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Crystalline silicon photovoltaic recycling planning: macro and micro perspectives

Jun-Ki Choi [a,*], Vasilis Fthenakis [b]

[a] University of Dayton, 300 College Park, Kettering Laboratories, Dayton, OH 45469, USA
[b] Photovoltaic Environmental Research Center Brookhaven National Laboratory Upton, NY 11973, USA

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ABSTRACT

The usage of valuable resources and the potential for waste generation at the end of the life cycle of photovoltaic (PV) technologies necessitate a proactive planning for a PV recycling infrastructure. To ensure the sustainability of PV in large scales of deployment, it is vital to develop and institute low-cost recycling technologies and infrastructure for the emerging PV industry in parallel with the rapid commercialization of these new technologies. There are various issues involved in the economics of PV recycling and we examine those at macro and micro levels, developing a holistic interpretation of the economic viability of the PV recycling systems. We developed mathematical models to analyze the profitability of recycling technologies and to guide tactical decisions for allocating optimal location of PV take-back centers (PVTBC), necessary for the collection of end of life products. The economic decision is usually based on the level of the marginal capital cost of each PVTBC, cost of reverse logistics, distance traveled, and the amount of PV waste collected from various locations. Our results illustrated that the reverse logistics costs comprise a major portion of the cost of PVTBC; PV recycling centers can be constructed in the optimally selected locations to minimize the total reverse logistics cost for transporting the PV wastes from various collection facilities to the recycling center. In the micro- process level, automated recycling processes should be developed to handle the large amount of growing PV wastes economically. The market price of the reclaimed materials are important factors for deciding the profitability of the recycling process and this illustrates the importance of the recovering the glass and expensive metals from PV modules.

1. Introduction

With the growing interest on the renewable energy, global photovoltaic manufacturing has been growing over the past 10 years and further annual growth of 15% is expected until 2020 (Fthenakis, 2009; van der Have, 2009). In 2011, more than 69 GW are installed globally and could produce 85 TWh of electricity every year (EPIA, 2012). A study on the feasibility of solar power to generate most of the electricity demand of the United States, shows that this can happen by 2050 or earlier (Zweibel et al., 2008; Alazraki and Haselip, 2007). Various new photovoltaic technologies have been introduced in the market and existing technologies have undergone further development. How all these developments will affect the fate of the end-of-life photovoltaic modules is uncertain. However, it is certain that the growing amount of PV production wastes together with the significant amount of retiring PV modules installed over the several decades would need to be safely disposed recycled. Proper end-of-life (EoL) management of PV will offer a sustainable solution to resource availability, economic feasibility and EoL environmental risks.

Regarding to the resource availability, there is a rich body of studies analyzing and forecasting the future resource availability via tools such as material (substances) flow analysis (Kim et al., 2009), dynamic modeling techniques (Spatari et al., 2005; Chen and Graedel, 2012; Marwede and Reller, 2012), prospective analysis (Choi et al., 2012) and uncertainty analysis (Eckelman and Daigo, 2008). Results from all these studies urge a proactive systems approach to resolve the issues on natural resources scarcity and material price increases. In addition to the resource availability, for a sustainable development where PV energy generation has a major role, PV systems must be affordable and life-cycle environmental impacts must be lower than those of alternatives (EPIA, 2009; Du and Graedel, 2011). There is a rich body of life cycle

* Corresponding author. Tel./fax: +1 937 229 5344, +1 937 229 4766.
E-mail addresses: jchoi1@udayton.edu (J.-K. Choi), fthenakis@bnl.gov (V. Fthenakis).

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analysis (LCA) studies which address the life cycle environmental performance of various PV technologies (Reijnders, 2010; Şengül and Theis, 2011; Giacchetta et al., 2013) along with life cycle costing analysis (Redpath et al., 2011). Most of these studies address the critical need of the efficient EoL management for different PV systems (Zackrisson et al., 2010). Some studies examined the potential need for PV recycling policies and demonstrated the need to encourage producer responsibility of PV manufacturing sector (Fthenakis, 2000; McDonald and Pearce, 2010). The PV industry in Europe has started building an infrastructure for recycling and this served them well in complying with the Waste Electrical and Electronic Equipment (WEEE) Directive and in being exempted from the Regulations for Hazardous Substances (RoHS). The inclusion of PV into the WEEE places sets the requirement for the industry to ensure collection and recycling of end of life panels. Since the industry needs to continue reducing the system costs to be sustainable in a competitive energy market, the cost of compliance must be minimized (Göllei et al., 2012). This requires the optimization of both the collection and the material recovery stages.

There are two main research questions we would like to address in this paper. First, develop a rigorous mathematical framework, with which to analyze the economic feasibility of Photovoltaic (PV) recycling systems; second, provide valuable insights into the complex interrelationships among the potential stakeholders in the PV recycling network and the policymakers for initiating PV recycling programs. Several issues must be accounted for in setting the optimal temporal and spatial system boundaries of a PV recycling infrastructure since various stakeholders are involved in it (Coelho and de Brito, 2013). Diverse aspects, such as the collection, distribution, inventory, and reclaiming of materials, need to be effectively managed. In the macro level, strategies are needed for allocating the centralized/decentralized collection and recycling facilities in the optimal locations to minimize the total recycling system costs. This includes determination of the capital costs to open up PV take-back centers (PVTBC), costs associated with the reverse logistics services for the collection of PV modules and transporting them to the recycling facilities. In the micro level, optimized process planning is required to ensure the profitability of the PVTBC. Potential PVTBC will face with some challenging decisions on the following issues; the material separations and purity of recovered materials, revenue structures of current and future recycling processes with regard to the volatility of the market price of materials/components, cost associated with the processing, macro logistics costs, and external environmental costs (e.g., landfill-tipping fees) and benefits (e.g., avoidance of waste management related risks).

We developed a framework of mathematical modeling to evaluate the economic feasibility of the macro-level reverse logistics planning and the micro-level recycling process planning of the PV waste by considering the multiple issues in PV recycling planning listed above. A case study of waste recycling from crystalline silicon PV manufacturing in Germany is presented to illustrate the applicability of the model to near-term planning of c-Si PV waste. For spatial boundary, we consider the German PV Cluster where more than 90 percent of German PV manufacturing capacities are located (GTAI, 2009).

2. Macro-level logistics modeling

Table 1 describes the major c-Si module manufacturers which cover about 90% of PV manufactured in Germany. There are few other manufacturers scattered relatively far from the eastern region of Germany. The macro logistics model allocate the optimized PVTBC locations based on the capacity limit, capital investment, distance traveled. One MW corresponds to about 75 tonnes of c-Si and 2% of manufacturing scrap is assumed. For transportation, we adopted a fuel price $6.88/gallon for Germany and a 10 tonne truck with a fuel efficiency of 20 mile/gallon. The logistics service costs were $21/hr salary for each truck driver, driving on average 60 mile/hr; a service-fee factor of 1.5 accounted for the overhead logistics costs.

Table 1
Crystalline silicon PV manufacturing cluster in eastern Germany.

PVTBC	Manufacturer	Location	Capacity 2010 [MW]	Expected capacity ~ 2015 [MW]	Total waste (thousand ton)
R1	Q-Cells	Thalheim	400	3795	7.9
R2	Sunways	Arnstadt	56	531	1.1
R3	Arise Tec	Bischofswerda	57	541	1.1
R4	SOLON	Berlin	100	949	2.0
R5	SOLON	Greifswald	130	1233	2.6
R6	Aleo/Bosch	Prenzlau	180	1708	3.6
R7	Solarwatt	Dresden	150	1423	3.0
R8	Centrosolar	Wismar	120	1138	2.4
R9	Algatec Solar	Prösen	100	949	2.0
R10	Heckert Solar	Chemnitz	90	854	1.8
R11	Asola	Isseroda	25	237	4.9
R12	Arinna	Berlin	20	190	4.0
R13	Solarworld	Freiberg	1100	10436	21.7
R14	Bosch Solar	Arnstadt	460	4364	9.1
R15	Conergy	Frankfurt (Oder)	750	7115	14.8
R16	Sovello	Thalheim	540	5123	10.7
		Total	3193	30293	84.5

A reverse logistic model is designed to allocate the optimized locations of PVTBC by considering the amount of PV wastes to be collected, distance traveled to PVTBC, and capital cost of opening the facility. In order to optimize the routing scheme and the location of collection/recycling sites, we introduced the location of the major PV manufacturers in the model. The base model solves the problem of the location of the capacitated facility by minimizing the objective function in Eq. (1). Descriptions of the variables are listed in the nomenclature section.

Minimize

$$\sum_{i=1}^{I}\sum_{j=1}^{J}(\tau_{ij}+\kappa_{ij})X_{ij}+\sum_{j=1}^{J}f_j\Lambda_j \tag{1}$$

Subject to

$$\sum_{j=1}^{J}X_{ij} = \phi_i \quad ,\forall j\in I \tag{2}$$

$$\sum_{i=1}^{I}X_{ij}\le\sigma_j\Lambda_j \quad ,\forall j\in J \tag{3}$$

$$\Lambda_j\in\{0,1\} \quad ,\forall j\in J \tag{4}$$

$$X_{ij}\ge 0 \quad ,\forall j\in I,\forall\in J \tag{5}$$

The objective function is the sum of the transportation costs (i.e., fuel price, fuel-efficiency of lorry, and distance traveled), and the costs of logistics services provided by the registered logistics company. Constraint (2) is the satisfaction of the supply from collection facility, showing that all of the collected PV materials are sent to recycling facility. The linear inequalities in constraint (3) take into account that the material collected from the location i can be served from the recycling center j only if a facility is located at node j. It also imposes the condition that recycling at the plant j cannot exceed its capacity if the facility is opened. Constraint (4) and constraint (5) are variable constraints showing the binary- and