Global status of recycling waste solar panels: A review

Yan Xu, Jinhui Li*, Quanyin Tan, Anesia Lauren Peters, Congren Yang

State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Tsinghua University, Beijing 100084, China

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A B S T R A C T

With the enormous growth in the development and utilization of solar-energy resources, the proliferation of waste solar panels has become problematic. While current research into solar panels has focused on how to improve the efficiency of the production capacity, the dismantling and recycling of end-of-life (EOL) panels are seldom considered, as can be seen, for instance, in the lack of dedicated solar-panel recycling plants. EOL solar-panel recycling can effectively save natural resources and reduce the cost of production. To address the environmental conservation and resource recycling issues posed by the huge amount of waste solar panels regarding environmental conservation and resource recycling, the status of the management and recycling technologies for waste solar panels are systematically reviewed and discussed in this article. This review can provide a quantitative basis to support the recycling of PV panels, and suggests future directions for public policy makers. At present, from the technical aspect, the research on solar panel recovery is facing many problems, and we need to further develop an economically feasible and non-toxic technology. The research on solar photovoltaic panels' management at the end of life is just beginning in many countries, and there is a need for further improvement and expansion of producer responsibility.

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1. Introduction

Solar, as a form of renewable energy, offers many advantages. It is safe, reliable, efficient, and non-polluting, and can be widely distributed. Solar energy—especially photovoltaic (PV) technology—has become a hot topic of global interest. The use of PV power...
has skyrocketed during the past several decades, as part of the global effort to expand clean energy production, and it presents enormous market potential. PV power is expected to produce a significant portion of the energy consumed worldwide, and to become one of the primary global energy sources in this century (Bakhiyi et al., 2014). Developed countries, such as the United States, Japan, and Germany, have launched large-scale PV development plans to stimulate the PV industry (Chi et al., 2014). The global demand for PV power increased from 1 GW (GW) in 2004 to 57 GWs in 2015: an annual growth rate of more than 20%, faster than any other industry, including other emerging renewable energy industries. It has been suggested that PV power will be the leading type of new energy development in the future (Luo et al., 2008; Winneker, 2013).

In China, the switch to solar energy may be an even more critical reform. In recent years, with the country’s rapid economic growth, environmental conditions have been deteriorating (Duan et al., 2008, 2011). In Beijing, for example, air pollution has become a key issue, as it affects the livelihoods and health of residents. Since the extensive utilization of fossil fuels is one of the main sources of air pollution, the energy industry has a major share of responsibility for solving these environmental problems. Fortunately, though, the trends in energy reform are changing the structure of the energy system, reducing the proportion of coal in power generation, and promoting the development of new energy sources. It has been estimated that the solar-energy resource reserves in China are equivalent to 1700 billion tons of standard coal each year, indicating an enormous potential for the development and utilization of solar energy resources in China (Liu and Zhang, 2010).

Nevertheless, solar panels themselves present another environmental issue: when their useful life is over, they become a form of hazardous waste. Because solar panels have a long service life, the recycling of waste panels was not a concern during their first 25 years of development. A considerable number of the first batch of solar panels installed are now being retired, however, and sound management of end-of-life solar panels is gradually becoming an important environmental issue (Aman et al., 2015). Solar-panel recycling is particularly beneficial for environmental protection, because silicon production is a process of intensive energy consumption, and the energy and cost needed to recover silicon from recycled solar panels are equivalent to only one third of those of manufacturing silicon directly (Choi and Fthenakis, 2010). In addition, the heavy metals lead, tin, and cadmium also predominate in solar panels (Bakhiyi et al., 2014; Galan et al., 2005), and these heavy metals can pollute the environment and pose threats to human health. Therefore, the recovery of waste solar panels can reduce energy waste and environmental pollution (CucchIELLA et al., 2015).

In July 2012, the European Union officially revised the waste electrical and electronic equipment (WEEE) directive, adding PV components as discarded electronic devices, so that they will be included under the ten categories of WEEE. Henceforth, solar PV elements will be included in the electronic waste management system, and must be collected and recycled (Bio Intelligence Service, 2011; McDonald and Pearce, 2010).

The newly launched PV waste management regulations require that all solar panels that have reached their end of life—whether from age or because they are damaged and their warranty period has expired—must be properly dealt with (Czanderna and Pern, 1996). Furthermore, all manufacturers of PV panels who supply components to the European market must pay a recycling fee. There are, however, few countries taking action outside the EU, primarily because there is an extremely low volume waste PV panels available for recycling, and the cost of recycling the panels is too high for the process to be cost beneficial (Yamashita et al., 2003; Wambach, 2004). There are only a handful of PV panel processing and recycling facilities around the world, and end-of-life solar PV panel management is a newly emerging field that needs further research and development.

The aim of this study was to provide an up-to-date review of the production and waste generation of solar panels and an outline of the present status of recovery efforts, including policies on end-of-life solar-panel management and recycling. This review also intends to provide a qualitative or semi-quantitative basis to support the recycling of PV panels, and to suggest future directions for public policymakers.

2. Types of solar panels and resources used in components

A typical solar-energy system consists of a solar panel, a solar controller, and a battery or group of batteries. If the output power is 220 V (AC) or 110 V, an inverter is also needed as part of the configuration (Fig. 1). Crystalline silicon solar panels are installed in solar arrays and have great recycling value.

Solar panels, also known as solar or photovoltaic modules (PV modules), work by using the photovoltaic effect of the semiconductor material in the panel to convert solar radiation directly into electrical energy. The solar panel is made up of several solar cells in series; these make up the key component of the system. The function of the battery group is to store the energy emitted by the solar panel when it is illuminated so that it can be supplied to the load at any time. The function of the controller is to automatically prevent overcharge of the battery. The function of inverter is to convert the direct current into alternating current.

Solar panels can be classified into three generations: (1) Crystalline silicon (monocrystalline or multi-crystalline); (2) thin film (amorphous silicon, cadmium telluride, copper indium gallium selenide - CIGS); and (3) concentrator photovoltaics and emerging technologies (CPV solar panels, dye-sensitized solar panels, organic solar panels, and hybrid panels). Since monocrystalline and polycrystalline silicon panels have higher conversion efficiency than thin film, they are presently (and will likely remain) the most widely used commercial solar-panel materials. Up until 2012, crystalline silicon panels accounted for about 90% of the global PV market, while third-generation solar panels have not yet been commercialized on a large scale.

Solar panels are the base power generation units of a solar energy system, and can be independently used. A typical panel includes an aluminum (Al) alloy frame, tempered glass, a battery piece, EVA (ethylene/vinyl acetate copolymer), and a backboard (TPT, Topotecan Hydrochloride) (Fig. 2) (Yin and Hao, 2009).

Tables 1 and 2 detail the PV panel composition and recyclable elements. After disassembly and extraction, the weight of the various resources from a typical solar panel is as follows: glass 54.7%, Al 12.7%, adhesive sealant 10%, silicon 3.1%, and other 19.5% (Cheng and Wang, 2007; Miles et al., 2005).

It can be seen that Al and glass account for a large proportion of PV panels, indicating that the loss of potentially reusable resources occurs across all types of PV panels. The loss of rare metals, in particular indium, gallium and germanium, is another effect of the non-recirculation of PV panels, which contain all of these rare metals. Indium is present in amorphous silicon and copper indium gallium selenide panels. Gallium is present in copper indium gallium selenide, concentrating photovoltaic (CPV) panels and emerging panel technologies. Germanium is present in amorphous silicon, concentrating photovoltaic (CPV) panels, and emerging panel technologies. While these rare metals account for only 1 percent of the PV panel volume, their value is significant.

After the recycling of PV panels, products can be obtained from reprocessing the components making up the Al frame, the silver
grid line, the tin copper wire and the glass. The crystalline silicon in crystalline silicon PV panels, and the rare metals such as indium, gallium, germanium, tellurium, in thin film PV panels, concentrator PV panels, and panels using other emerging technologies, can be recycled for new equipment production, and these advantages are attracting increasing interest from researchers globally. However, mixed plastic is difficult to recycle for use in products, although it can be used for energy. In addition to these advantageous materials, there are toxic heavy metals, such as cadmium and lead, although these account for less than 1% wt. of the PV panels. These heavy metals will sink in the residues from recycling and cause the residue to be classified as hazardous waste that needs to be sent to a hazardous-waste landfill.

End-of-life solar-panel recycling can effectively save natural resources and reduce the cost of production. It also provides a large number of semiconductors and other raw materials for the solar-panel industry itself. While current research into solar panels is focused on how to improve their efficiency and production capacity, the recycling and dismantling of waste panels are seldom considered. There are still, for instance, no specific solar-panel recycling plants. Yet recovering Si and other raw materials from waste solar panels could be a promising approach to compensate for the consumption of Si and other raw materials in the production process. Consequently, the need for environmentally sound management of waste solar panels has become urgent, especially because no effective collection or disposal system for the increasing stream of waste solar panels has been developed or implemented.

3. Production of solar panels and related waste generation

The development and utilization of renewable energy are necessary because the consumption of fossil-fuel energy has led to environmental issues, such as climate change and air pollution. Solar energy is an important one of these renewable energy sources. Fig. 3 shows that the global installed capacity of PV increased from 23.0 GW in 2009 to 207.9 GW in 2016. Germany is the country with the largest installed capacity, although its proportion of world installation decreased from 27% in 2011 to 20% in 2015 (Fig. 4). From 2011 to 2015, China’s share of the global PV market increased from 4% to 22%. In 2013, Europe had the greatest share of the global PV market, but a dramatic change occurred in 2014 as Asia took the lead from Europe, now representing 60% of the global market (Weckend et al., 2016).

Table 1
Composition of a solar-energy system.

<table>
<thead>
<tr>
<th>Units</th>
<th>Main components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tempered glass</td>
<td>Glass</td>
</tr>
<tr>
<td>Battery piece</td>
<td>Silicon, cadmium, selenium, tellurium, gallium, molybdenum, indium, etc.</td>
</tr>
<tr>
<td>EVA (ethylene/vinyl-acetate copolymer)</td>
<td>(C2H4)4(C4H6O2)y; chemical properties: general polymer</td>
</tr>
<tr>
<td>Backboard</td>
<td>TPT, TPE, etc.</td>
</tr>
<tr>
<td>Al alloy frame</td>
<td>97% Al</td>
</tr>
<tr>
<td>Junction box</td>
<td>Box body (including copper or plastic terminal), lid, diode, cables, connectors</td>
</tr>
<tr>
<td>Silica gel</td>
<td>Highly active adsorption materials, and amorphous material with chemical formula SiO2-nH2O</td>
</tr>
</tbody>
</table>

Table 2
Composition of crystalline silicon solar panels.

<table>
<thead>
<tr>
<th>Recyclable material</th>
<th>Content (kg/kWp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame</td>
<td>Al 12.771</td>
</tr>
<tr>
<td>Polycrystalline silicon chips</td>
<td>Si 3.101</td>
</tr>
<tr>
<td>Silver bar line</td>
<td>Ag 0.03</td>
</tr>
<tr>
<td>Tinned wire</td>
<td>Cu 0.451</td>
</tr>
<tr>
<td>Glass</td>
<td>Glass 54.721</td>
</tr>
<tr>
<td>Background</td>
<td>Plastic 17.091</td>
</tr>
<tr>
<td>Adhesive sealant</td>
<td>10%</td>
</tr>
</tbody>
</table>
Taking China as an example: according to the forecast of solar-panel waste by the Chinese Association of Renewable Energy, China's solar-panel waste began to be produced in 2015, and the cumulative amount of waste will increase rapidly starting in 2020, becoming critical around 2030. Therefore, the disposal and recycling of solar panels will become an important environmental issue in China over the next decade or so (Feng, 2011; Wang et al., 2014).

The amount of global installed PV panels is rising sharply and is expected to grow rapidly in the coming years, as the normal useful life of a solar panel is 25 years. The total quantity of end-of-life PV panels is anticipated to reach 9.57 million tons by 2050 (Monier and Hestin, 2011). Fig. 5 shows the market share of solar panels by technology group. In 2014, silicon-based (C-Si) panels owned 92% of the market share; those based on copper indium gallium (di)selenide (CIGS), 2%; and those based on cadmium telluride (CdTe), 5%; with 1% going to those based on other materials (CPV, dye-sensitized, organic, hybrids). From 2014 to 2030, the market share of C-Si PV panels is expected to decrease from 92% to 44.8%, while third-generation PV panels’ market share has been rising rapidly, and is expected to reach 44.1%, up from 1%, over the same period of time.

Therefore, among discarded solar products, the most important to recycle in the next few years are, in order: silicon-based (C-Si) panels, CIGS, CdTe, and other types. The main environmental problems linked with PV panels, if they are not properly disposed of, are: leaching of lead, leaching of cadmium, loss of recoverable resources (1 million tons of Al, 0.3 million tons of silicon, 7.4 million tons of glass) and loss of recoverable rare metals (silver, indium, gallium and germanium). From the point of view of reducing carbon emissions by recycling, it has been shown that the carbon emissions from recycled Al production comes to only 4.16% of the emissions for the same amount of Al produced from natural minerals (Ding et al., 2012). Taking the recycling of CIGS PV panels as an example, when the collection, transportation, recycling, and disposal stages are all considered, the carbon emissions for the recycling of Ga and In would be 230 kgCO2-Eq for 1 m² CIGS PV panels, according to an assessment by Peters (2016). Thus there will be a significant potential for carbon emissions reduction when the collection, transportation, and recycling of waste PV panels are effectively organized.

However, in addition to small amounts of cadmium and lead, PV panels contain other substances that are hazardous to both humans and the environment. Nevertheless, while such other materials may also leach from PV panels, these two hazardous substances—cadmium and lead—produce the largest effects on both groups, even though they account for less than 1% of the content of PV panels.

4. Techniques for solar-panel recycling

Currently, research into solar-panel recycling is being carried out mainly in Europe, Japan, and the United States (Bohland and Ansimov, 1997; Bombach et al., 2005, 2006; Doni and Dughiero, 2012; Palitzsch and Loser, 2012). Most solar-panel recycling studies have focused on silicon extraction and the recycling of rare metal elements. At present, there are three methods of processing waste solar panels: component repair, module separation, and the removal of silicon and other rare metal elements from among the components. Fig. 6 shows the recycling techniques for the different kinds of solar panels.

4.1. Component repair

The replacement of components is intended to overhaul systems and prevent the electrical failure of board groups, but does not involve the separation of components or materials recycling. Lin et al. (2011) adopted two kinds of methods to dismantle and analyze faults in the junction box, which can increase the output power of old solar panels. However, such methods can only be used if the external junction box and outer layer encapsulation film are
aging. Further processing becomes necessary when the components age.

4.2. Module separation

Physical separation includes the mechanical separation of broken panels but does not involve separating out any particular type of material.

Doi et al. (2001) prescribed the recovery of silicon panels from conventional crystalline silicon solar panels using an organic solvent method. From tests using multiple types of organic solvents to dissolve the EVA film, it was found that trichloroethylene could melt cross-linked EVA samples kept at 80 °C. Applying this method to a “one-panel” module (125 × 125 mm), it was found that mechanical pressure is necessary to suppress the swelling of the EVA. After immersing the module in trichloroethylene at 80 °C for ten days, the silicon panel was recovered successfully with no damage.

Dong (2009) studied a method of dismantling solar panels and component separation based on physical and chemical properties, structure, and materials. By comparing the advantages and disadvantages of the three methods for solar-panel disposal (artificial disassembly, use of an organic solvent, and heat treatment), they identified the heat treatment process as the optimal solution. The crystal silicon processing method consists of three steps. First, the Al electrodes on the backs of the panels are removed with a sodium hydroxide solution. Next, the silver positive electrode grid line is recovered using a saltpeter solution. Finally, an HF solution is used to remove any anti-reflectors on the surface of the polysilicon, to recover and recycle high-purity polysilicon. Yingli New Energy Resources Co., Ltd. of China studied a physical method for recycling solar-panel components. First, during the artificial disassembly, panels were crushed and cryogenically broken further into tiny particles, yielding a mixture of different types of materials that could be processed using the electrostatic separation method. However, this method is not sufficient for extracting a single component in the developmental stage. And manual methods, even those using various tools, are insufficient for dismantling crystalline silicon solar panels. However, much of the current research on the topic is focused on crystalline silicon solar panels, and the technology required to dismantle them is the critical part of the method. Actually extinguishing the EVA film by using high-temperature pyrolysis, or dissolving the EVA by using acid, alkali and organic solvents, have been effective techniques.

Kim and Lee (2012) used an organic solvent-assisted ultrasonic method to improve the dissolution rate of the EVA, and utilized trichloroethylene, o-dichlorobenzene, benzene, toluene, and other organic solvents to dissolve the EVA film from solar panels. They

Fig. 6. Recycling techniques for various types of solar panels.
<table>
<thead>
<tr>
<th>Key technology</th>
<th>Methods</th>
<th>Results - advantages</th>
<th>Disadvantages</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component repair</td>
<td>Two kinds of methods to dismantle and analyze faults in the junction box</td>
<td>Can increase the output power of old solar panels</td>
<td>Can be used only if the external junction box and outer layer are aging</td>
<td>Lin et al. (2011)</td>
</tr>
<tr>
<td>Module separation</td>
<td>Organic solvent method</td>
<td>Mechanical pressure is critical to suppress the swelling of the EVA. The silicon panel was recovered successfully with no damage</td>
<td>Organic liquid waste produced</td>
<td>Doi et al. (2001)</td>
</tr>
<tr>
<td></td>
<td>Compared three methods: artificial disassembly, use of organic solvent to dissolve components, and heat treatment</td>
<td>The heat treatment process was the optimal solution</td>
<td>Did not involve the resource recovery of silicon</td>
<td>Dong (2009)</td>
</tr>
<tr>
<td></td>
<td>Artificial disassembly, crushing, cryogenic breaking and electrostatic separation</td>
<td>Obtained a mixture of different types of materials</td>
<td>Not sufficient for single component separation; still in the laboratory research stage</td>
<td>Yingli New Energy Resources Co., Ltd. of China</td>
</tr>
<tr>
<td></td>
<td>Organic solvent-assisted ultrasonic method</td>
<td>Significantly shortens the dissolution time of EVA in organic solvents</td>
<td>Organic liquid waste produced</td>
<td>Kim and Lee (2012)</td>
</tr>
<tr>
<td>Heat treatment and chemical etching methods</td>
<td>Module separation</td>
<td>Module separation</td>
<td>Non-purified silicon wafers</td>
<td>Klugmann-Radziemska et al. (2009, 2010a,b)</td>
</tr>
<tr>
<td>Recycling of silicon</td>
<td>Cement-based thermal insulation system and chemical method</td>
<td>Recycling of silicon</td>
<td>Organic liquid waste produced</td>
<td>Fernandez et al. (2011)</td>
</tr>
<tr>
<td>Recycling of rare metals</td>
<td>Grinding and hydrometallurgy</td>
<td>Recycling of indium and gallium</td>
<td>High price of chemicals</td>
<td>Guangdong Xiandao Rare Material Co., Ltd. (2011)</td>
</tr>
<tr>
<td></td>
<td>Physical and chemical methods: blasting, mechanical processing and dissolution of the semiconductor, and precipitation, plating and ion exchange</td>
<td>Recycling of cadmium telluride; net cost estimated at $0.04–$0.06/W</td>
<td>High price of chemicals</td>
<td>Sasala et al. (1996)</td>
</tr>
<tr>
<td></td>
<td>Recycling (CdTe and CIS) by wet mechanical treatment such as grinding and flotation, or dry mechanical processing methods such as vacuum blasting</td>
<td>Recycling (CdTe and CIS)</td>
<td>Process is complicated</td>
<td>Berger et al. (2010)</td>
</tr>
<tr>
<td></td>
<td>Treated multiple types of solar panels together. Two physical methods were used: panels were broken and then heat-treated or broken with a hammer</td>
<td>Mix of recycled polysilicon, amorphous silicon, and CdTe solar panels; glass directly recycled</td>
<td>All types of mixtures, hard to separate</td>
<td>Granataa et al. (2014)</td>
</tr>
</tbody>
</table>
studied the effects of the concentration of different solvents, temperatures, ultrasonic power, radiation times, etc. The results showed that at 450 W ultrasonic power and a temperature of 70°C, the EVA film could be completely dissolved in 3 mol/L of toluene after one hour. This method significantly shortens the dissolution time of EVA in organic solvents, but could also lead to an organic liquid waste problem. Klugmann-Radziemska et al. (2009, 2010a,b) explored the feasibility of recycling silicon from waste crystal silicon solar-panel components by heat treatment and chemical methods. First, the panels were divided into their constituents of flat glass, Al frames, and backplanes by heat treatment; then, the chemical method was used to remove the reflector on the surface of the panel, the p-n semiconductor junction, and the before-and-after surface metal electrodes. The heat treatment and organic solvent processing methods are often used to separate the various components of solar panels (Katsuya et al., 2003). Crystalline silicon panels consist of a panel electrode and an anti-reflection film coating, and a series of chemical etchings must be conducted to reduce the panel groups to pure silicon wafers. The chemical etching process involves removing the metal layer, removing the reflector, and doping the p-n junction, followed by surface polishing, cleaning, and drying.

4.3. Extraction of silicon and rare metal elements from components

Silicon and precious metals can be recycled from solar panels. Thin-film solar-panel recycling has been the subject of considerable research (Berger et al., 2010). Fernandez et al. (2011) studied crystal silicon panel recycling in a cement-based thermal insulation system. They used the chemical method, with acid, alkali solvent, and organic solvents to remove or dissolve the EVA film. Vital Materials Limited Company (Guangdong Xiangao Rare Material Co. Ltd., 2011) processes solar panels containing materials such as indium and gallium using hydrometallurgy, after fine grinding to recover the materials from the solar panels. Their process includes liquid extraction, with gallium salt and lithium salt added to the water extraction; separation; recycling; filtering; etc. Sasalaet al. (1996) recycled the cadmium telluride from thin-film solar panels using physical and chemical methods. First, mechanical processing was performed via blasting with 40,000 psi water. Second, the semiconductor and metal were dissolved with 6% sulfuric acid and 15% hydrogen peroxide. Third, precipitation, plating, and ion exchange were conducted. Results showed that the net cost was $0.04–$0.06/W. Berger et al. (2010) also studied the recycling of thin-film solar panels, such as recycling CdTe and CIS by wet mechanical treatment: for example, using grinding and flotation, or by dry mechanical processing methods such as vacuum blasting. Granata et al. (2014) treated multiple types of solar panels together. Two physical methods were used to mix together recycled polysilicon, amorphous silicon, and CdTe solar panels, which were broken and then heat-treated or broken with a hammer before the glass was directly recycled.

Table 3 summarizes various solar-panel recycling technologies. There are many studies on the laboratory processing of solar panels, but only two methods of complete treatment process have been investigated for industrial application and development. Deutsche Solar, a company that deals with crystalline silicon solar-panel modules, and First Solar Company, have both adopted the method of mechanical and chemical processing for thin-film solar panels (McDonald and Pearce, 2010).

The reprocessing of solar panels in China is limited to the repair of components and simple separation, which fail to classify and recycle the particular constituents, and are inferior to techniques used abroad. However, the treatment and disposal technologies applied in other countries have problems as well. For example, the crushing process produces a large amount of dust containing glass fiber and resin, emanates poison gas, and creates noise pollution (Yang et al., 2004). The inorganic acid dissolution method can be effective for EVA separation only, and the process produces nitrogen oxides and other harmful gases (Bruton et al., 1994), which require respiratory protection equipment for employees to avoid associated health risks. Further, the method does not consider the removal of frames or the reuse of silicon wafers, and the residual liquid is hard to dispose of.

The EVA dissolution time for conventional organic solvents is much longer, although it can be significantly shortened by using ultrasonically assisted organic solvents. However, it also generates a large amount of volatile organic liquid waste, which is difficult to treat. The heat treatment method combined with chemical processing is the most advanced technology in this regard, but it has the downside of generating waste gas from pyrolysis, and requires high energy consumption.

5. Policies for solar-panel recycling

Britain was the first country in the European Union to formally approve the EU’s WEEE directive on photovoltaic components processing. The British regulations, which took effect on January 1, 2014, require all the PV panels produced or imported into the UK market to have a registered product conformity plan, and all manufacturers of solar panels must provide all of the critical data related to the panels, such as the number produced or imported and their distribution channels.

Germany has also revised its electrical and electronic equipment (WEEE) regulations, requiring that all photovoltaic component manufacturers and importers register their products and assume obligations for end-of-life treatment; offenders will face huge fines.

In the Czech Republic, PV Cycle, a European organization responsible for WEEE-compliant PV module take-back and recycling, and Retina, a photovoltaic waste processor, have entered into a joint venture for the recovery and recycling of waste solar panels. As a non-profit, member-based organization, PV Cycle offers collective and tailor-made waste management and legal compliance services for companies and waste processors throughout the world. Their staff includes solar-panel waste management consultants as well as traditional scientists. Retina, meanwhile, will be responsible for the Czech Republic’s rehabilitation and recycling management.

WEEELABEX organization, located in Czech, is also involved in a project aimed at collecting, storing, processing, and recycling waste electrical and electronic equipment throughout Europe, including the preparation of standards and the monitoring of waste-processing companies.

Very few countries outside the EU market have taken any measures to regulate waste solar panels. Japan, though, has taken a first step toward solar-panel recycling. Not only have the national first-class solar-energy equipment manufacturing enterprises actively participated in research on recycling technology, together with the advanced European countries, but a local company has also researched and developed recovery technology. The environment ministry has also required manufacturers to be involved in recycling waste solar panels. In addition, a Japanese wholly owned subsidiary of Shell Oil Company formally joined the European photovoltaic international organization. And NPC, a solar-panel manufacturing and inspection equipment manufacturer, is setting up a joint venture with the industrial waste-processing Hamada Company to recycle solar panels. The two companies will jointly participate in the New Energy Industrial Technology Development organization (NEDO) implementation of 2016 photovoltaic recycling technology development projects.
Although it lags behind Europe, the U.S. state of California, as the single largest solar market, has a proposal to supervise and control the processing of waste solar-equipment components. DTSC (California department of toxic substances control) plans to limit the landfill disposal of components containing harmful substances by promoting recycling. In 2010, DTSC proposed a solar-panel manufacturer recycling project, to treat solar panels as hazardous waste. American silicon film pane producer and utility-scale project developer First Solar has established factories in the United States, Germany, and Malaysia, for recycling solar-equipment waste. Through recycling and reuse, about 95% of the Cd and about 90% of the glass can be reused for new components. In less than a decade, China has become the world leader of installed PV capacity, while policies and regulations for solar-panel recycling are still non-existent there (Ding et al., 2016; Zhao, 2012). Even the environmental protection organization has not studied the solar-panel waste problem, and there are few recycling enterprises or institutions. Only a handful of enterprises, such as Yingli and Trina Solar Company, are carrying out research on solar panels, and these projects have only been active for a few years. The Chinese Environmental Science Research Institute is carrying out an environmental management study of the photovoltaic industry’s impact on the environment, including the effects of recycled solar-equipment components. Yet these efforts are hindered by the paucity of waste components available for research, since presently, most PV panels have not yet reached the end-of-life stage. The extended producer responsibility system has been proven to be an effective approach for the management of many types of waste, especially electronic waste (Weckend et al., 2016). Strengthening producers’ responsibility through the life cycle of PV panels could be an efficient approach for sustainable material management, and relevant measures could be implemented from the following aspects (Eberspacher and Fthenaki, 1997; Frisson et al., 1998; Fthenakis, 2000; Fthenakis et al., 2008). First, the responsibility of carrying out eco design should be strengthened in the existing regulations, since the design stage helps to minimize the impacts on environment and resources from the production, collection and recycling processes (Miao, 2015). Second, the use of recycled materials in the production of new panels should be encouraged by setting target percentages, while still guaranteeing quality product performance and safety. Third, incentive measures should be legislated, to encourage producers to participate in collection and recycling activities, to take advantages of the producers’ logistic network for new products and manufacturing technology, and establish a closed-loop green supply chain (Qu, 2015). In addition, information disclosure will allow public participation in monitoring the producers’ responsibility implementation, with mandatory disclosure to the public and targeted disclosure to the collection and recycling sectors (Tang, 2007).

6. Discussion and conclusions

Current research on solar panels has focused mainly on how to improve the production efficiency of crystalline silicon solar panels. However, processes for retrieving and dismantling waste panels should also be considered. In China, there is no dedicated crystalline silicon solar-panel recycling system; therefore, the direct disposal of retired solar panels is a serious issue, as recoverable resources are being wasted. Solar-panel recycling is a long, involved process, and the recycling system chain is incomplete. Although there are no rare earth metals in solar panels, the positive panel terminals are made of silver, which has recycling value, and there are numerous other valuable elements—including indium, gallium and germanium—within the components. Yet recycling waste solar panels presents several problems, such as the release of solvent emissions during the recycling process. However, by using an activated carbon fiber adsorption recycling condensation device along with a solvent refining and dewatering device, the organic gas generated can be turned into a high-purity liquid organic solvent after recycling. Hence the process can meet the requirements for recycling, reduce the discharge of pollutants into the atmosphere, and protect the environment. Although the investment in environmental protection equipment can significantly increase a company’s production costs, it can also create economic benefits associated with environmental protection.

Future outcomes of current research, development and testing efforts for photovoltaic-panel recycling techniques are difficult to assess. Another challenge for the recycling of PV panels is their long lifetime, estimated as 25 years. Not enough policies are currently being developed to handle these problems. Policies and regulations on solar-panel recycling have until now been omitted from the waste electrical and electronic equipment (WEEE) directive in China. We propose that a recycling industry standard be developed for waste from photovoltaic power generation, requiring manufacturers to be responsible for recycling. Policies and regulations to encourage recycling and safe disposal of waste should be devised as well. At the same time, the management of waste panels and hazardous waste is necessary, and a penalty can be assessed for improperly disposing of, or buying and selling, waste panels. Also, the government should take measures to compel solar equipment manufacturing firms to disclose environmental information, strengthen the supervision of the media, the public, and non-governmental organizations, and achieve a good balance among the stakeholders. The results of this review demonstrate the need to extend the responsibilities of the producers not only in the PV manufacturing sector but also throughout the entire energy industry.

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References


