system efficiencies and mineral limits. Although it is very difficult to provide a global limit to the expansion of solar power, an overview of materials needed for large-scale implementation shows that many of the estimations found in the literature are hardly compatible with the rest of human activities. Overall, solar could be more limited than supposed from a technological and sustainable point of view. Marwede and Reller [12] suggested that recycling of production scrap and EoL PV modules is essential due to the potential negative environmental impacts of cadmium contamination from CdTe-based PV and the possible shortage of the metal tellurium in the future. They proposed a dynamic material flow model for the life cycle of CdTe-based PV modules for estimation of global tellurium flows until 2040. The results depicted that efficiency measures at process and cell level will reduce the specific tellurium demand per watt peak such that the total tellurium demand starts to decline after 2020 despite further market growth, and thus the CdTe-based PV industry has the potential to fully rely on tellurium from recycled end-of-life modules by 2038. However, in order to achieve this goal, material efficiency must be substantially improved and efficient collection and recycling systems have to be built. Olson et al. [13] provided an analysis of PV module components by weight, embedded energy and environmental impact. According to him, the silicon wafer and the EVA contribute 14% to the weight, but account for a respective 83% of the embedded energy, 66% of the climate change impact and 51% of the water impact associated with a PV module. Therefore, it is conceivable that it will eventually be desirable to recycle them (either as feedstock, wafer, or even cell) in the next few decades from the perspective of environmental protection.

In order to investigate the feasibility of PV module recycling, this paper first presents an overview of currently commercially available PV modules in Section 2. Then, potential recycling pathways including manufacturing waste recycling, end-of-life module recycling, remanufacturing and reuse, are introduced in Section 3. For each pathway, proven technologies are presented. The advantages and disadvantages of the technologies are described and research and development needs are discussed. Then, studies on the evaluation of potential environmental economic benefits of establishing PV recycling business are also reviewed. Finally the conclusions are presented in Section 4.

2. Overview of currently commercially available PV modules

The photovoltaic (PV) effect is the basis of the conversion of light to electricity in photovoltaic, or solar cells. Therefore, it is natural that PV modules are basically categorized by the type of light-absorbing materials used. Also, it is reasonable to categorize PV modules by manufacturing technologies. Generally speaking, PV modules can be classified into two categories, conventional "1st generation" crystalline silicon (c-Si) wafer-based module and "2nd generation" thin-film module. Fig. 1 shows the general structure of the two types of PV modules.

Silicon wafer-based PV module is the most common type of solar cell manufactured in the world [14]. It also has been the dominant one for the supply of power modules into photovoltaic application. The commercially available multi-crystalline silicon solar cells have an efficiency around 14–19%. It is asserted that an increasing proportion of multi-crystalline silicon (or poly-crystalline silicon) and mono-crystalline silicon is going to be used for high-efficiency solar cells while thinner wafers and ribbon silicon technology continue to grow. Braga et al. [15] reviewed the recent advances in chemical and metallurgical routes for photovoltaic (PV) silicon production and found that production of (solar-grade silicon) SoGSi, which is the main component of c-Si cells, can be five times more energy efficient than the conventional Siemens process. Macdonald et al. [16] described an alternative approach to implementation of the impurity-photovoltaic (IPV) effect in crystalline silicon, referred to as electronically coupled up-conversion that avoids two of the major problems associated with the conventional IPV approach—namely, recombination of minority carriers generated in the base by a single photon, and parasitic

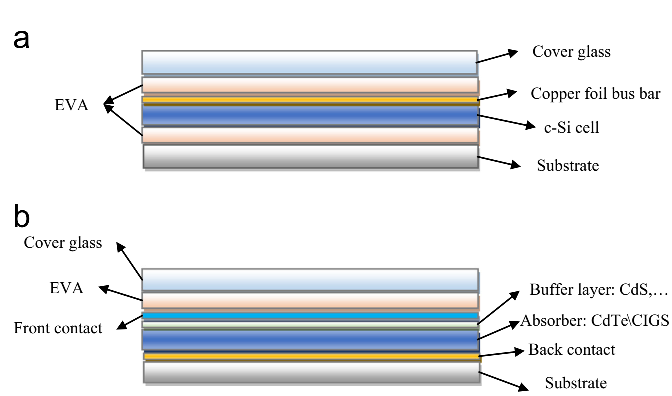

Fig. 1. Common structure of (a) c-Si wafer-based and (b) thin film PV modules.