PHOTOVOLTAIC RECYCLING PLANNING: MACRO AND MICRO PERSPECTIVES

Jun-Ki Choi\(^1\) and Vasilis Fthenakis\(^2\)

\(^1\) Assistant Professor, University of Dayton, USA
\(^2\) Professor, Columbia University and Brookhaven National Laboratory, USA

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Disclaimer: results shown in this presentation do not represent views of any industries and associations
Motivation

- **PV industries will face challenging material separation decisions**
  - Volume of defective and EoL module is increasing
  - Various cell & module production technologies
  - Fluctuation of material prices
  - Environmental legislations

- **Must evaluate the trade-offs between different cost and revenue structures**
  - Spatial and temporal issues
  - Dynamic modeling is required

- **PV Take Back Center (PVTBC) will need quantitative decision tools to evaluate the optimal level of processing**
  - Encourage research opportunities for technology, recycling process design, and controls.
Waste Scenarios (Germany only)

- German Installation Data, Photon Magazine
- Market share data
- EPIA Solar Gen V
- EPIA Outlook 2013 policy-driven data
- Assumptions
- Life Span
- Manufacturing scrap
- Breakage (packaging, transportation, Installation)
- Collection rates
Time Horizon for PV Recycling Infrastructure Planning

This presentation focuses on...
short term planning + recycling of c-Si + manufacturing scrap only +
as of 2010
Economic challenges of PV recycling

1. **Macro level: Logistics/transportation:** Where to locate the recycling center?
   - How many PV take back centers needed
   - Efficient routing/ logistics
   - Optimized location

2. **Micro level: Recycling Process:** How to maximize the revenue of each recycling plant?
   - Cost and benefit of process improvement
   - Fluctuation of Incoming module and market price of materials

- Generic mathematical models are developed
Logistics Study: German PV Manufacturing Cluster

90% c-Si PV mfg
General model for optimal PVTBC location

- MILP
- Objective function: minimize the total system cost

\[
\min \quad z = \sum_{i=1}^{I} \sum_{j=1}^{J} (\tau_{ij} + \kappa_{ij}) X_{ij} + \sum_{j=1}^{J} f_j \Lambda_j
\]

s.t. constraints

- Determine the optimal locations of PVTBCs by optimizing the economic trade-off of:
  - Max. capacity of a designated PVTBC
  - Capital cost to open up PVTBC
  - Distance, Transportation cost, fuel price, labor, service fee..
  - Amount of incoming waste

Amount of PV waste generated from each facility for 5yrs
What if: Single sole PVTBC case – no optimization
Optimization results: selection of PVTBC candidates

Model allocates optimal locations:
Decision is based on the quantity of manufacturing scraps from each collection points and the distances between the collection points to recycling points, subject to capital cost constraints.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Capital cost/PVTBC (SK)</th>
<th>Annual capacity/PVTBC (tonne)</th>
<th>Total reverse logistics cost (SK)</th>
<th>Optimal system cost (SK)</th>
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<tbody>
<tr>
<td>S1</td>
<td>4,000</td>
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Selected PVTBCs:
- S1: R16
- S2: R13 + R15
- S3: R12 + R14 + R15 + R16
- S4: R1 + R6 + R7 + R13 + R14 + R15 + R16
Emission reduction from transportation

### TABLE 1. Optimization Scenario

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### TABLE 2. Emission and Global Warming Potential of Four Scenarios

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<tr>
<th>Scenario</th>
<th>Total travel (1000 km)</th>
<th>CO₂ (tonnes)</th>
<th>CH₄ (kg)</th>
<th>N₂O (kg)</th>
<th>Total GWP (tonne-CO₂eq)</th>
</tr>
</thead>
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<tr>
<td>S1</td>
<td>1,283</td>
<td>82</td>
<td>345</td>
<td>302</td>
<td>180</td>
</tr>
<tr>
<td>S2</td>
<td>625</td>
<td>54</td>
<td>226</td>
<td>198</td>
<td>118</td>
</tr>
<tr>
<td>S3</td>
<td>346</td>
<td>22</td>
<td>93</td>
<td>82</td>
<td>49</td>
</tr>
<tr>
<td>S4</td>
<td>275</td>
<td>18</td>
<td>74</td>
<td>65</td>
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PV recycling process planning

Photo credit: K. Wambach et al. 2010, IEA Hamburg
Crystalline Silicon Recycling Process (Solar World Automated Plant)

- **Auto feeder (k=1)**
  - Logistics company deliver modules from various collection points
  - j=1 (bal 1,1 =1)

- **Separation of junction box (k=2)**
  - j=2 (bal 2,2 =0.9767)

- **Thermal Treatment (k=3)**
  - j=3 (bal 3,2 =0.0233)

- **Automatic Loading System**
  - Automated Sorting System

- **Automatic Separation (k=4)**
  - j=4 (bal 4,3 =0.8724)

- **Advanced Chemical Process**
  - j=5 (bal 5,3 =0.1043)

- **Chemical treatment (k=5)**
  - j=6 (bal 6,4 =0.0210)
  - j=8 (bal 8,4 =0.6206)
  - j=9 (bal 9,4 =0.1754)

- **Waste**

- **Silicon**
  - j=7

- **Glass**
  - j=11

- **Aluminum Frame**

- **Copper Wire**

- **Plastic**

- **Junction box**

Steps:
- k=1 Auto feeder
- k=2 Separation of junction box
- k=3 Thermal Treatment
- k=4 Automatic Separation
- k=5 Chemical treatment

Balances:
- bal 1,1 =1
- bal 2,2 =0.9767
- bal 3,2 =0.0233
- bal 4,3 =0.8724
- bal 5,3 =0.1043
- bal 6,4 =0.0210
- bal 8,4 =0.6206
- bal 9,4 =0.1754
- bal 10,4 =0.01
- bal 10,4 =0.01
- bal 10,4 =0.01
- bal 10,4 =0.01
General model for recycling process

- LP

Max.

\[
\sum_{t=1}^{T} \sum_{i=1}^{I} \sum_{k=1}^{K} \sum_{j=1}^{J} \alpha_{j_k} \Omega_{ijkt} - \sum_{t=1}^{T} \sum_{i=1}^{I} \pi_{it} \omega_{it} - \sum_{t=1}^{T} \sum_{i=1}^{I} \sum_{k=1}^{K} c_k \tau_{ik} \Psi_{it} - \sum_{t=1}^{T} \sum_{i=1}^{I} \sigma_{i} \pi_{it} \Lambda_{it}
\]

- Subject to
  - Material flow balance (incoming, transition, outgoing materials)
  - Capacity limit of equipment
  - Minimal inventory setup

- GAMS (General Algebraic Modeling System) is used.

Key parameters

- Exogenous parameters
  - Cost of incoming upstream modules
  - Shipping costs for downstream materials
  - Market price of materials
  - Secondary handling fees

- Endogenous parameters
  - Capacity of equipment
  - Processing time
  - Processing costs (thermal, mechanical, chemical and automated treatments)
  - Capital and labor costs (hourly or annual salary based)

- Experimental Design
  - Sensitivity analysis for comparing different scenarios
Cost Benefit Sensitivity Analysis

@ 10% increase

Material | Market price ($/kg)
--- | ---
Glass | 0.07
Al | 2
Cu | 7
Si | 2.5

Conclusion

- Models are developed for a near-term (2010-2015) forward analysis of recycling manufacturing waste from c-Si PV production facilities in Germany.

- Real process model can be readily developed for various technological scenarios by using real data.

- Logistics modeling can be extended to larger geographical area (i.e. EU, USA).

- Detailed downstream modeling is necessary for future works (i.e. optimizing shipping of reclaimed materials and waste).

- Work is in progress on developing an integrated framework that can guide policy planners/non profit organization who wish to set up an economically feasible PV recycling infrastructure in any region.
Thanks for your attention

BNL
Long Island Solar Farm – 32MW

Jun-Ki Choi
Contact: jchoi1@udayton.edu