*Cost Optimization of Decommissioning and Recycling CdTe PV Power Plants*
Fthenakis et al.

## Executive Summary

This paper evaluates the cost of decommissioning utility-scale ground-mount CdTe PV power plants. The paper utilizes publicly available industry data and General Algebraic Modeling System (GAMS) optimization, to maximize the net revenue from this activity. The paper considers several decommissioning scenarios which may ultimately affect decommissioning costs and returns including buried and unburied cables, variable transportation distances, and variable storage and warehousing requirements. The paper also explored open-loop and closed-loop recycling programs for some of the rarer elements including tellurium, comparing their efficiencies.

The reselling prices of recycled materials determine the revenue of recycling, which is a most influential factor in the cost structure. Identifying the most sensitive material helps the company make better choices and increase the profit. The study included sensitivity analyses for recycling revenues, disposal fees, as well as market prices for Tellurium, Copper, Alumnium, Steel, Glass, and Cadmium.

The recycling of structure and modules could create a profit of $ 1.58 per module area, the major revenue coming from the copper of the cables and the steel and aluminum of the module mounting and support. Planning for easy recovery of materials from closed-loop recycling in addition to those from the modules could further add to the profitability of recycling.

# Cost Optimization of Decommissioning and Recycling CdTe PV Power Plants

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*Abstract* — **This paper evaluates the cost of decommissioning, at the end of their lives, utility-scale ground-mount CdTe PV power plants in the U.S.-SW, based on publicly available industry data and General Algebraic Modeling System (GAMS) optimization, to maximize the net revenue from this activity. The recycling of structure and modules could create a profit of $ 1.58 per module area, the major revenue coming from the copper of the cables and the steel and aluminum of the module mounting and support. Planning for easy recovery of materials from the BOS in addition to those from the modules could further add to the profitability of recycling.**

## I. Introduction

With the rapid global deployment of photovoltaic (PV) power systems, the future cumulative amount of end-of-life (EOL) waste PV panels is projected to increase rapidly.[1] Without proper treatment, the wastes could cause environmental impacts from potential leaching of regulated metals commonly found in PV modules such as compounds of lead, cadmium, and selenium. Also, the loss of energy-intensive resources (e.g., solar-grade silicon, glass, aluminum, and copper) and rare metals (e.g., silver, indium, tellurium and gallium) could in the future lead to resource depletion.

Most of the initially installed PV modules globally are currently operating. For CdTe PV, the post-installation annual breakage rate is 0.05% per year in the first ten years of operation and 0.01% per year in operating years 11-25 [2].

The first-generation solar modules are silicon-based, and do not require any rare materials other than Ag. The second-generation solar modules, like thin-film CdTe and CIGS modules, involve elements of limited availability (e.g., Te, Ga, In). Thus, the EOL solar modules could become a significant secondary source of these materials. Also, recycling of EOL PV modules resolves environmental concerns associated with waste management.

This paper describes a cost optimization of decommissioning EOL CdTe PV power plants and recycling the elements from the modules and the metals from the supporting and mounting structures. We used industry and market data and optimized the rate of recycling using the General Algebraic Modeling System (GAMS), extending an earlier module recycling GAMS model described by Choi and Fthenakis (2010) [3].


Figure 1. Locations of 12 projects developed by First Solar and the assumed recycling plant location based on capacities and distances

We examined decommissioning and recycling scenarios from large CdTe PV plants in the southwest of the United States. Twelve of First Solar's PV power plants are in CA, AZ and NV, and those represent 2893 MWac, or over half of First Solar's existing projects within the United States.

Fig. 1 shows a potential location of a recycling plant based on its distance to those 12 solar farms and their capacities, to minimize the total transportation cost.

## II. Methodology

### A. Recycling Process

First Solar has established the recycling of their modules and manufacturing scrap since the beginning of their operations. Currently, First Solar recycles manufacturing scrap and field returns in their production facilities and sends glass fragments to glass product manufacturers and a "filter cake" containing Cd, Te, Cu to a CdTe supplier, who extracts and purifies tellurium and cadmium in conjunction with their primary CdTe operations. In some cases, plastic is also recovered for use in rubber products; however, it was not included in our model optimization.

The top diagram in Fig. 2 shows the original cadmium flow in the whole industrial chain of First Solar modules. Specifically, the CdTe supplier extracts and purifies tellurium and cadmium byproducts from copper and zinc producers, respectively.

A future option called closed-loop recycling could involve the separation in the recycling center of Cd and Te using selective ion exchange, followed by purification and synthesis of CdTe in the same or a different operation [4]. The bottom diagram in Fig.2 represents this closed loop option.

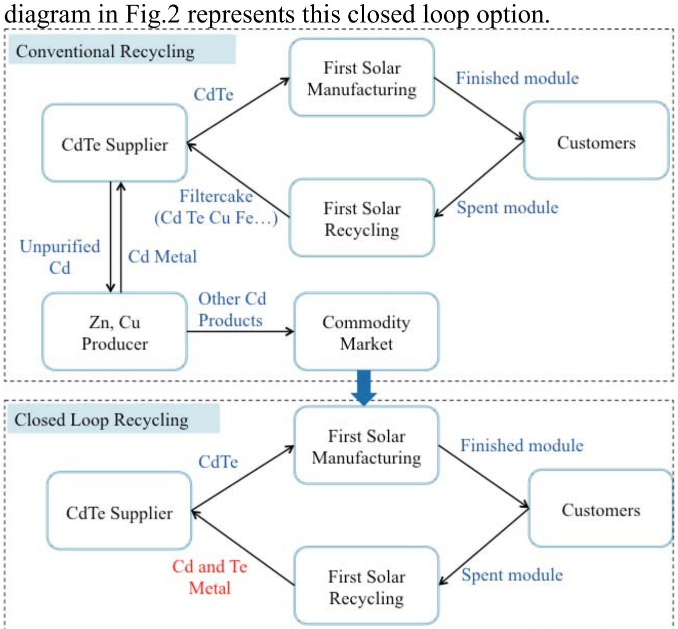


Figure 2. Recycling options

This integrated closed loop option not only simplifies the industrial chain, but could also reduce the total recycling cost.

The mounting and support structure and the cables will first be removed and delivered for metal recovery, while the modules are sent to a recycling plant, where a dry crushing and wet etching process is used as the basic delamination and metal-glass separation process in First Solar. The EOL modules will be loaded onto the auto-loading system, followed by a shredder and a hammer mill. Then the module fragments are immerged into acid solutions that leach the metals out and the later are recovered with selective pH precipitation. In subsequent steps, the materials are separated from the liquids and are recovered as feedstock in glass product manufacturing.

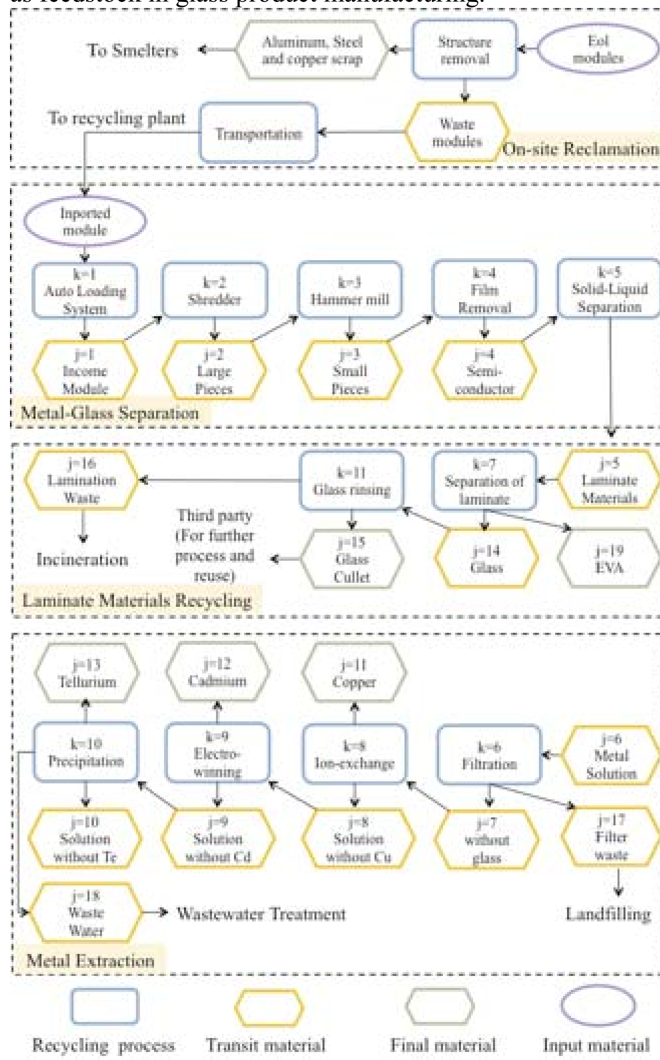


Figure 3. CdTe module recycling process map

In the conventional commercial recycling process, the leachate with the metal compounds is condensed in a thickening tank, and forms filter cake. The filter cake is then transported to a third party for processing.

However, as mentioned, the closed loop recycling would enable a recycler to directly use the leach solution to extract the metals. The leachate, or metal solution, goes through a 3-stage filtration to get rid of glass scrap, and the filter waste (e.g. glass fines) is landfilled. [5] Then the leach solution passes from a series of ion-exchange columns that retain copper and cadmium. The last step is to precipitate tellurium from the effluent solution.

Another recycling route is the recycling of glass. First the encapsulant layer is separated from the glass cullet in a vibrating screen. The separated glass is then discharged and rinsed for further recycling. At the end, all the plastic waste is either landfilled, handled in incineration plants for energy recovery, or used in rubber products. [6][7]

### B. GAMS optimization model

We used GAMS to optimize the choice between recycling and storage of decommissioned parts. The objective is to maximize the net revenue from the recycling process described above, thus:

Objective function is to maximize:

$$z = \sum_{j,k,t} V_{jk}\Omega_{jkt} - \sum_{i,t} N_{it}T_i - \sum_{i,k,t} C_k\Upsilon_{it} - \sum_{i,t} I_t\, T_{it}\Lambda_{it} \quad (1)$$

Subject to:

$$\Omega_{jkt} = E_{jk}\sum_{i} \Upsilon_{it} \quad (2)$$

$$\Lambda_{it} = \Lambda_{i(t-1)} + N_{it} - \Upsilon_{it} \quad (3)$$

Indexes (shown in Fig. 3):

$i$ Solar farm; $i \in \{1, \ldots, 12\}$

$j$ Transit or output material; $j \in \{1, \ldots, 22\}$

$k$ Decommissioning and recycling processes; $k \in \{1, \ldots, 13\}$

$t$ Monthly time series; $t \in \{1, \ldots, 204\}$

Parameters:

$V_{jk}$ Revenue/Cost of material $j$ derived from $k$ [\$/kg]

$N_{it}$ Quantity of modules from $i$ in period $t$ [kg]

$T_i$ Transportation cost of modules from $i$ [\$/kg]

$C_k$ Processing cost on $k$ [\$/kg]

$I_t$ Percentage of inventory cost to the incoming cost [%]

$E_{jk}$ Weight percentage of $j$ derived from $k$ [%]

Variables:

$\Omega_{jkt}$ Quantity of $j$ derived from $k$ in period t [kg]

$\Upsilon_{it}$ Quantity of modules from $j$ recycled in period $t$ [kg]

$\Lambda_{it}$ Quantity of modules from $i$ stored as inventory in $t$ [kg]

The first term in (1) stands for the revenue/expense from a recyclable material/waste output. It includes all the on-site structure materials, cables and optional cable trays. Additionally, note that those on-site materials will be separately sent to a nearby smelter and the extra cost will thus be considered inclusively. The second term is a fixed transportation, proportional to the distance from each solar farm to the assumed location for the recycling plant. The third term gives the processing cost for modules step by step, and the last term indicates the corresponding inventory cost on each group of incoming modules. Equations (2) and (3) constrain the material balance and inventory balance respectively. Besides, the limit of processing capacity and the minimum safety storage level also play a part in the optimization problem.

### C. Base scenario description

- *Plant capacity*

The capacity of the recycling plant is assumed to be 60,000 metric tons per year. Considering the operational continuity of recycling plant and the maximum storage time length, the plant is primarily designed for the large number of EOL modules in 2038-2042, during which more than 80% of the solar modules from the projects in Fig. 1 are expected to be decommissioned.

The capacity in the base scenario will guarantee that all the incoming modules could be recycled within the following 2 years.

- *Optimized inventory level*

The inventory level refers to the quantity of modules stored in warehouse in a certain period for future recycling. If inventories are too high, then money would be tied up in capital; if not sufficient, then stock-outs may paralyze the whole recycling chain. Some operations typically have 0.5~1 % of the year's capacity in stock.

- *Solar panel*

The specifications of the CdTe PV panels vary among the 12 projects. The reference solar panel in this research is assumed to be First Solar Series 3™ Black PV module; nevertheless they all have the same area (0.72 $m^2$) and weight (12 kg), and have a 25-year performance warranty and a 10-year product warranty.

The approximate composition of these panels is listed in Table I. [8]

TABLE I
MATERIAL COMPOSITION AND RECYCLING RATIO

| | Weight [kg] | wt [%] | Recycling rate [%] |
|---|---|---|---|
| Glass | 11.527 | 96.061 | 90 |
| Copper | 0.00132 | 0.011* | 90 |
| Cadmium | 0.00708 | 0.059* | 90 |
| Tellurium | 0.00900 | 0.075* | 90 |
| Encapsulant | 0.314 | 2.614 | - |
| Other | 0.142 | 1.180 | - |
| Total | 12.000 | 100.000 | - |

* 5% fluctuation in wt (%)

- *On-site reclamation*

The on-site reclamation costs include two parts, the aboveground and underground structures removal. The aboveground reclamation cost is proportional to the plant capacity, while the costs of underground structure removal is also related to the percentage of recycled underground cables and the unit digging cost.

For ground-mounted PV systems, several scenarios were explored regarding the recycling of wires on the ground. In the basic scenario, all cables underground would be dug out and recycled. However in reality, the recycling decision on the buried cables usually depends on the local permitting authority. We further examine this in a sensitivity analysis.

- *Optional cable tray*

In the base case, we assumed all cables were buried underground, while we also explored the scenario when the cables were mounted in above-ground cable trays, which contain steel and aluminum that also need to be recycled when reclaiming the cables.

Table II shows the major parameters of the basic scenario.

TABLE II

MODELING PARAMETERS FOR BASE CASE

| Description | Unites |
|---|---|
| Weight per module | 12 kg |
| Area per module | 0.72 $m^2$ |
| Capital cost for inventory | 1.96%/month |
| Inventory safety level | 0.5% of year's capacity |
| Steel weight in cable tray scenario | 3.3 tonne/MWac |
| Aluminum weight in cable tray scenario | 2.1 tonne/MWac |
| CdTe recovery rate | 90% |
| Metal reclamation loss | 10% |
| Transportation cost (22t truck) | $1.2 per km |
| Distance to smelters | 160 km |
| Structure scrap value | 50% of its metal price |

## III. RESULTS

Table III gives the breakdown of the net revenue on recycling. The importing cost on transportation is a fixed cost, which relates to the weight of incoming modules.

TABLE III

BREAKDOWN OF COST MODEL

| Revenue/cost | Involved Variables | Optimized value ($/module area*) With Cable Tray | Optimized value ($/module area*) Without Cable Tray |
|---|---|---|---|
| Module revenue | Recycling Quantity | 1.668 | |
| Recycling waste disposal cost | Recycling Quantity | -0.038 | |
| Structure scrap revenue | Recovery rate of undergro-und cables | 4.634 | 4.439 |
| On-site cost | Recovery rate of undergro-und cables | -2.761 | -3.265 |
| Cost of importing modules | Transport-ation unit cost | -0.207 | |
| Cost of transporting structure scraps to smelters | Transport-ation unit cost | -0.067 | -0.064 |
| Cost of processing | Recycling quantity | -1.596 | |
| Cost of inventories | Inventory quantity | -0.053 | |
| Total | | 1.578 | 0.882 |

**note that module area in this normalization includes all the corresponding mounting and support structure.*

Fig. 2a shows the amount of end-of-life modules for recycling and inventory in each period.

In the first 7-8 years, the quantity of retired modules would be much less than those in the following years, and careful planning would be needed to manage recycling capacity. A second designing plan considers for the continuity of the operation, and is compared to the original one.

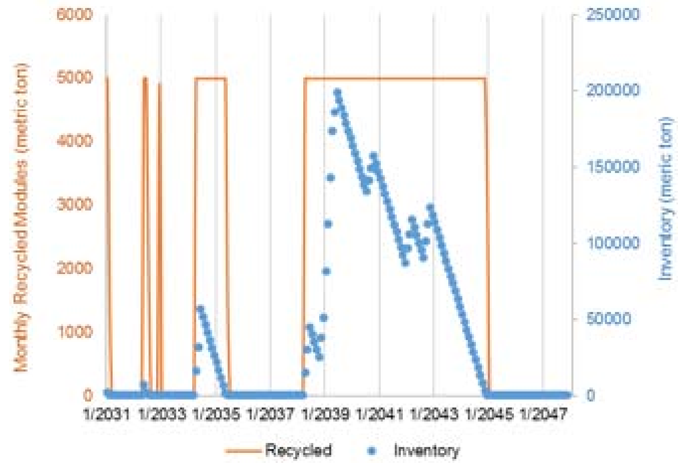


Figure 2a. Quantity of inventory and recycling in base scenario

As shown in Fig. 2b, the recycling plant will be constructed in 3 phases. Starting with a small capacity of 8,000 ton/yr, the plant will expand to 30,000 ton/yr after 3 years, then finally increased to its max capacity of 60,000 ton/yr in 2038, when numerous modules are imported into the plant. The inventory cost will correspondingly increase by 15%.

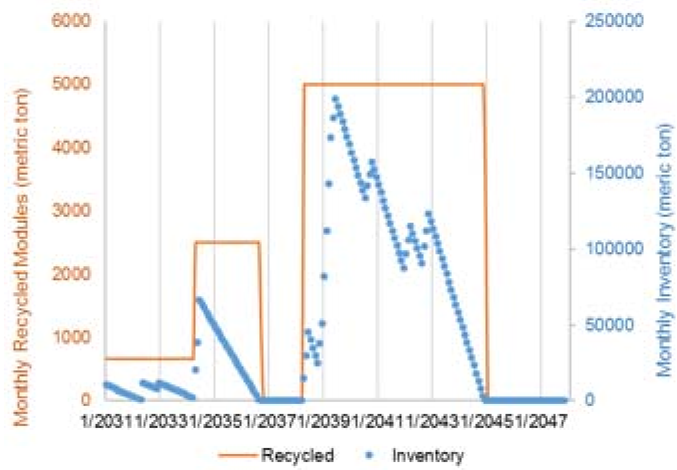


Figure 2b. Quantity of inventory and recycling in 3-phase mode

First Solar has a development plan on designing a smaller and mobile recycling facility[9], which could minimize the transportation costs and could become a solution for the operational continuity problem during the early low recycling volume period.

The on-site reclamation cost could vary with location, especially the digging cost for the buried cable. In the case where most of the wires in the PV system are buried underground, reclamation plans may assume that part or all of copper may be abandoned. However, as discussed below, we found considerable value in digging out and recovering underground cables. From the specifications of the target 12 solar farms, we estimated the potential revenue of digging out the end-of-life cables.

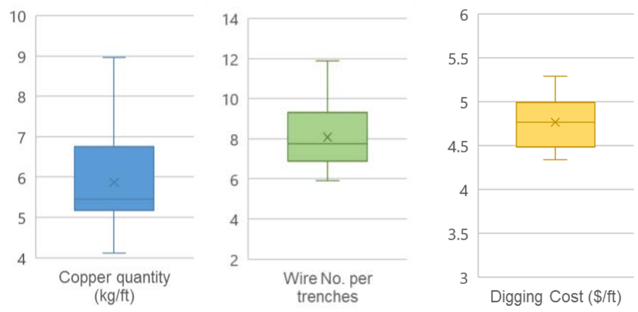


Figure 3. Box plots on the copper quantity, wire number and digging cost of buried cable

As shown in Fig. 3, every foot of underground cable conduits contains about 8 cables accounting for about 6 kg of copper. Consider the copper scrap price is between 50% to 95% of its metal price [10], then in most cases the revenue is profitable. Besides, some local authorities require the removal of underground structure. Thus, in the base scenario, we assumed that 100% of the buried cables will be removed and recycled.

## IV. Uncertainty Analysis

### A. *Plant capacity*

As discussed in the previous part, the capacity of the recycling plant not only affects the inventory cost on imported modules, but also affects the continuity of its operation. Besides, it may also be restricted by regulation on the maximum storage year of waste. Two operation modes, referring to the 1-phase and 3-phase modes respectively, were discussed in the base scenario. The sensitivity of the capacity is analyzed accordingly in Table IV.

However, the capacity has a great impact on the max storage time. In the base case, it takes no more than 2 years to recycle a group of imported modules, while with a disposal capacity of 70,000 metric ton/yr it takes only 1 year. Besides, it saves more than 1 million dollars for storage while it also costs more on the initial capital investment. Of course, the choice of capacity should also be based on the potential CdTe solar projects in the future.

Respecting to the continuity of operation, the 3-phase mode (Fig. 2b) performs much better than the 1-phase mode (Fig. 2a), despite the relatively higher inventory cost.

TABLE IV
Sensitivity Analysis on Recycling Capacity

| Capacity (ton/yr) | Operation Mode | Inventory Cost | | Max. Storage year | Intermittent Interval (months) | Net Revenue ($/module) |
|---|---|---|---|---|---|---|
| | | $/module | Additional cost (over base scenario) | | | |
| 70000 | 1-phase | -0.039 | -$632,367 | 1.1 | 69 | 1.592 |
| | 3-phase | -0.049 | -$180,676 | | 18 | 1.583 |
| 65000 | 1-phase | -0.046 | -$316,184 | 1.5 | 67 | 1.585 |
| | 3-phase | -0.055 | $90,338 | | 18 | 1.577 |
| 60000 | 1-phase | -0.053 | $0 (Base) | 2.0 | 66 | 1.578 |
| | 3-phase | -0.062 | $406,522 | | 18 | 1.569 |
| 55000 | 1-phase | -0.063 | $451,691 | 2.6 | 64 | 1.569 |
| | 3-phase | -0.070 | $767,875 | | 18 | 1.561 |
| 50000 | 1-phase | -0.073 | $903,382 | 3.3 | 62 | 1.558 |
| | 3-phase | -0.080 | $1,219,565 | | 18 | 1.551 |

### B. *Recovery value*

The reselling prices of recycled materials determine the revenue of recycling, which is a most influential factor in the cost structure. Identifying the most sensitive material helps the company make better choices and increase the profit.

In the sensitivity analysis, the total cost is re-calculated when the selling price or disposal fee of a recovered material is increased by 10%. A comparison among different materials is shown in Fig. 4, with the higher recycling revenue associated with copper and steel under both scenarios with/without cable trays. The variation of the revenue caused by the selling price of the recovered materials is considerable. Tellurium has by far the highest recovery value per unit mass, so it will be less influenced by transportation costs. .

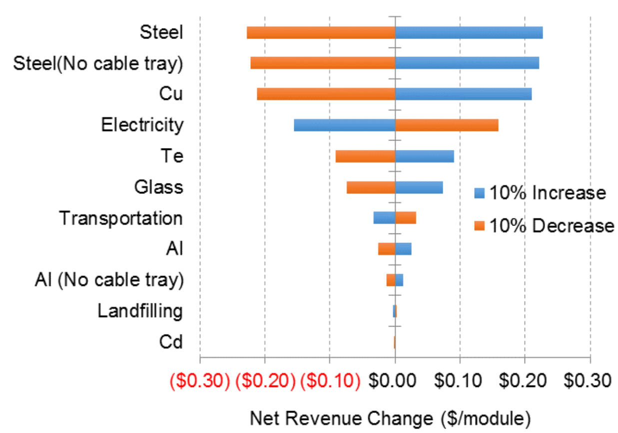


Figure 4. Net revenue sensitivity analysis assuming a 10% fluctuation in each material price or processing cost

The market price varies substantially, especially for metals, so we investigated the sensitivity of net recycling revenue to changes in the prices of the recovered materials. Fig. 5 shows the results of a low price and a high price sensitivity scenario. In the low-price scenario, the market price was set to 50% of its value in the basic scenario, and in the high price scenario it was set to 150%. From these results, we see that the recycling process could be very profitable when the market prices for the recovered materials are relatively high, and aluminum is a major contributor to this profit.

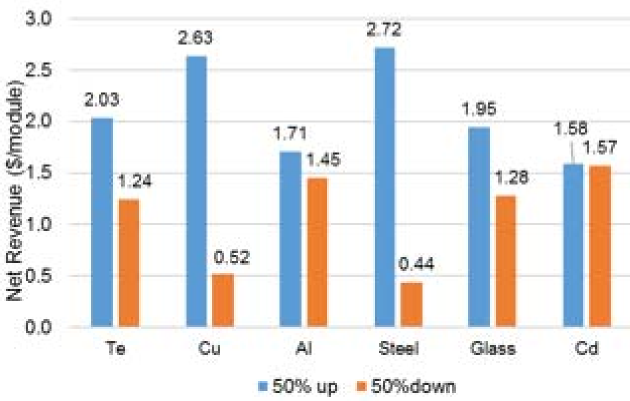


Figure 5. Net revenue sensitivity analyses assuming a +/-50% change in each material price under cable tray scenario

*5.3 The recovery rate of buried cables and digging cost*

It is helpful to see how the recycling revenue changes with the recovery rate of buried cables and the related digging cost, since copper substantially contributes to the profit. Table V provides the net revenue under different recovery rates and cost referring to buried cables.

TABLE V
SENSITIVITY ANALYSIS ON DIGGING COST AND RECOVERY RATIO ($/module area)

| ($/MWac) Cost / % Recovery | 4,000 | 6,000 | 8,000 | 10,000 | 12,000 |
|---|---|---|---|---|---|
| 100% | 1.133 | 1.008 | 0.882 | 0.756 | 0.630 |
| 75% | 0.641 | 0.547 | 0.453 | 0.358 | 0.264 |
| 50% | 0.149 | 0.086 | 0.023 | -0.040 | -0.103 |
| 25% | -0.344 | -0.375 | -0.407 | -0.438 | -0.470 |
| 0% | -0.836 | | | | |

The recovery of underground cables would be profitable since each foot of trench contains copper wires valuing $24-52, while the digging cost is only around $5/ft assuming depths of 2-4 ft. However, recovery of buried copper may not be accounted for in PV decommissioning plans.

## VI. CONCLUSIONS

From the result of the optimization model, the whole recycling process could make a profit of up to $1.58 per module, the major revenue coming from the copper, steel and aluminum of the module mounting and support.

The cost varies with the fluctuation in the quantity of incoming modules and structures. The selling prices of recovered materials, especially steel, Cu and Al also greatly affect the net revenue from recycling. Based on our preliminary results and discussion the following suggestions for reducing the cost of recycling are made:

Regional transit centers could be set up. A transit center would serve as a buffer between solar plants and a recycling plant, making its operation more stable. Also, with a transit center, the recycling plant could control its inventory level and rate of processing to minimize the total cost.

In the cost model, the revenue could also be time related. As shown by sensitivity analysis the influence of market prices could be significant; thus, it will be useful to simulate the effect of market fluctuations.

## ACKNOWLEDGEMENT

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