Evolution of First Solar’s Module Recycling Technology

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First Solar’s Long-Standing Leadership and Commitment to Recycling

• Established first global and comprehensive module recycling program in the PV industry in 2005

• Only PV company offering globally available high-value recycling

• Recycling facilities are operational in all manufacturing plants

• Scalable to accommodate future high volumes — ~48,000 metric tons recycled to date

• Continuously improving processes and technology and reducing operational costs

First Solar is the industry leader in responsible module end-of-life management.
First Solar Product Development Approach

• Striving for continuous improvement of our technologies and ensuring recyclability
• Recyclability is fully integrated in module design
• Budgets for the product development projects include recycling process upgrades
• All technology improvement projects are tracked through CMS (Change Management System)
• Development Engineering Projects are gated through several phases of their development
• Module improvement projects require timely implementation of recycling process upgrades
Recycling Technology
First Solar’s Module Recycling Technology – Version 1

Warranty End-of-Life/Manufacturing Module Scrap

Dry Process

Shredder → Hammermill → Semiconductor Material Dissolution → Solid-Liquid Separation

Precipitation

Dewatering

Glass Rinsing

Glass-Laminate Material

Clean Glass

Unrefined Semiconductor Material (USM)*

Laminate Material Separated from Glass

Wet Process
Third Party Refining Process to Semiconductor Grade CdTe

- Size Reduction
- Pulping
- Main Leach
- Copper Treatment
- Tellurium Reduction
- Cadmium Precipitation

- TeO₂ to Electro-winning
- Cd(OH)₂

USM
Product Recovery and Quality

• Up to ~90% of the module weight is recovered; most of this is glass.
  - Glass will be reused in new glass products

• Estimated recovery of Te and Cd is up to ~95%
  - The unrefined semiconductor material is packaged for further processing by a third party recycling partner to create semiconductor material for use in new modules.

• Material which is not able to be recovered is disposed of in accordance with waste disposal requirements, e.g., laminate.
First Solar’s Recycling Process Design Progression

**V1 Recycling (2006)**
- Based on the mining industry
- Batch process
- **Moving glass and liquid from process to process**
- Volume output – 10 tons/day
- Capital investment - $5M

**V2 Recycling (2011)**
- Based on the chemical industry
- Batch process
- Based on keeping the glass fixed and moving the liquids thru the material
- Volume output – 30 tons/day
- Capital investment - $7M
First Solar’s Module Recycling Technology – Version 2

~ 95% recycling of semiconductor material
~ 90% recycling of glass
The Future of PV Recycling

- **3rd generation continuous process recycling**
  - More efficient 7/24 operations
  - 30 tons/day capacity
  - Higher quality USM
  - Targeting costs below hazardous waste disposal by 2015

- Recycling facilities will be smaller and mobile by 2027
  - In-country recycling will minimize transportation costs

- **4th generation high volume recycling**
  - 350 tons/day capacity for large markets
First Solar Recycling Relative Cost Trend

- Recycling Process Relative Cost
- Recycling Production (MT/Wk)

Continuously Driving Down Costs for Sustainable PV Recycling

- V1
- V2
- V3
- V4
- V-Mobile


Normalized Recycling Process Cost

Recycling Production Volume (MT/Wk)
Life Cycle Benefits of CdTe PV Module Recycling

- Recycling requires energy and materials
  - This increases the life cycle environmental impact of CdTe PV
- Recycling produces products (copper, glass, CdTe)
  - This displaces primary sources of these products
  - This is counted as environmental credit
- The credits are greater than the impacts
  - The net impact is beneficial

<table>
<thead>
<tr>
<th>Process</th>
<th>Value</th>
<th>Unit per module m²</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Materials and Fuels</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transport (20 tonne truck)</td>
<td>11.2</td>
<td>tonne-km</td>
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<tr>
<td>Recycling electricity</td>
<td>4.4</td>
<td>kWh</td>
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<tr>
<td>Sulfuric acid</td>
<td>0.083</td>
<td>kg</td>
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<tr>
<td>Deionized water</td>
<td>5.4</td>
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<tr>
<td>Hydrogen peroxide (50% in water)</td>
<td>0.57</td>
<td>kg</td>
</tr>
<tr>
<td>Sodium hydroxide (50% in water)</td>
<td>0.10</td>
<td>kg</td>
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<tr>
<td><strong>Emissions</strong></td>
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<tr>
<td>Cd emissions to air</td>
<td>5.89×10⁻⁹</td>
<td>kg</td>
</tr>
<tr>
<td>Cd emissions to water</td>
<td>8.92×10⁻⁸</td>
<td>kg</td>
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<tr>
<td><strong>Waste to Treatment</strong></td>
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<td></td>
</tr>
<tr>
<td>Disposal of plastics to municipal incineration</td>
<td>0.62</td>
<td>kg</td>
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<tr>
<td>Disposal of inert glass waste to inert waste landfill</td>
<td>0.13</td>
<td>kg</td>
</tr>
</tbody>
</table>

Socio-Economic and Environmental Benefits of High Value PV Recycling

• All PV technologies require responsible end-of-life management
  — Use of environmentally sensitive materials (Pb, Cd, As, In, Se) compounds are common in the industry
  — Reclaiming critical materials (Ag, In, Te) is important to long-term sustainability of PV

• High value recycling provides socio-economic and environmental benefits
  — Maximizes resource recovery and minimizes impact of environmentally sensitive materials
  — Reclaiming energy and carbon intensive materials (Si) reduces the life cycle impacts of PV
  — Inclusion of PV in the EU WEEE Directive is expected to yield ~ 16.5 billion EUR in 2050*

• Ambitious recovery targets which go beyond mass-based approach are needed

Ensuring Sustainable Supply of Raw Materials through Recycling

- Minimizing environmental impacts and maximizing resource recovery
- 10–50% of the Te needed for CdTe PV production could realistically come from EOL modules by 2040
- Material and conversion efficiency measures combined with recycling reduces tellurium demand per Watt peak
- “The CdTe-PV industry has the potential to fully rely on tellurium from recycled end-of-life modules by 2038”
  - Improvements in material efficiency
  - Scaling of efficient collection and recycling systems

Fig. 8. Tellurium feedstock in the “breakthrough” scenario.