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Development of the Photovoltaics Recycling Network

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Abstract: The Photovoltaics (PV) industry has grown rapidly over 15 years. As the number of PV installation sites increases, the amount of the end-of-life PV products will subsequently increase. Therefore, an appropriate recycling process for the PV industry should be established. This paper described the current situation regarding the economic profits, the recycling policies, and the recycling infrastructure in the PV industry. In order to address the PV recycling issue, a recycling network has been developed to facilitate the PV recycling process. The network considered the facility location and the transportation route optimization, the cost and the environmental impact analysis, and the trade-off analysis. The network can assist the PV recycling process to any local areas.
Keywords: PV recycling, PV recycling optimization, PV recycling cost performance, PV recycling network

1. Introduction

The market for photovoltaics (PV) has been growing world-wide during the last 15 years [1, 2]. In 2015, 50.6 GW new solar PV were installed worldwide. In 2016, a record 14.8 GW of PV capacity was installed in the United States, which brings the US total installed PV capacity to 78 GW. The industry is poised to increase to 100 GW over the next five years. As the number of PV systems increases, the mass of PV waste will increase as well. The amount of End-of-Life (EoL) PV will approach 13.4 million tons worldwide, including approximately 1.8 million tons located in the US by 2025.

2. PV technology

PV Technology applies semiconductors to generate electric energy from solar radiation. The common types of PV material include Monocrystalline Silicon, Polycrystalline Silicon, Amorphous Silicon, Cadmium Telluride (CdTe), and Copper Indium Gallium Selenide (CIGS). The used PV modules could be treated with panel dismantling, transportation, thermal treatment, material separation, chemical treatment, and material reclaiming. The material reclaiming process recovers the valuable and high demand elements such as Si, Se and Zn. These glasses are then collected for reproduction while the junction boxes and other wastes are landfilled.

3. Economic profits on PV recycling

The end-of-life PV are desirable to be recycled because several high demand elements such as Se, Zn, Fe, and Ag are contained. Those elements are the pillar of national industry [7]. Appropriately recycling of those elements can eliminate the resource scarcity and material supply threat [8, 9], subsequently, helping stabilize the security of the national economy. On the other hand, recycling the existing EoL PV can also reduce the risk of the material shortage and the material oversupply, as a result, smoothing the price fluctuation of the PV industry [10]. In addition, the market price of some materials utilized in the thin-film and crystalline PV technologies has drastically increased in the recent years [11, 12]. High profit is even expected to be achieved by recycling elements In and Ga in CIGS PV, which is a type of thin-film panel [13, 14].

4. Necessary on PV recycling

The used PV should be recycled because they contain tons of toxic elements and energy intensive materials. The typical toxic elements in PV are As, Cd, and Se. As and Cd have a 6 and 4 tenfold toxicity index over common elements such as Cu [15]. Those hazardous materials need to be reclaimed thoroughly to ensure the health of both the environment

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and human beings. Besides, energy intensive components such as silicon wafers can be recovered during the pyrolysis by recycling the mono- and poly- crystalline PV [16]. In industry, producing 0.256 gram silicon wafers consumes 1,600 g secondary fossil fuel and 32,000 g water [17]. By implementing the recycling process, energy intensive materials, such as semiconductor elements, aluminum, and glass, can be retrieved effectively for remanufacturing of the CdTe and c-Si PV [10]. The technical and economic feasibility of the retrieving process has been verified by a previous researcher [18].

5. Economic status on PV recycling industry

Although PV recycling technologies are available for both silicon and thin-film based modules [19, 20], the recycling process has not been deployed in most countries due to the shortage of effective collection infrastructure and incentive polices. The potential trade-off among the cost factors should be seriously evaluated in order to ensure the cost effectiveness of PV recycling. Previous studies showed that transporting reclaimed materials among stakeholders has enormous economic and environmental impacts on recycling planning [21, 22]. Choi and Fthenakis [23] showed that the size of PV Recycling Center (PVRC) should be optimized so that the annual incoming PV waste is processed economically. The study was intended to guide the recycling of the current PV waste generated from manufacturing scrap and the long-term end-of-life planning has not been addressed. The economic feasibility of end-of-life recycling has also been debated. Cucciela et al. [9] reported that the annual capacity of a PV recycling plant should reach a certain capacity in order to provide sufficient economic incentives in the recent PV installation rates in Italy. Goe et al. [24] also concluded that the material recovery cost is more expensive than directly disposing based on the current technology and policies in the state of New York. It is obvious that recycling is the most environmentally friendly approach to treat the retiring PV [25]. However, the economic feasibility of the recycling process is still under exploration. Confronting the rapid commercialization of the PV industry, the adoption of constructive policies such as imposing higher fee and taxes are vital to the retiring PV recycling process. There is also a need to appeal to stakeholders to get involved as much as possible [2, 24].

6. PV recycling regulations in Europe and US

In Europe, recycling of EoL electronic goods is regulated by the Waste Electrical and Electronic Equipment (WEEE) Directive. The directive included PV and required all PV module manufacturers who sell in EU countries to have recycling programs in place [26, 27]. The industry had initiated the voluntary program with PVCYCLE in 2010, which now oversees compliance with the WEEE [28]. In the U.S., there are no policies (yet) directly related to the development of PV recycling and no legal obligations to process waste. Thus, cost optimization of recycling is imperative for the industry to voluntarily undertake such initiative. Because reverse logistics networks are complex, a systematic approach is needed to minimize the cost and subsequently, make PV recycling be a profitable operation.

7. PV recycling infrastructure

Some EoL PV recycling infrastructure have been proposed by previous researchers. Fthenakis devised a recycling infrastructure to demonstrate the feasibility of thin-firm solar cells recycling. In the infrastructure, both the centralized and decentralized scenarios are discussed with the quantitative parameters included [16]. Considering the complexity of the recycling process in collection and transportation aspects, a mathematical framework was recommended to resolve the PV recycling problem. The paper demonstrated an operational recycling framework to recycle the thin-film PV manufactured by First Solar Corporation [29]. The same authors also published their mathematical model regarding the economic feasibility to recycle the EoL crystalline silicon PV in both macro and micro perspective in Germany [2, 23]. Cucchiella etc. provided a financial analysis of recycling the EoL PV modules in Italy by considering the factors of technology, environment, and economy, as well as a sensitivity analysis between these factors [9]. Goe etc. performed a tradeoff analysis between multi-criteria by using both mathematical method and Geographical Information System (GIS) selection tools to research the optimal location to site the PV recycling centers in the state of New York [24]. While much research has been conducted on PV recycling, there is not a complex infrastructure that considers the entire recycling process on facility location selection, and the transportation routing and economic performance. A complex recycling network needs to be developed to facility the PV recycling process.

8. Reverse logistics network

There is also literature available regarding the characteristic and construction of reverse logistics networks based on recovering other products [30-33]. Most studies are limited to investigating solutions for economic feasibility on the EoL management of electronic appliances and information technology (IT) products such as computers, monitors, laptops, and cellphones. The fast turnover of consumer electronics creates a large waste stream of obsolete electronic waste, providing opportunities to establish a relatively stable and economically viable recycling infrastructure.

9. Location optimization

Approaches to location allocation problems in PV recycling have been studied. Choi, etc. performed a location optimization for the PV recycling facilities among a finite set of locations with a short-time of five years based on the current PV installation situation in Germany. The objective of the optimization is to minimize the total travel distance. The capacity limitation of each recycling center and other realistic restrictions are considered as constraints in the model. CPLEX was employed as the optimization solver to generate solutions [23]. These authors reiterated the supremacy by appropriately allocating the PV recycling facility while recommending the recycling scheme for the First Solar Company. It turned to be the most favorable scenario was expected to save $107,000 per month, while a $151,000 loss was anticipated every month in the least profitable scenario [29]. There were also location allocation models performing the recycling process for other products. Louwers developed a location allocation framework to collect, preprocess, and redistribute carpet waste with complete flexibility on location selection. The networks were employed in Europe based on the supply-driven reuse, and in the United States based on the demand-driven reuse [34].

10. PV recycling network

A general network was developed to facilitate the PV recycling process. Figure 1 shows the overall structure of the PV recycling network. There are four steps in the network. First, a database should be created with the input data of PV installation, various costs for PV recycling, distance matrices between PV Installation Site (PVIS), PVRC, Transportation Company (TC), and environmental impact index packages. Second, for determining the optimal location of PVRC, a facility location optimization model should be developed. The model should be able to assess the transportation scenario, the economic performance, and the environmental impact. Third, in order to decide the transportation routes between PVIS, PVRC, and TC, the optimal distribution model should be developed. Last, the framework should be able to perform trade-off analyses between scenarios for guiding decision makings.

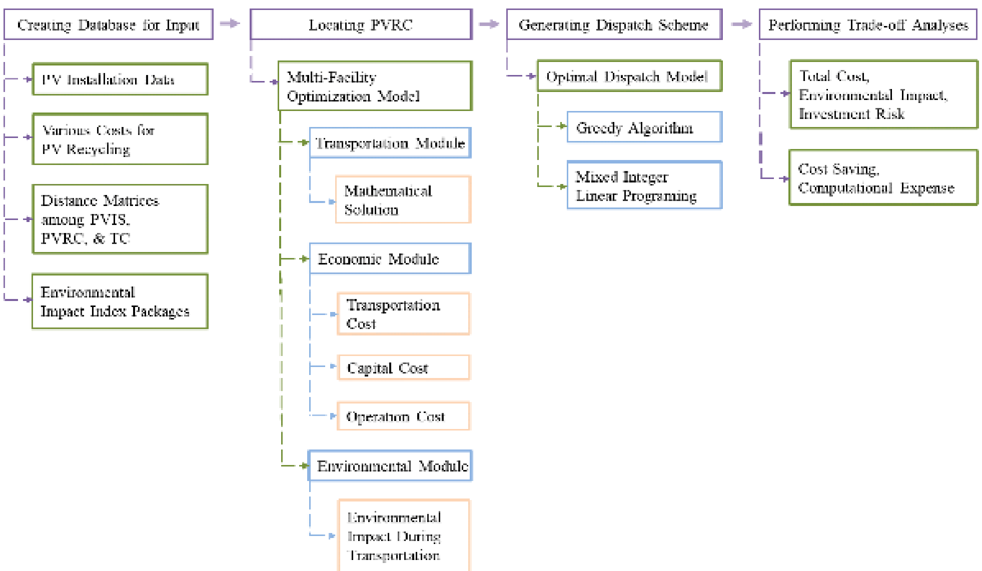

Figure 1. Structure of PV recycling network

10.1 Creating database for input

The database consists of four parts. They include PV installation data collected by the U.S. National Renewable Energy Laboratory [14] under the U.S. Department of Energy. The database also contains various costs associated with setting up PVRC from PV recycling industry, the distance matrices among PVIS, PVRC, and TC, and the environmental impact index packages to evaluate the environmental impact of recycling scenarios.

10.2 Locating PVRC

The model should be able to generate multiple optimal scenarios varied by the number of PVRC and recycling periods. While optimizing, the model should be able to include realistic constraints such as the regional restrictions for building PVRC and the annual recycling capacity of each PVRC. In addition, the model should be able to handle the exponentially increased PV amount. Due to the exponentially increased amount of waste, several individual recycling periods, such as short, mid, and long terms should be separately considered. As the output, the model can give the geographical location of PVRC, the total transportation distance, the break-down cost including the transportation cost, the capital cost, and the operation cost, and the environmental impact of each scenario in each recycling period.

10.3 Generating distribution scheme

Since the amount of PVIS increases significantly year by year, the optimization model should be smart enough for creating the distribution directives efficiently to satisfy the exponentially increased amount of PVIS. While performing the optimization process, the model should also be able to include the maximum annual capacity of each TC and PVRC as physical constraints. As a result, an optimization model among three parameters: PVIS, TC, and PVRC needs to be constructed to distribute the most optimal TC to ship each PVIS to the closest PVRC. In order for the optimization process to be effective, alternate optimization algorithms should be considered and compared. Common optimization algorithms include Greedy Algorithm and Mixed Integer Linear Programing.

10.4 Performing trade-off analyses

First, trade-off analyses should be performed among the total cost, the environmental impact, and the investment risk. Those three factors are affected by the location, the quantity, and the annual capacity of PVRC. Typically, lower total cost usually goes with higher environmental impact and investment risk. As a sustainable action, PV recycling is bringing tremendous environmental benefits on resource depletion and toxicity hazard. However, more positive effects are expected in the PV recycling process. As another sustainable manner, the environmental impact should be considered to make PV recycling much greener. In addition, as stakeholders, investment risk is much more attractive than short-term investment profit. Therefore, multiple scenarios with trade-off analyses among cost, environmental impact and investment risk should be conducted for assisting decision-making in PV recycling.

Second, while operating the distribution optimization among TC, PVIS, and PVRC, the first question should be addressed is whether the optimization process is necessary. It is not necessary to implement the optimization process if the total cost before and after the optimization are similar. The results from the optimization process should search for the global minimum, but the process could be significantly time consuming. Thus, sensitivity analyses should be performed among scenarios to explore the necessity of the optimization process. As the result of the sensitivity analyses, recommendations on whether the optimization should be performed for a particular PV recycling case should be concluded.

11. Conclusion

The paper addressed the recycling issue in the PV industry. The paper described the economic statue on PV recycling industry, the current regulation in PV recycling, the PV recycling infrastructure, and the reverse logistics networks with the location optimization in PV recycling. The paper also proposed a recycling network to facilitate the PV recycling process. The uniqueness of the proposed recycling network is the network consists of creating database for input, locating PVRC, generating dispatch scheme, and performing trade-off analyses. The network was able to optimize the location of PVRC, assess the economic and the environmental performance, optimize the transportation routes between PVIS, PVRC, and TC, and perform trade-off analysis between the cost, the environmental impact, the investment risk, and the computational expense. The network can be applied to local areas to assist the PV recycling process. The optimization mechanism and the application can be expended in the future research.

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