A Model for Optimization of PV Recycling Planning

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Graphic credit: EPIA
DfE & Lifecycle of PV

Design for Environment

- Raw material
- Upstream Mfg
- Mfg & Assembly
- Wafer
- Cell
- Connections
- Module
- Use
- End of Life
Recycling R&D at BNL: CdTe and CIGS PV Modules

Did You Know?
Silicon can be reclaimed and reintroduced into cell production.

Cells

Discussion
Should a module take back system be mandatory?
Yes

About Us
At pv recycling, llc we work with photovoltaic module manufacturers to develop take back and recycling infrastructures for damaged, defective, and degraded modules. Through this collaboration we promote...
How to plan for setting up efficient PV recycling infrastructure?
Large Solar Plants (current & planned)

Graphic credit: Photon Magazine
Where to locate collection, dismantling and shredding centers to optimize the cost?

- Density of population, insolation
- Third party reverse logistics company?
- PVTBC in manufacturing facilities?
- Stand alone near to installation site?

How to utilize current recycling infrastructure of other product parallel to PV recycling?

How to maximize the revenue and/or minimize the cost of recycling plant?
Max. Revenue and Min. Cost => Max Profit

- Type of PV to be recycled
- Market value of the reclaimed raw materials
- Volume of being recycled
- Economics of the hazardous waste management
- Variation of landfill tipping fees
- Shipping methods
- Processing costs
- Inventory
- Capital, labor, other
There are various current PV manufacturing technologies

New state-of-art technologies to market

- DOE: Technology Pathway Partnership, Next Gen. PV, PV Tech Incubator, Energy Innovation Hubs
- NREL incubator program
- Stimulus money

Development of new recycling technologies should be parallel to rapid trend of new PV manufacturing technology
PVTBC will face challenging material separation decisions

Must evaluate the trade-offs b/w different cost and revenue structures

PVTBC will need quantitative tools to evaluate the optimal level of processing

Computationally tractable generic model to provide sensitivity analysis on key parameters

Encourage research opportunities for technology, recycling process design, and controls.
First Solar's recycling process

Collection:
The modules are collected in containers and loaded into a shredder using a forklift.

Shredder:
In the first step, the solar modules are shredded coarsely.

Hammer mill:
A hammer mill is used to break the module debris into around 4-5 mm pieces. This separates the laminate foil layer from the glass.

Film removal:
The semiconductor layer is removed in a leaching process inside a slowly turning stainless steel drum. At the start of each leaching process, sulfuric acid and hydrogen peroxide are added to dissolve the Caffe.

Precipitation:
The separated metal components are purified in a three-stage precipitation system and then concentrated. The resulting filter cake is given to a third party for metal recycling. The remaining metals are used in commercial products or new solar modules.

Glass rinsing:
The glass is washed to remove all the remaining semiconductor material residue on the glass.

Separation of glass and lamination materials:
Glass and larger pieces of EVA foil, which previously held together both sections of the module's glass, are separated in a vibrating sieve.

Removal of solid and liquid materials:
The content of the drum is slowly fed into a solid-liquid separation unit. The solid material is brought to the surface by a rotating screw, while the liquid remains in the unit.

Graphic credit: Photon Magazine
Process flow for modeling

Waste Module
Unloaded from Truck
k=1

k=2 Shredder

k=3 Hammer Mill

Water

H₂SO₄
H₂O₂

NaOH

k=4 Film Removal

k=5 Solid-Liquid Separation

k=6 Precipitation

k=7 Dewatering

k=8 Glass EVA Separation

k=9 Glass rinsing

k=10 Filter waste

k=11 Glass, other waste

k=12 EVA

k=13 Glass Cullet

j=1

j=2

j=3

j=4

j=5

j=6

j=7

j=8

j=9

j=10

j=11

j=12

j=13

j=14

j=15

Na₂SO₄ (Waste water treatment)

Filtercake CdTe

Smelter

Market

Landfill

EVA

Landfill

Glass Cullet

Dust (PM size)

Need Cleaning

To Recycler

Collection site

EOL PV

PV Module
Objective function

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

- Revenue from output materials
- Cost of incoming modules
- Processing cost
- Inventory cost of incoming modules

Subject to
- Material flow balance (incoming, transition, outgoing materials)
- Capacity limit of equipment
- Minimal inventory setup
Scenarios are analyzed with variations of following:

- Cost of Incoming PV module
  - Freight, packaging, labor costs
- Shipping costs
  - Transportation to landfill, labor costs
- Market price of CdTe filter cake
- Market price of glass cullet
- Landfill tipping fees

GAMS¹ (General Algebraic Modeling System) is used.

¹http://www.gams.com/
Variation of Landfill Tipping Fees

- **U.S.:** Average Landfill tipping fee in the US is $34/ton
- **Germany:** $300-$400/ton
- **U.K.:** $15-$40/ton
- **Vermont:** $65/ton
- **Wyoming:** $10/ton
- **Japan:** $200/ton
- **S. Korea:** $100/ton
# of Scenario
$2^5 = 32$

Decision Tree

- **Incoming PV module cost**
  - $0.3 / kg
  - $0.05 / kg
  - $0.02 / kg

- **Shipping cost**
  - $0.05 / kg

- **Landfill tipping cost**
  - $0.01 / kg

- **Market price of CdTe**
  - $0.02 / kg
  - $0.05 / kg

- **Market price of glass cullet**
  - $0.172 / kg
  - $0.3 / kg
  - $2.12 / kg
  - $0.167 / kg
  - $0.325 / kg

Base Scenario

Scenario #
**Sensitivity Analysis**

Total: 672 tons  
Module/month: 58195

Recycling Profit

<table>
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<tr>
<th>Scenario #</th>
<th>(Cents / W)</th>
<th>$/month</th>
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<tbody>
<tr>
<td>1</td>
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<tr>
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<td>0.67</td>
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<td>17</td>
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</tbody>
</table>

- 1: Base scenario  
- 2: Higher glass cullet price  
- 3: Higher CdTe price  
- 5: Higher Landfill tipping fees  
- 9: Higher shipping cost  
- 17: Higher cost for incoming PV
Profit breakeven point for scenario 17 with variation of incoming module cost.

PVTBC will remain profitable as long as the total incoming module cost does not exceed this value.
Performed a preliminary study of recycling processes

Created a mathematical model for analyzing the profitability of recycling technologies

Intend to extend this model for building a general framework of various type of PV recycling planning.
Intelligent Design

Washington Post, March 30, 2005
What will be the relationship among
- Environmental system
- Economic system
- Engineered system
- Human (as final consumer or labor input)

Need of integrated multiscale modeling
- Enables to analyze the effect of change in one system to another
- In various spatial and temporal scale
Network between Systems

Solar Energy

Ecosystem
- Lithosphere
- Atmosphere
- Biosphere
- Hydrosphere

Natural Resources as raw materials

Emission

Impact of emission on human health

Economy
- Final Demand
- Value Added

Human Resources

Ecosystem impact due to anthropogenic emissions

Consumption of natural resources (O$_2$ in air)

Emissions (CO$_2$ in respiration)

Engineering
- Product System Level design
- Process System Level design

Product
Commodity

Recycling

Eco-design
Future Research

- Analyze the effect of *policy* in the macro economy level to the PV industry through *Multiscale Integrated Analysis*.

- Analyze the *macro-level PV waste flow* through World Input-Output Model.

- *Hybrid input-output LCA* for analyzing the effect of recycling to the reduction of resource uses and emissions.
Thank you