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END-OF-LIFE MANAGEMENT OF CRYSTALLINE SILICON PHOTOVOLTAIC MODULE

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PV manufacturing has been growing over the past 10 years and further annual growth of 15% is expected until 2020 [1]. A study on positioning a grand plan for solar power shows how vast PV arrays and other renewable energies can provide significant amount of electricity and total energy needs by 2050 [2]. Various new PV 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 PV modules is uncertain. In addition, the market price of some rare earth materials utilized in the manufacturing of the various PV technologies has exponentially increased in the past five years [3]. Therefore, it is necessary to set a proactive strategic recycling plan for the treatment of the disposed PV wastes.

There are three different types of PV waste; end-of-life modules, manufacturing scraps, and defect form packaging and transportation. Among these, end-of-life PV modules (Figure 1-a) are the major source for the recycling process and a prospective waste prognosis showed that the future amount of PV waste will grow exponentially. Figure 1-b illustrates the schematic of crystalline silicon (c-Si) recycling processes. This process consists of five major steps. First the unloaded modules transported from the collection sites will be loaded to the automatic conveyor system to enter into the recycling process. Then the junction boxes are removed manually. Thermal treatment burns off the laminates to facilitate the separation processes. From the separation steps, copper wire, aluminum frame, glass, and waste are separated. During the next step the solar cells are treated chemically. Surface and diffusion layers are removed subsequently by cleaning steps. Cells and wafer breakage are cleaned by etching techniques. Regarding to the reclaimed materials and waste, the following outlet parameters are considered. Junction box is processed by an electronic scrap waste treatment company (collection cost paid by photovoltaic take-back center, PVTBC). Plastic is burned off after the thermal treatment (*i.e.* incineration cost paid by PVTBC). Waste goes to land fill and PVTBC pays landfill tipping fees. Aluminum can be reused while glass, copper, and silicon can be sold to recycling companies. The thermal process could be improved with regards to its throughput, cycle time and yield. The yield of recovered cells depends largely on type, design and state of the modules to be processed. Design dependent factors that affect results of the thermal process are the type of laminate and crystal, the dimensions of the embedded cells, and the material and dimensions of bonds and soldering.

Figure 1–a. Retired PV module in Chevetogn, Belgium after 25+ years of service

Figure 1–b. Simplified c–Si recycling process and the reclaimed material

There are various issues involved in the economics of PV recycling in the macro and micro level. 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 issues such as the optimal level of marginal capital costs to open up PVTBC, costs associated with the reverse logistics services for the collection of PV modules and transporting them to the recycling facilities. Various stakeholders (e.g., dismantlers, recyclers, smelters) must be taken into account in the recycling infrastructure. In the micro-level, optimized process planning is required to ensure the profitability of the PVTBC. Potential PVTBC will face some challenging decisions in the following issues; material separation, revenue structures of current and future recycling processes with regard to the volatility of the market price of materials/components, cost associated with processing, reverse logistics costs, and external social costs, such as landfill-tipping fees.

Therefore, this study developed a generic mathematical modeling framework to evaluate the economic feasibility of the macro-level reverse logistics planning and the micro-level recycling process of the PV waste by considering the complex issues of the PV recycling planning listed above. A mixed integer programming and a linear programming are applied to the macro logistics and micro process planning models respectively. A case study of the crystalline silicon PV waste recycling in Germany is presented to illustrate the applicability of the models.

First, the macro-level reverse logistics model is designed to allocate the optimized locations of PVTBC by considering the amount of PV wastes to be collected, distance traveled (routing schemes) to PVTBC, and capital cost of opening the facility. The base model solves the optimization problem of the location of the capacitated facility by minimizing the objective function subject to the various constraints. 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. Figure 2 illustrate one of the examples of the results after running the model. With the variation of the marginal capital cost for opening up a PVTBC, the model suggest the best candidate locations to open up PVTBCs by considering the amount of waste from each collection locations and the cost associated with the reverse logistics to transport the waste from each locations to the designated PVTBCs.

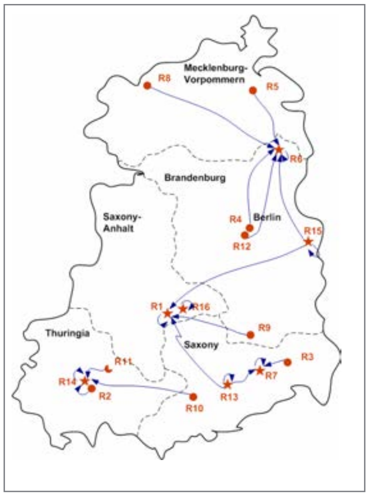

Fig. 2. Optimized locations of the PV recycling centers (red star) in the eastern part of the Germany.

In the micro-level recycling process level, the main objective of each PVTBC is to maximize the revenues from selling the materials recovered from the collected PV modules to the price varying markets for reclaimed materials while minimizing the cost associated with processes, transportation, capital, and inventories. The base optimization model decision set determines how much material to process by which equipment, in what period to process it, and if applicable, how much inventory should be held each period. Various experimental designs provide sensitivity analysis on key parameters. Figure 3 illustrates the sensitivity of the economics of recycling facilities when there is a 10% hike of each parameter in the recycling process. Exogenous parameters include cost of incoming modules (e.g. freight, packaging, logistics), and shipping cost to landfill or secondary material processing companies. Endogenous parameters include capacity level of the each equipment, processing time, processing costs, capital investment and labor costs.

Based on the current study, following general conclusions can be claimed from German case study. In order to ensure the economics of the PV end-of-life management systems, PVTBC should be constructed in an optimally decentralized location to minimize the total reverse logistics cost to transport PV wastes from various collection facilities to the PVTBC. In the recycling process level, advanced and automated energy efficient recycling processes should be integrated to handle the large amount of growing PV wastes economically. Market price of the reclaimed materials is important factor for deciding the profitability of the recycling process. Therefore, it is important to recycle thin-film PV modules (i.e., CdTe, CIGS) where some rare earth materials can be reclaimed. This study focused on the short term planning which currently accounts for the available PV waste. However further study will adopt strategies to consider the complex waste flows generated from different spatial (i.e. US), temporal (i.e. future), and technical (i.e. various technologies) aspects. Lastly, further study will experiment the life cycle environmental implication of the PV recycling along with the economic feasibility.

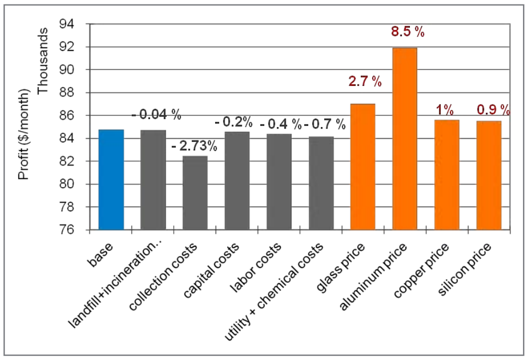

Fig. 3. Sensitivity of the photovoltaic take–back centers to the modeling parameters. (i.e., current market prices of the copper and silicon are higher than those of aluminum and glass. However, reclaimed amounts of the Al and glass cullets are much larger than the copper and silicon contents)

References

[1] Fthenakis, V.M., Sustainability of photovoltaics: The case for thin-film solar cells. Renewable and Sustainable Energy Reviews, 2009. 13, p. 2746-2750. [2] Zweibel, K., J. Mason, and V.M. Fthenakis, A Solar Grand Plan, Scientific America, Jan. 2008. p. 48-57. [3] "Global market outlook for photovoltaics until 2013" European Photovoltaic Industry Association. Available at http://ec.europa.eu/economy_finance/events/2009/20091120/epia_en.pdf