A Voluntary Take Back Scheme and Industrial Recycling of Photovoltaic Modules

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Sources of secondary Silicon

- mc crystallization
- cz crystallization
- brick sawing
- other applications
- wafering
- Semiconductor industry
- cell processing
- Si with bulk impurities for remelting
- module assembly
Recycling of ingot parts

- cut off sides
- surface cleaning and etching
- cut off bottom and tops
- surface cleaning and etching

as received

after first treatment

multicrystalline ingot-growing: sides

shaping

surface cleaning

etching

crystallization: raw material
Recycling wafer and cell scrap

- Broken wafer
- Wafer with emitter and AR-Coating
- Cell breakage

Flowchart:
1. Removal of non-Si-impurities
2. Etching
3. Crushing
4. Etching
Green production policy

Sound environmental strategy

– Resource saving production and technologies
– Recycling of by-products along the value chain if possible
– Continuous adaptation to growing demands
– Careful selection of material for long lifetime, reparable and recyclable products
Added values

• Improvement of reputation of the PV community
• Additional feedstock
• Sustainable thinking creates shareholders value
• Cost savings by global standardisation
• Creation of an international environmental data base for PV
• Integration in EMAS /EN14000 certification
• Cost minimisation of waste treatment
• Ensures high quality standards of waste treatment
• Profitable international research cooperations
EU waste policy

Sustainable product design
  high ranking of durable, reparable products
  recycling of components (keeping the value)

Extended producer responsibility,
Polluter pays
therefore

Manufacturer obligation of taking back their products
  Si-wafer
  Silicon
  Silver and other valuable metals
  Glass
  Metal
Prerequisites of recycling

• Responsibility
  – Finance (polluter pays principle)
  – Legislation
  – Incentives

• Organisation
  – Management system
  – Logistics
  – Best available technology
  – Communication and education

• Resources and Environment,
  – External auditing
  – LCA
  – Transparency
End Of Life Modules

• Sources:
  – Manufacturing waste
  – Transportation
  – System assembly
  – Other defects
  – Spent modules

• Main defects
  – Broken glass
  – Electrical defects
  – Delamination
  – Other
### Assumptions

<table>
<thead>
<tr>
<th>Loss Type</th>
<th>Percentage</th>
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</thead>
<tbody>
<tr>
<td>Production losses</td>
<td>0.20%</td>
</tr>
<tr>
<td>Transport, and mounting damage, wrong system designs</td>
<td>0.50%</td>
</tr>
<tr>
<td>Cumulated losses in first 2 years</td>
<td>0.80%</td>
</tr>
<tr>
<td>Total (damages of new modules)</td>
<td>1.50%</td>
</tr>
<tr>
<td>Damage of installed systems (blanket estimation)</td>
<td>0.30%</td>
</tr>
</tbody>
</table>
Waste forecast

Year

[t]


Germany Total Europe USA Japan Rest of World

35,397 t 132,750 t
Objectives

- Promote the protection of the climate and the environment in enhancing increased and sustainable use of PV technology.

- Create a positive environment for the ongoing growth of the PV industry

- Install an overall waste management policy
  - guarantees highest economically feasible collection and recovery rates
  - appropriate treatment of waste PV modules.
Mixed system approach

- **Industrial waste**
  - Production
  - Transport
  - Installation
  - Replacement

- **End-user**
  - Free collection of systems > e.g. 2kWp
  - Bring in to installer small quantities
  - Other negotiable
Preconditions: high-value recycling

Avoid any unnecessary damage!

Dismount system carefully
Do not bend or break
Use standard packaging systems for transportation
Inform about materials and hazardous substances
Specify demands for material returned
<table>
<thead>
<tr>
<th>Thin film modules</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td><strong>Producer A</strong></td>
<td><strong>Producer B</strong></td>
<td><strong>Producer C</strong></td>
<td><strong>Producer D</strong></td>
<td></td>
<td></td>
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<tr>
<td>Recycling Fractions</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Glass</td>
<td>75.27</td>
<td>84.6</td>
<td>83.5</td>
<td>89.78</td>
<td></td>
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<tr>
<td>Aluminium</td>
<td>15.05</td>
<td>10.15</td>
<td>12.29</td>
<td>0.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indium</td>
<td>0.02</td>
<td>0.02</td>
<td>0.13</td>
<td></td>
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<tr>
<td>Copper (Cable)</td>
<td>1.51</td>
<td>0.85</td>
<td>0.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gallium</td>
<td>0.01</td>
<td>0.01</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recovery Fraction</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polymers</td>
<td>6.52</td>
<td>5.08</td>
<td>3.67</td>
<td>9.84</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hazardous</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.0005</td>
<td></td>
<td>0.1336</td>
<td>-</td>
<td>-</td>
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# Crystalline Si modules

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td><strong>Weight/kWp</strong></td>
<td>103.6 kg/kWp</td>
<td>102.3 kg/kWp</td>
</tr>
<tr>
<td>Glass</td>
<td>62.7%</td>
<td>74.16%</td>
</tr>
<tr>
<td>Frame (e.g. AlMgSi0.5)</td>
<td>22.0%</td>
<td>10.30%</td>
</tr>
<tr>
<td>EVA</td>
<td>7.5%</td>
<td>6.55%</td>
</tr>
<tr>
<td>Solar cells</td>
<td>4.0%</td>
<td>3.48%</td>
</tr>
<tr>
<td>Backsheet foil (Tedlar)</td>
<td>2.50%</td>
<td>3.60%</td>
</tr>
<tr>
<td>Junction box</td>
<td>1.2%</td>
<td></td>
</tr>
<tr>
<td>Adhesives</td>
<td>1.16%</td>
<td></td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>Rel. amount after Oekopol</th>
<th>Rel. amount (2007)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Metals and Si</strong></td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>Cu</td>
<td>0.37%</td>
<td>0.57%</td>
</tr>
<tr>
<td>Ag</td>
<td>0.14%</td>
<td>0.06 – 0.1%</td>
</tr>
<tr>
<td>Sn</td>
<td>0.12%</td>
<td>0.12 – 0.16%</td>
</tr>
<tr>
<td>Pb</td>
<td>0.12%</td>
<td>0.0 – 0.07%</td>
</tr>
<tr>
<td>Si</td>
<td>3%</td>
<td></td>
</tr>
</tbody>
</table>
Mechanical separation, laminated glass recycling
- High capacities available
- Very universal process, **cost benchmark**
- Impure fractions
- Hardly possible to sell
- Great dependency on module construction and materials used

Chemical and/or mechanical treatment
- Focus to thin film modules
- Costs of waste treatment of chemicals used
- Strong dependency on materials used

Thermal separation
- Very universal process, **cost benchmark**
- Material use, material separation
- Waste gas cleaning, dust removal

Waste incineration, smelters
- High capacities available
- Very universal process, **cost benchmark**
- Waste disposal of residues
Life Cycle Assessment
The recycling of modules was evaluated concerning its environmental effects by an LCA.
For all impact categories the disburden due to the reuse of silicon, metals and glass is higher than the burden of the environment due to the recycling process itself or a treatment in a waste incinerating plant, respectively a direct landfilling.

Recovery rates
waste incineration: 10 - 20%
Recycling: > 75%
Comparison of 3 waste treatment technologies

- abiotic depletion
- global warming (GWP100)
- ozone layer depletion (ODP)
- human toxicity
- photochemical oxidation
- acidification
- eutrophication

Options:
- highvalue recycling
- incineration
- simplified process
Recycling of Germany’s oldest PV system, “Pellworm”

- Double-glass modules with stainless-steel frames
- Cell type: Multicrystalline 100 x 100 x 0.4 mm
- Backsheet metallisation: Al (< 1 % Ag)
- PVB polymer lamination
- Ultrasonic welding of interconnectors
- Dimension: 460 x 560 mm
- Number of cells in module: 20
Second-generation systems

- 252,720 Wp have been recycled – 15,795 modules containing 315,900 cells (cell efficiency: 8 %) and 88 % of the original efficiency
- Total efficiency of six new systems: 237,788 Wp
- New cell efficiency: 12-14 %
- 3.3 tons of steel recycled
- 487 kg broken cells recrystallized into new silicon ingots
- 18 tons of glass returned into glass-recycling loop
Recycling of Chevetogne system

Installed in 1983 in Chevetogne: Belgium’s first PV system

- Double-glass modules with stainless-steel frames
- Cell type: 4-inch monocrystalline
- Backsheet metallisation: Ag
- EVA polymer lamination
- Soldered interconnectors
- Dimension: 460 x 800 mm
- Number of cells in module: 36
Recycling of 1,900 modules in Freiberg, 2009

<table>
<thead>
<tr>
<th></th>
<th>Input [kg]</th>
<th>Relative amount [%]</th>
<th>Output [kg]</th>
<th>Yield [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>5.93</td>
<td>65.82</td>
<td>5.75</td>
<td>96.96</td>
</tr>
<tr>
<td>Plastics</td>
<td>0.94</td>
<td>10.43</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Cells, broken cells</td>
<td>0.26</td>
<td>2.89</td>
<td>0.22</td>
<td>84.62</td>
</tr>
<tr>
<td>Cu</td>
<td>0.09</td>
<td>1.00</td>
<td>0.07</td>
<td>77.78</td>
</tr>
<tr>
<td>Al</td>
<td>1.58</td>
<td>17.54</td>
<td>1.58</td>
<td>100.00</td>
</tr>
<tr>
<td>Junction box</td>
<td>0.21</td>
<td>2.33</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Total</td>
<td>9.01</td>
<td>100.00</td>
<td>7.62</td>
<td>84.57 **</td>
</tr>
</tbody>
</table>

* Energy recovery

** Mixed components: 0.24 kg (2.66 %)
Current situation

Returned modules:
• Predominantly damaged products
• Dismantled frames
• Reduced valuable metal
• Wide variety of module types
• Reduced cell thickness
Rate of whole cells

Number of pieces

Cell thickness

180 µm

2007

2008

recovered cells
Requirements for new treatment

Reasons for need of new procedure
• Increasing volume of defective solar modules
• Declining recovery of whole cells
• Inefficiency of manual glass-cell-connector separation
• Wide product variety

Objectives of new process
• High recycling rates
• Valuable end product
• Cost efficiency

Key points of new procedure
• Removal of organic components in thermal process step
• Automated separation of components
• Advanced chemical process
Recycling of PV modules: New automated process

Sorting and classing

Chemical treatment

Crystallization

Thermal treatment

End of life

Used in new PV installation
Thermal treatment of modules at 600°C
Sorting and classing

After thermal treatment, separation of components

Frames
Ribbons
Glass
Chemical treatment of cell fractions to remove coatings
Use of purified cell fractions to make new ingots

<table>
<thead>
<tr>
<th></th>
<th>R [Ωcm]</th>
<th>LTLD [µs]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.08</td>
<td>4.29</td>
</tr>
<tr>
<td>2</td>
<td>1.21</td>
<td>4.77</td>
</tr>
</tbody>
</table>
Past and future recycling process of PV modules

Current Process
- Manual Feeding
- Thermal Treatment
- Manual Sorting

Delivered Modules
- 2007
- 2008
- 31.05.2009

Automatic Process
- Higher Throughput
- Automatic Feeding
- Thermal Treatment
- Automatic Classing and Sorting

delivered modules, expected
Environmental evaluation module recycling

Source of data: Ecoinvent-data base
Software: Sima pro
Method: CML baseline method 2000

- etching
- recycling of glass
- transport
- recovered silicon
- recycling of Cu
- landfill
- recycling of aluminum
- material separation

Graph showing the percentage reduction in various environmental impacts: abiotic depletion, global warming (GWP100), ozone layer depletion (ODP), human toxicity, photochemical oxidation, acidification, eutrophication.

Bar chart details:
- abiotic depletion
- global warming (GWP100)
- ozone layer depletion (ODP)
- human toxicity
- photochemical oxidation
- acidification
- eutrophication

Legend:
- yellow: etching
- green: recovered silicon
- blue: recycling of aluminum
- orange: material separation
- dark green: recycling of glass
- purple: recycling of Cu
- red: landfill
- brown: transport

Note: The chart does not show specific percentage values for each category, but it illustrates the relative reduction in environmental impacts.
Global Warming Potential (GWP100)

- Potscrap
- Wafer breakage
- Cell breakage
- Tops + bottoms
- Sides
- Material with metallic bulk impurities
- Silicon, solar grade

Greenhouse gases related to the recycling process (CO2-equivalent)
### Economy versus ecology

#### Best Ecological Benefit
- High product quality
- Good product quality
- Medium product quality

#### High Ecological Benefit
- Wafer breakage
- Partially processed cells
- Remelted mc silicon

#### Good Ecological Benefit
- Recycling of PV modules and solar cell breakage

<table>
<thead>
<tr>
<th>Range of cost according to yield [EUR/kg]</th>
<th>High Ecological Benefit</th>
<th>Good Ecological Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Wafer breakage</td>
<td>Recycling of PV modules and solar cell breakage</td>
</tr>
<tr>
<td>Low</td>
<td>Pot scrap</td>
<td>Remelted mc silicon</td>
</tr>
<tr>
<td>low</td>
<td>mc bottoms</td>
<td></td>
</tr>
<tr>
<td>high</td>
<td>mc sides</td>
<td></td>
</tr>
<tr>
<td></td>
<td>mc tops</td>
<td></td>
</tr>
</tbody>
</table>
Summary and outlook

• Modules can be recycled in industrial processes with a recycling quota up to 90% and more even today

• The take back and treatment systems must be economically and environmentally feasible utilizing best available practices and external auditing

• All module producers should commit to their extended responsibilities and become members of PVCYCLE Association or similar systems to be installed globally.

• Standardisation and best practice approaches can help saving money and obtain best results

• International cooperation is essential
Back in to the Sun!

Thank you for your attention!