Preliminary DRAFT

PHOTOVOLTAIC RECYCLING PLANNING: MACRO AND MICRO PERSPECTIVES

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ABSTRACT

The usage of valuable resources and the generation of emissions during the life cycle of photovoltaic (PV) technologies dictate our proactive planning for a sound PV recycling infrastructure to ensure its sustainability. Some global PV manufacturers have begun recycling PV wastes generated from the PV manufacturing processes and the End-of-Life (EoL) PV modules. Therefore, it is vital to develop and institute economically feasible recycling technologies and infrastructure for the emerging PV industry in parallel with the rapid commercialization of these new technologies. Many issues must be accounted for in setting the optimal temporal and spatial system boundaries on the prospective PV recycling infrastructure since various stakeholders are involved in it. The issue of management covers diverse aspects, such as the collection, distribution, inventory, and reclaiming of materials. Therefore, a holistic consideration of the economic viability of the entire PV recycling network systems is necessary. We have developed mathematical models to analyze the profitability of recycling technologies and to guide tactical decisions for allocating optimal location of the PV take-back center.

INTRODUCTION

PV manufacturing has been growing over the past 10 years and further annual growth of 15% is expected until 2020 [1, 2]. A study on positioning a grand plan for United States solar power shows how vast PV arrays and other renewable energies can provides significant amount of electricity and total energy needs by 2050 [3]. Various new PV technologies have been introduced in the market and the existing technologies undergo significant further development. How all these developments will affect the fate of the PV wastes is uncertain. However, it is certain that the growing amount of PV productions wastes together with the significant amount of retiring PV modules installed over the several decades need to be disposed in somehow. In addition, the market price of some rare earth materials utilized in the manufacturing of the various PV technologies has been exponentially increased in past five years [4-5]. Therefore, it is necessary to set a proactive strategic planning for the treatment of the disposed PV wastes. One option would be the recycling PV wastes to reclaim those rare earth materials. However, economics of the prospective PV recycling has to be tested to initiate a sound recycling program. There are various issues involved in the economics of PV recycling in 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 a PV take-back center (PVTBC), costs associated with the reverse logistics services for the collection of PV modules and transporting them to the recycling facilities. Account must be taken of the various stakeholders (e.g., dismantlers, recyclers, smelters) in the recycling infrastructure.

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 following issues; the 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 the processing, reverse logistics costs, and external social costs, such as landfill-tipping fees.

Therefore, we have developed a generic mathematical modeling framework 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 complex issues of the PV recycling planning listed above. A case study of the crystalline silicon PV waste recycling in Germany is presented to illustrate the applicability of the models.

MODELING

MACRO LEVEL LOGISTICS PLANNING MODEL (M1): The reverse logistics 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. Case study will show the specific locations that we considered for the modeling.

The base model solves the problem of the location of the capacitated facility by minimizing the objective function in Eq. (1). 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 non-negativity-conditions.

Minimize

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

Subject to

$$\sum_{j=1}^{J}X_{ij}=\phi_i \qquad ,\forall j\in I \qquad (2)$$

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

$$\Lambda_j\in\{0,1\} \qquad ,\forall j\in J \qquad (4)$$

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

MICRO LEVEL PROCESS PLANNING MODEL (M2): The main objective of the 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 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. Some examples of experimental design include various shipping decisions, landfill tipping fees, decision for incoming material, and variation of market price for reclaimed materials.

The objective function seeks to maximize the profit of the PVTBC. In the objective function (6), the first term represents the revenue/cost from the final output materials, the second term calculates the cost associated with the incoming PV module, the third term models the processing costs, and the last term captures the inventory costs of the incoming modules. The constraint (7) is the capacity limit of equipment (i.e., the processing time for entire process should not exceed the capacity of equipment during each period). Constraint (8) represents the material-flow balances. Constraint (9) enforces the inventory balances. We assumed that the PVTBC is not experiencing any problems with storage capacity; viz., there is no constraint limiting the storage space for incoming products. However, the PVTBC is encumbered constrained by the need to protect the recycling process from deprivation of material. Therefore, constraint (10) enforces the safety stock level (minimum level). Constraints (11) and (12) are non-negativity conditions.

Maximize

$$\sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{j=9}^{14}r_{jk}N_{ijkt}-\sum_{t=1}^{T}\sum_{i=1}^{I}\lambda_{it}m_{it}-\sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{k=1}^{K}c_k p_{ik}X_{it}-\sum_{t=1}^{T}\sum_{i=1}^{I}h_t\lambda_i I_{it} \qquad (6)$$

Subject to

$$\sum_{i=1}^{I}p_{ik}X_{it}\le q_{kt} \qquad (7)$$

$$f_{ijk}X_{it}-N_{ijkt}=0 \qquad (8)$$

$$I_{i,\,t-1}+m_{it}-X_{i\,t}=I_{it} \qquad (9)$$

$$I_{it}\ge S_t \qquad (10)$$

$$X_{it}\ge 0 \qquad (11)$$

$$N_{ijkt}\ge 0 \qquad (12)$$

We have applied mixed integer programming for the macro logistics planning model (M1) and the linear programming schemes for micro process planning model (M2) with the Generic Algebraic Modeling System (GAMS) to resolve the optimization problems. Various experimental designs are set up to perform sensitivity analysis for comparing different scenarios with the variation of exogenous (external) and endogenous (process) parameters. 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.

CASE STUDY

TEMPORAL AND SPATIAL SYSTEM BOUNDARIES: Several challenges make recycling PV modules different from recycling other products. Compared to most consumer electronics, the life of PV modules is much longer, spanning into decades. Additionally, the construction of PV modules differs from that of consumer electronics in the sense that PV modules are not designed for disassembly. Thus, new processes and techniques must be employed for recycling them. Finally, the general location of PV manufacturers does not coincide with the location of installed modules. Large scale (utility level) solar farms are usually located in the remote area where sizable amount of land s are available.

Regarding to the first challenge, different time horizon and strategies should be considered to manage the complex waste flows generated from past installation, current and future production of various PV technologies efficiently. Waste analysis and prognosis provide an insight for planning to setting up recycling infrastructure in various time frames. In a relatively short term, PV recycling infrastructure planning should focus on locating the optimized recycling facilities based on the amount of PV waste flow of manufacturing scraps for both crystalline silicon (c-Si) and thin film cell/module/systems. In addition to time horizon, it should be also noted that the regions where major PV manufacturers are placed are quite different with the places where major PV systems have been installed. Considering the current situation and the data availability, we focus on the short term planning of c-Si PV waste generated from the PV manufacturing process. For spatial boundary, we consider the German PV Cluster where more than 90 percent of German PV manufacturing capacities are located.

WASTE PROGRNOSIS: The amount of PV waste generated has direct correlation with the growth of the PV market. PV has two different major waste streams; end of life (EoL) uninstalled waste and manufacturing scraps. Both types required to be disposed at certain time. Due to the large number of uncertainty, quantifying the exact figure is a demanding task. Some of major factors that influencing the quantity of waste generated includes: amount of PV production, weight per Wp, rate of production scraps during the production stages, rate of premature waste during the transportation and installation of PV system, failure rate during use, and the useful life. These parameters vary in accordance of different PV technologies and some uncertainty analysis should be implemented. Figure 1 illustrates our waste prognosis of the German PV based on the various historical and market information. Although this information is not directly used for the current short-term PV recycling planning, this information will be used for the future mid-term and long-term recycling analysis in Germany. Two different scenarios so called the conservative and the proactive approaches are used. Proactive scenarios focus to the higher growth rate of market than the conservative scenarios.

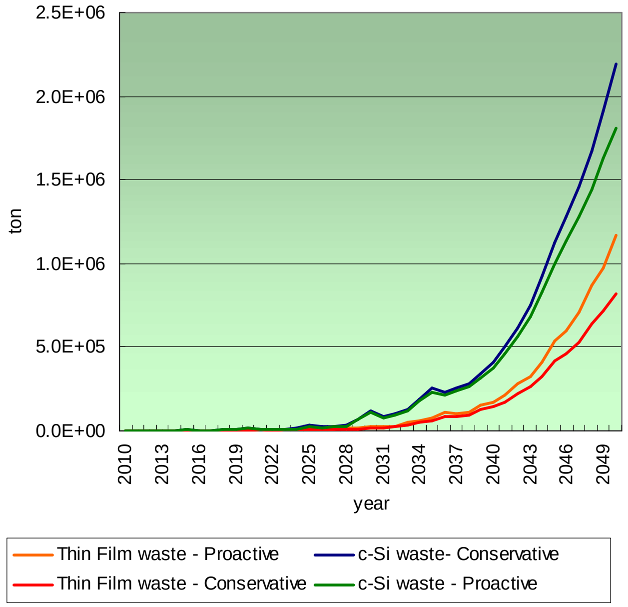

FIGURE1 – EXPECTED AMOUNT OF PV WASTE IN GERMANY

TABLE 1 – LEADING C-SI PV MANUFACTURERS IN GERMAN PV CLUSTER; LOCATION, MANUFACTURING CAPACITY, EXPECTED PV WASTE

PVTBC #	Manufacturer	Location	Capacity 2009 [MWp]	Expected Capacity 2009 ~ 2015 [MWp]	Total production waste ~2015 (Ton)
R1	Q-Cells	Thalheim	400	3795	7904
R2	Sunways	Arnstadt	56	531	1107
R3	Arise Tec	Bischofswerda	57	541	1126
R4	SOLON	Berlin	100	949	1976
R5	SOLON	Greifswald	130	1233	2569
R6	Aleo/ Bosch	Prenzlau	180	1708	3557
R7	Solarwatt	Dresden	150	1423	2964
R8	Centrosolar	Wismar	120	1138	2371
R9	Algatec Solar	Prösen	100	949	1976
R10	Heckert Solar	Chemnitz	90	854	1778
R11	Asola	Isseroda	25	237	494
R12	Arinna	Berlin	20	190	395
R13	Solarworld	Freiberg	1100	10436	21735
R14	Bosch Solar	Arnstadt	460	4364	9089
R15	Conergy	Frankfurt (Oder)	750	7115	14819
R16	Sovello	Thalheim	540	5123	10670
		Total	3193	30293	84530

REVERSE LOGISTICS PLANNING MODELING: Table 1 describes the major c-Si module manufacturers which cover about 90% of PV manufactured in Germany in the year 2009. There are few other manufacturers scattered relatively far from the eastern region of Germany. The macro logistics model (M1) allocate the optimized PVTBC locations based on the capacity limit, capital investment, distance traveled. 1MW is 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.

RECYCLING PROCESS PLANNING MODELING: We have applied the micro level process planning model (M2) for a c-Si PV recycling process. Three different cases of the recycling scenarios are considered. Specification of each process types are described in the Table 2. Single pilot and full pilot plants utilize the manual separation for the low throughput of c-Si module recycling. Compared to the pilot plant, automated plant has enhanced features such as automated loading and energy efficient automated sorting system instead of manual works, and some advanced chemical process.

TABLE 2 – THREE DIFFERENT PV RECYCLING PROCESS CONSIDERED IN THE CASE STUDY

	Single pilot	Full pilot plant	Automated plant
Capacity	1876 module (~ 17ton)	185 ton/year	20,000 ton/year
Processing type	Manual separation	Manual separation	Automated Separation
Throughput	Low	Low	High
Recovery rate	85%	85%	96%
Type of PV	mono-Si module	Crystalline modules	Mixed modules
Spatial Boundary	Single solar farm	Germany	EU

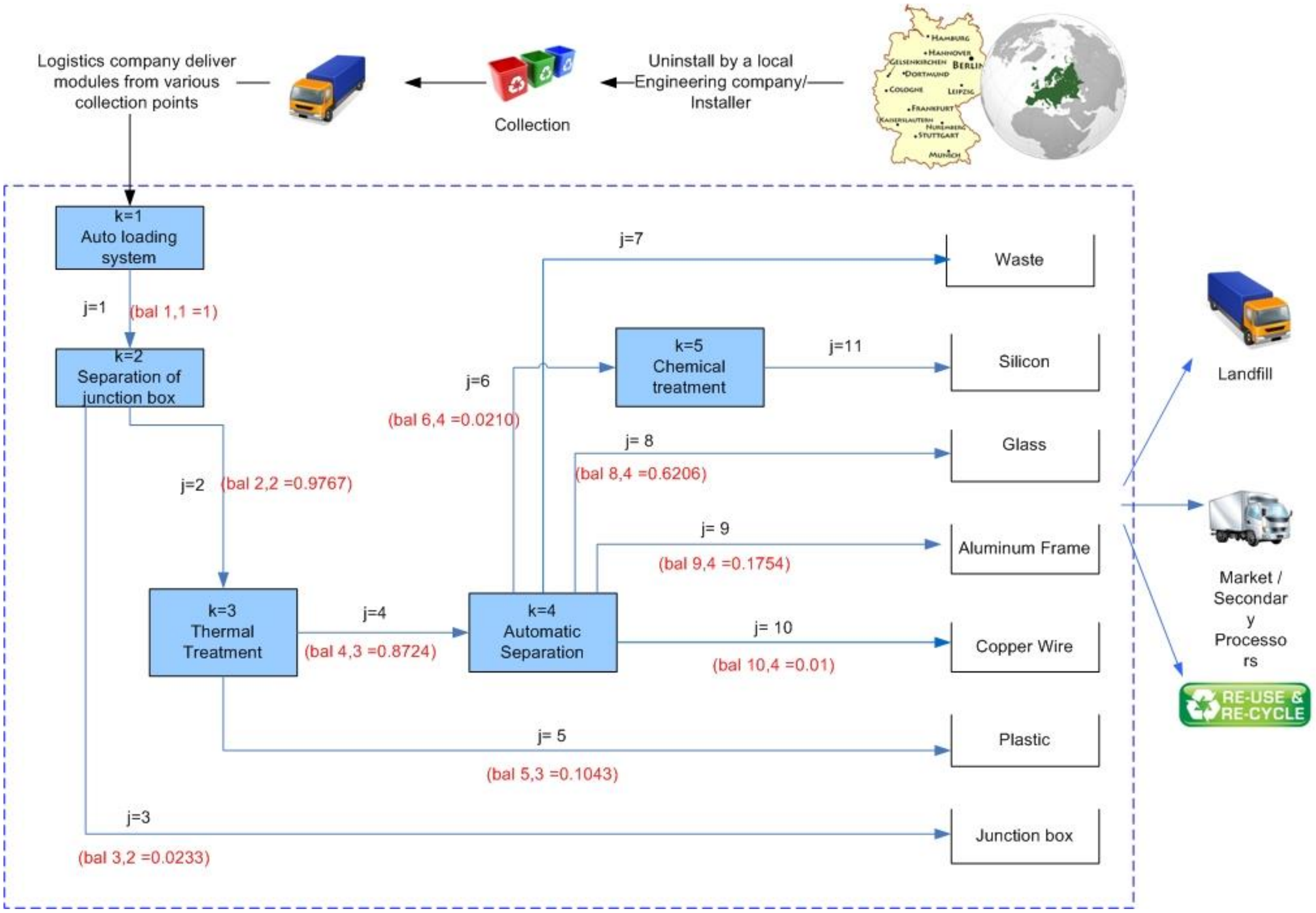

FIGURE 2- PROCESS DIAGRAM FOR AN AUTOMATED RECYCLING OF C-SI PV WASTE

Figure 2 illustrates the schematic c-Si automated recycling processes by R16. Schematic process flow for the pilot plant is not described in here but it has similar flow. This automated plant process consists with 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 by 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, following outlet parameters are assumed. Junction box is processed by an electronic scrap waste treatment company (collection cost paid by 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 regarding 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 type of laminate, crystal type and dimensions of the embedded cells, material and dimensions of bonds and soldering. Table 3 describes the material composition and throughputs considered in the recycling process.

TABLE 3 – MATERIAL COMPOSITION AND THROUGHPUTS OF THE C-SI PV WASTE RECYCLING PROCESS [6]

	Input/ module [kg]	Relative amount [%]	Output/ Module [kg]	Yield [%]
Glass	5.93	65.82	5.75	96.96
Plastics	0.94	10.43		
Cells	0.26	2.89	0.22	84.62
Cu	0.09	1	0.07	77.78
Al	1.58	17.54	1.58	100
Junction Box	0.21	2.33		
Total	9.01	100	7.62	

Additional mixed components (Glass+Si+Cu): 0.24 kg

RESULTS

Table 4 describes one of the examples of the logistics optimization results after running the M1. 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. Annual maximum capacity of one PVTBC is assumed as 20,000 metric ton per year. Total capital cost is the sum of the capital cost for each selected PVTBC location. Total reverse logistics cost is the summation of all the transportation and reverse logistics service costs. Total system costs are the summation of the total capital cost and the total reverse logistics cost. For example, the model suggests allocating only one PVTBC (R16) if the capital cost per PVTBC is more than $479K. When the capital cost per PVTBC is in the range of $295K~$479K, the model suggests to open up two recycling centers in different regions (R13 & R15). Model allocates more PVTBCs in the decentralized locations by finding the optimal level of the total system costs. Although total capital cost fluctuates with the increased number of the decentralized locations that model selected, total optimal system costs decrease. This can be explained by comparing the rate of decrease in total reverse logistics costs to the rate of increase in total capital costs adds-up. Total reverse logistics cost decrease more than the capital cost adds-up by saving the total distance traveled for transporting PV wastes from collection sites to the designated recycling centers.

TABLE 4 – OPTIMAL LOCATIONS AND THE LEVEL OF TOTAL SYSTEM COSTS

Capital cost ($K)*	optimal cost ($K)	selected location	total capital cost($K)	total reverse logistics cost($K)	Total system optimal cost($K)
$479	$1,715	R16	$479	$1,237	$1,715
$295	$1,352	R13+R15	$590	$762	$1,352
$174	$993	R13+R15+R16	$522	$471	$993
$144	$868	R13+R14+R15+R16	$576	$292	$868
$48	$393	R5+R13+R14+R15+R16	$240	$153	$393
$31	$294	R6+R8+R13+R14+R15+R16	$186	$108	$294

*capital cost/ PVTBC (lower bound)

Figure 3 illustrates the fact that the total reverse logistics costs exponentially decrease with the marginal increase of the recycling centers in the decentralized locations. Appropriate level of the capital costs per operating each PVTBC have to be first determined by the manager of the recycling program to decide the total number of the optimized PVTBC. Then, the total savings from the reverse logistics costs can be estimated by the model.

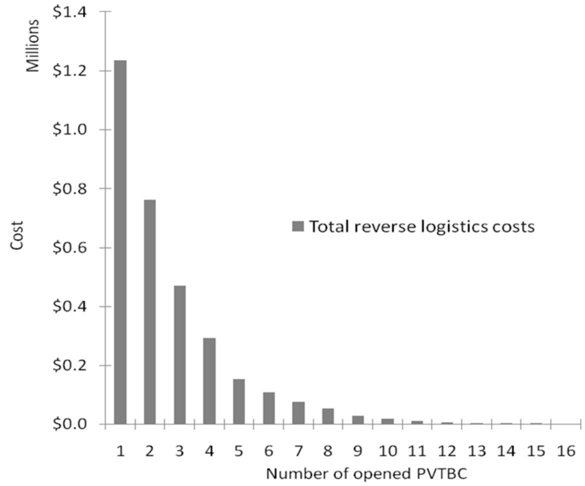

FIGURE 3 – CHANGE OF TOTAL REVERSE LOGISTICS COSTS VS. NUMBER OF PVTBC SELECTED BY MODEL

Figure 4 shows the percentile breakdown of the revenue/cost structure for each case. Chevetogn is one of the oldest solar farms located in Chevetogn, Belgium. Deutsche Solar collected the retired PV module from the site and recycled them with their single pilot plant. Chevetogn recycling case is considered to be a single process while the full pilot plant is assumed to be operated for years with the information given from the previous section. As can be seen from the first two bars in the graph, both single process and the full pilot plant case are not cost effective recycling options since they utilize labor intensive manual separations and old equipment which is not very energy efficient. In addition, the pilot plant cannot process significant amount of incoming PV wastes. On the other hands, for the automated plant case, it can be profitable recycling option when we assume the maximum capacity 20K ton/year. It utilizes faster automated sorting systems, more energy efficient thermal processes, and advanced chemical processes. However, collection cost is relatively high portion in this scaled up process because it is assumed that PV wastes are collected from various locations in EU. Our further breakdown of the profitability explained that the automated plant can be profitable as long as the amount of incoming waste per year exceed 19,000 ton. This can be explained by comparing the rate of change in the revenue to the rate of change in the total costs. The rate of increase in revenue becomes larger than the rate of increase in the collection and process costs as the amount of the incoming waste per year increases.

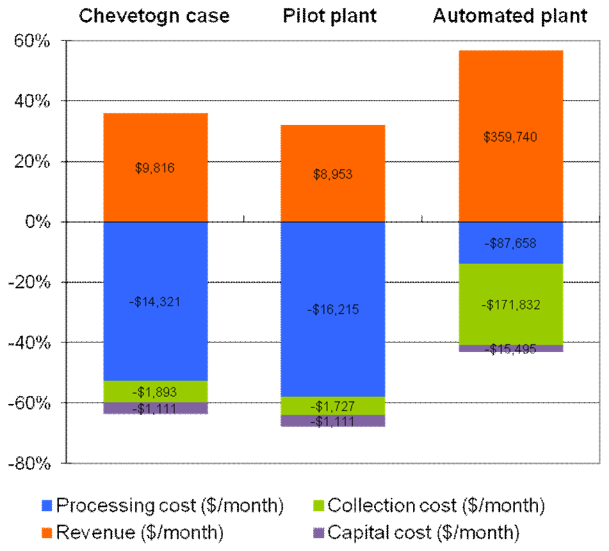

FIGURE 4 – COMPARISON OF COST/REVENUE BREAKDOWN FOR THREE RECYCLING CASES

Figure 5 illustrate the sensitivity of the profit to the various exogenous and endogenous parameters in the recycling process. Left bar indicates the possible profit from the base case automated recycling process. Each bar next to the base case shows the change of the profit when there is 10% hike of each parameter (i.e. 10% increase of cost/price). For example, if the waste collection costs increased by 10% because of the increase in any of the cost factors such as the fuel price, labor and the distance traveled, then the total profit of the recycling center will decrease about 2.7%. Other costs such as waste treatments, capital costs, processing costs are less sensitive to the profit compare to the collection costs which the recycling center has to pay to the third party reverse logistics company. Four bars on the right hand side illustrates the percentage increase of the profit when there is 10 % increase in the market price of materials that the PVTBC is reclaiming and selling to the secondary markets. As of year 2011, average market price of glass, aluminum, copper, silicon are assumed to be $0.07/kg, $2/kg, $7/kg, $2.5/kg respectively[7]. Market prices of aluminum and glass are relatively more sensitive to the profit than the prices of copper and silicon although the market prices of the copper and silicon are higher than those of aluminum and glass. This can be explained by the amount of the reclaimed material. Reclaimed amounts of the aluminum and glass cullets are much larger than the amount of copper and silicon by weight.

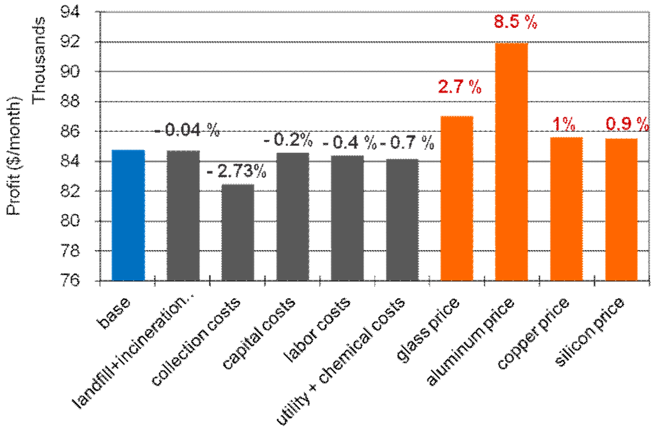

FIGURE 5 – SENSITIVITY OF PROFIT TO VARIOUS PARAMETERS

CONCLUSION

There are various types of commercial PV manufacturing technologies with an expected life time of 25+ years. Therefore, different time horizon and strategies should be considered to manage the complex waste flows generated from the past installation, current, and future production of various PV technologies efficiently. In a relatively short term, PV recycling infrastructure planning should focus on locating the optimized recycling facilities based on the amount of PV waste flow of manufacturing scraps for both crystalline silicon (c-Si) and thin film cell/module/systems. When major amounts of EoL c-Si modules are expected to be generated, mid/long term planning strategies are required and the amount of retired modules from the major installation sites should be considered. This should consider thin film EoL modules along with all other types of PV wastes retiring from the utility scale solar farms.

Our study focused on the short term planning. Mathematical models are designed to test the economic feasibility of the macro level reverse logistics planning and the micro level process planning of the c-Si recycling process with the German case. Following general conclusions can be stated with our case study results. In order to save the total recycling systems planning cost, PVTBC should be constructed in the optimally decentralized location to minimize the total reverse logistics cost for transporting the PV wastes from various collection facilities to the PVTBC. The decision is 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. 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 are important factors for deciding the profitability of the recycling process and this pose the importance of the recycling of thin-film PV module (i.e., CdTe, CIGS) where some rare earth materials can be reclaimed.

NOMENCLATURE

The following nomenclature is used for the

Macro logistics planning model (M1)

Indices:

i	Location of collection; $i \in \{1, \dots, I\}$
j	Location of tentative recycling plant; $j \in \{1, \dots, J\}$

Parameters:

ϕ_i	Capacity of inventory in collection facility located at i
σ_j	Maximum recycling capacity of the recycling facility located at j
κ_{ij}	Logistics service cost per weight quantity of waste PV collected at i, and transported to the recycling center j
τ_{ij}	Transportation cost per weight quantity of waste PV collected at i and recycled at j
f_j	Fixed capital cost to open a recycling center at j

Variables:

Λ_j	A binary variable to model the choice of ñopeningò a recycling facility at the site j. where, $\Lambda_j = \left\{ \begin{array}{ll} 1 & \text{if facility is open at j} \\ 0 & \text{otherwise} \end{array} \right\}$
X_{ij}	Weight quantity of PV module sent from *i* to recycling plant *j*.

Micro process planning model (M2)

Indices:

i	Group of incoming products; $i \in \{1, \dots, I\}$, where $I = 1$
j	Type of transit and final output materials; $j \in \{1, \dots, J_1\}$ for transit materials and $j \in \{J_1+1, \dots, J_2\}$ for final output materials, where $J_1 = 9$ and $J_2 = 14$
k	Type of equipment and tooling; $k \in \{1, \dots, K\}$, where $K = 9$
J_k	Set of output materials that are processed in equipment *k*
T	Time period; $t \in \{1, \dots, T\}$, where time period is week

Parameters:

c_k	Processing cost on equipment *k*
f_{ijk}	Percentage weight of transit and final output material *j* from product *i* that can be separated by equipment *k*
h_t	Capital cost for the inventory per time unit
m_{it}	Weight quantity of incoming product *i* in period *t*
p_{ik}	Processing time per weight unit of product *i* on equipment *k*
q_{kt}	Processing capacity of equipment *k* in period t
r_{jk}	Revenue (positive) or cost (negative) per kg of final output material *j* separated by equipment *k*
λ_{it}	Prices of one kg of incoming product *i* per period *t*
S_t	Safety inventory level per period

Variables:

N_{ijkt}	Weight quantity of output *j* from incoming product *i* separated by equipment *k* after the first cycle in time period *t*
I_{it}	Inventory of incoming product *i* at the end of time period *t*
X_{it}	Weight quantity of incoming product *i* scheduled to be recycled in period *t*

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