CHALLENGES AND OPPORTUNITIES

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Growing PV panel waste represents a new environmental challenge, but also unprecedented opportunities to create and pursue new economic avenues.

This report presents global projections for future PV panel waste volumes to 2050 in two scenarios.

Policy action, R&D and supporting analyses are needed to address the challenges ahead; enabling frameworks can be adapted to the needs and circumstances of each region or country.

End-of-life management could become a significant component of the PV value chain and can spawn new industries, supporting considerable economic value creation.
KEY FINDINGS

Lessons can be learned from the experience of the European Union in developing its regulatory framework to help other countries move up the learning curve faster and adapt locally-appropriate approaches.

Considerable technological and operational knowledge about PV panel end-of-life management already exists in many countries. This can guide the development of effective waste management solutions, helping to address the projected large increase in PV panel waste.
The world’s total e-waste reached a record of 41.8 million metric tonnes in 2014. Annual PV waste was 1000x less in the same year. Yet by 2050, the PV panel waste added annually could exceed 10% of the record global e-waste added in 2014.
CUMULATIVE PV WASTE: TOP 5 REGIONS 2050

- China: 20 million, 13.5 million
- US: 10 million, 7.5 million
- Japan: 6.5 million, 7.5 million
- India: 4.5 million, 7.5 million
- Germany: 4.4 million, 4.3 million

2050: 78 million tonnes of PV panel waste globally
POTENTIAL VALUE CREATION

Cumulative PV capacity:

- **2030**
  - Cumulative PV capacity: 1,600 GW
  - Life cycle: Enough raw material recovered to produce 60 million new panels (equivalent to 18 GW)
  - Cumulative PV panel waste: 1.7 - 8 million tonnes
  - Cumulative Value Creation: USD 450 million alone for raw material recovery
    - New Industries and employment

- **2050**
  - Cumulative PV capacity: 4,500 GW
  - Life cycle: Enough raw material recovered to produce 2 billion new panels (equivalent to 630 GW)
  - Cumulative PV panel waste: 60 - 78 million tonnes
  - Cumulative Value Creation: USD 15 billion alone for raw material recovery
    - New Industries and employment

IRENA
International Renewable Energy Agency
As R&D and technological advances continue with a maturing industry, the composition of PV panels is expected to require less raw materials.

Rapid global PV growth is expected to generate a robust secondary market for panel components and materials.

As current PV installations reach the final decommissioning stage, recycling and material recovery will be preferable to panel disposal.
SOLAR PV PANEL WASTE PROJECTIONS
THE MODEL

Step 1

- a: Conversion of capacity (GW) to PV panel mass (mt)
- b: Estimation of PV panel losses (probability of failures during life cycle)

Step 2

- Regular-loss scenario modeling
- Early loss scenario modeling
THE MODEL

Empirical data on failure modes

- 6% Unknown defect
- 5% Optical failure
- 5% Delamination
- 10% Transport damage
- 19% Power loss
- 19% Defect cell interconnect
- 19% J-box and cables
- 10% Glass breakage

Probability Loss functions (Weibull curves) for PV panels

\[ F(t) = 1 - e^{-\left(\frac{t}{T}\right)^\alpha} \]

where
- \( t \) = time in years
- \( T \) = average lifetime
- \( \alpha \) = shape factor, which controls the typical S shape of the Weibull curve
THE MODEL

Model
Regular-loss scenario input assumptions
- 30-year average panel lifetime
- 99.99% probability of loss after 40 years
- extraction of Weibull model parameters from literature data (see Table 5)

Early-loss scenario input assumptions
- 30-year average panel lifetime
- 99.99% probability of loss after 40 years
- inclusion of supporting points for calculating non-linear regression:
  - installation/transport damages: 0.5%
  - within first 2 years: 0.5%
  - after 10 years: 2%
  - after 15 years: 4%
- calculation of Weibull parameters (see Table 5)

Data input and references
- The 30-year average panel lifetime assumption was taken from literature (Frischknecht et al., 2016).
- A 99.99% probability of loss was assumed as an approximation to 100% for numerical reasons using the Weibull function. The 40-year technical lifetime assumption is based on depreciation times and durability data from the construction industry (Greenspec, 2016).
- The early-loss input assumptions were derived from different literature sources (IEA-PVPS, 2014a; Padlewski, 2014; Vodermeyer, 2013; DeGraaff, 2011).
The scenarios portrayed here should be considered order of magnitude estimates and directional rather than highly accurate or precise, owing to the simple assumptions and lack of statistical data.

<table>
<thead>
<tr>
<th>Uncertainty I:</th>
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</thead>
<tbody>
<tr>
<td>Available data on PV panel failure modes and mechanisms</td>
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<table>
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<tr>
<th>Uncertainty II:</th>
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<tr>
<td>Time lag between failure and end-of-life phase</td>
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<tr>
<th>Uncertainty III:</th>
</tr>
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<tbody>
<tr>
<td>Probability of PV panel losses assumes state-of-the-art today and no learning curve</td>
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</tbody>
</table>

This study developed two scenarios – regular-loss and early-loss – to account for the above uncertainties. To refine estimates in the future, monitoring and reporting should yield better statistical data to strengthen waste stream forecasts.
THE RESULTS – EARLY-LOSS SCENARIO

- Mass of installed capacity (year)
- Mass of end-of-life PV panels (per year, early-loss scenario)
- Ratio of waste vs. installed mass (early-loss scenario)
THE RESULTS – REGULAR-LOSS SCENARIO
PV PANEL COMPOSITION AND WASTE CLASSIFICATION
# Panel Composition & Technology Trends

## C-Si

<table>
<thead>
<tr>
<th>Year</th>
<th>Material Composition</th>
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<tbody>
<tr>
<td>2014</td>
<td>Glass, Copper, Silver</td>
</tr>
<tr>
<td>2030</td>
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</tr>
</tbody>
</table>

- **2014**: Phase-out expected before 2030

## Thin Film

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- **2014**: Glass, Copper, Silver
- **2030**: Glass, Copper, Silver

**Legend**

- **Aluminium**
- **Copper**
- **Other Metals (Zn, Ni, Sn, Pb, Cd, Ga, In, Se, Te)**
- **Sealants**
- **Silicon**
- **Polymer**
- **Compound Semiconductor**
- **Silver**
- **Glass**
All PV Panel technologies contain trace amounts of hazardous materials such as lead, tin, zinc, cadmium, selenium, indium, gallium and others.

Depending on the jurisdiction, different waste characterization tests and methods can lead to different classifications of PV panel waste.

Typically, standardized leaching tests and material concentration limits determine the classification and minimum requirements for treatment and disposal.
PV PANEL WASTE MANAGEMENT OPTIONS
There are a variety of options for end-of-life management structures and financial responsibility: Extended Producer Responsibility, Polluter-Pays-Principle, Public-Private-Partnerships, B2B & B2C solutions.

- Physical and financial management systems
- Minimum Requirements & High Value Recycling
CASE STUDIES
CASE STUDIES span range of market and recycling infrastructure maturity
GERMANY – a mature market

Germany will clearly be one of the first and largest markets for PV recycling technologies in coming years.
UNITED KINGDOM – a young market

A market with almost no historic PV waste and mandatory EOL regulation from the beginning.
JAPAN – advanced market without PV specific waste regulations

A PV pioneer market with recent rapid growth potentially leading to a large increase in waste by 2040.
USA – established growing market without PV specific waste regulations

Voluntary collection and recycling of end-of-life PV has been provided by several PV industry stakeholders.
CHINA – leading market without PV-specific waste regulations

Because of China’s rapidly developing PV industry and market, PV Panel recycling is receiving more attention from government and producers.
The original National Solar Mission (JNNSM) target was recently increased to 100 GW by 2022 – progress towards this would increase projections.
VALUE CREATION FROM END-OF-LIFE PV PANELS
REDUCE REUSE RECYCLE

PV R&D has set priority topics for material use reduction or substitution for different components commonly used in today’s PV Panels

Recycling processes for thin-film and crystalline silicon PV panels have been developed and to some extent implemented on industrial scale, but more development is needed

Significant recovery potential for different material streams can be realized through high-value recycling
From a value standpoint, silver is by far the most expensive component per unit of mass of a c-Si panel – consuming today about 15% (incl. losses) of the global silver production. Reduction of this is a clear technology target.
RECYCLE – example processes for CdTe and C-Si

First Solar Recycling Process

Recycling Scheme proposed by NEDO/FAIS in Japan
Cumulative technical potential for end-of-life material recovery under regular-loss scenario.

- Glass: 965,100 mt
- Polymer: 101,300 mt
- Aluminium: 75,000 mt
- Silicon: 29,500 mt
- Copper: 7,200 mt
- Other Metals (Zn, Ni, Sn, Pb, Cd, Ga, In, Se, Te): 390 mt
- Compound Semiconductor: 310 mt
- Sealants: 120 mt
- Silver: 90 mt
EXTENDING THE VALUE CHAIN

**R&D Organisations**
- Public and private institutions
- Producers

**Repair/Re-use services industry**
- Producers
- Independent services partners
- Producer-dependent contract and service partners (e.g. installation and construction companies)
- Waste collectors and companies
- Pre-treatment companies

**Recycling treatment industry**
- Public waste utilities and regulators
- Waste management companies
- Pre-treatment companies
- Producers
CONCLUSIONS: THE WAY FORWARD
CONCLUSIONS

Enabling frameworks will play a central role in supporting sustainable end-of-life practices for PV – public sector institutions and the private sector should cooperate early to establish these.

A system-level approach to PV end-of-life management can enhance the integration of different stakeholders, including PV suppliers and consumers alike, as well as the waste sector.

R&D, education and training, and supporting data and analyses are all needed to support PV end-of-life management.

Stimulating investment and innovative financing schemes for PV end-of-life management is necessary to overcome financing barriers and ensure the support of all stakeholders.