Clean Energy States Alliance Webinar

Solar PV Recycling: Issues and Considerations for State Decision-Makers

August 23, 2018

Clean Energy States Alliance

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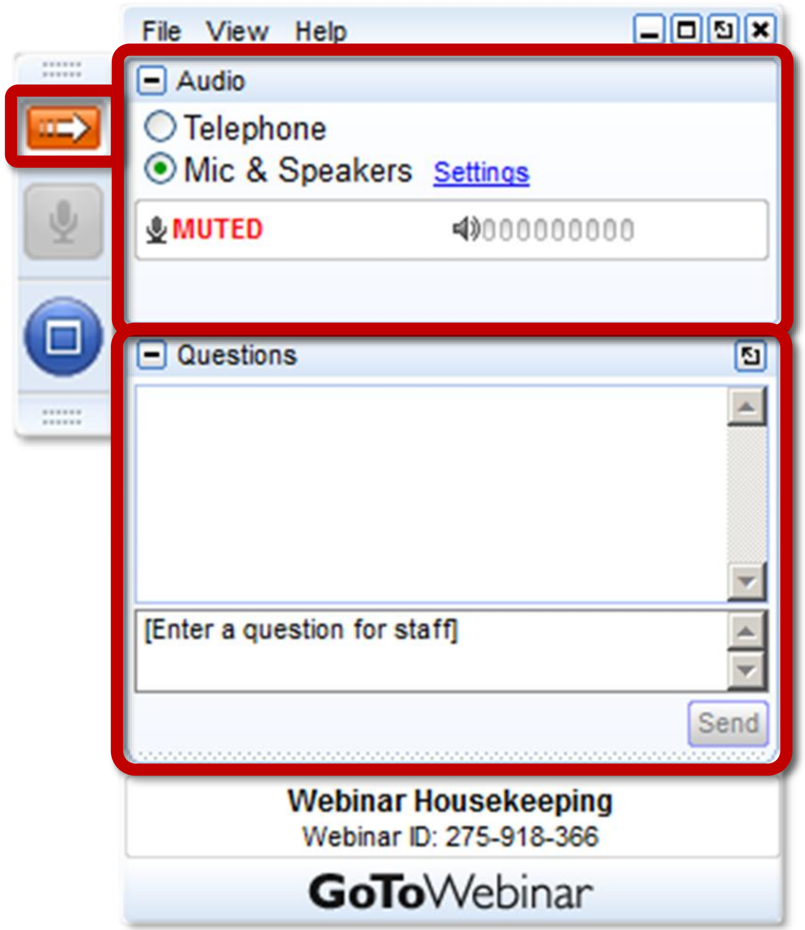

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- The Solar Technical Assistance Team (STAT) is a network of solar technology and implementation experts who provide timely, unbiased, credible, and obkectie expertise to assist poliymakers and regulators in making informed decisions about solar programs and policies

- STAT is a project of the U.S. Department of Energy Solar Energy Technologies Office that is implemented in partnership with NREL.

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https://www.nrel.gov/technical-assistance/states.html

Solar PV Recycling: Issues and Considerations for State Decision-Makers

Webinar Speakers

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States Alliance

NATIONAL RENEWABLE ENERGY LABORATORY

Clean Energy States Alliance

Solar PV Recycling: Issues and Considerations for State Decision-Makers

Garvin Heath, PhD

August 23, 2018

Disclaimer

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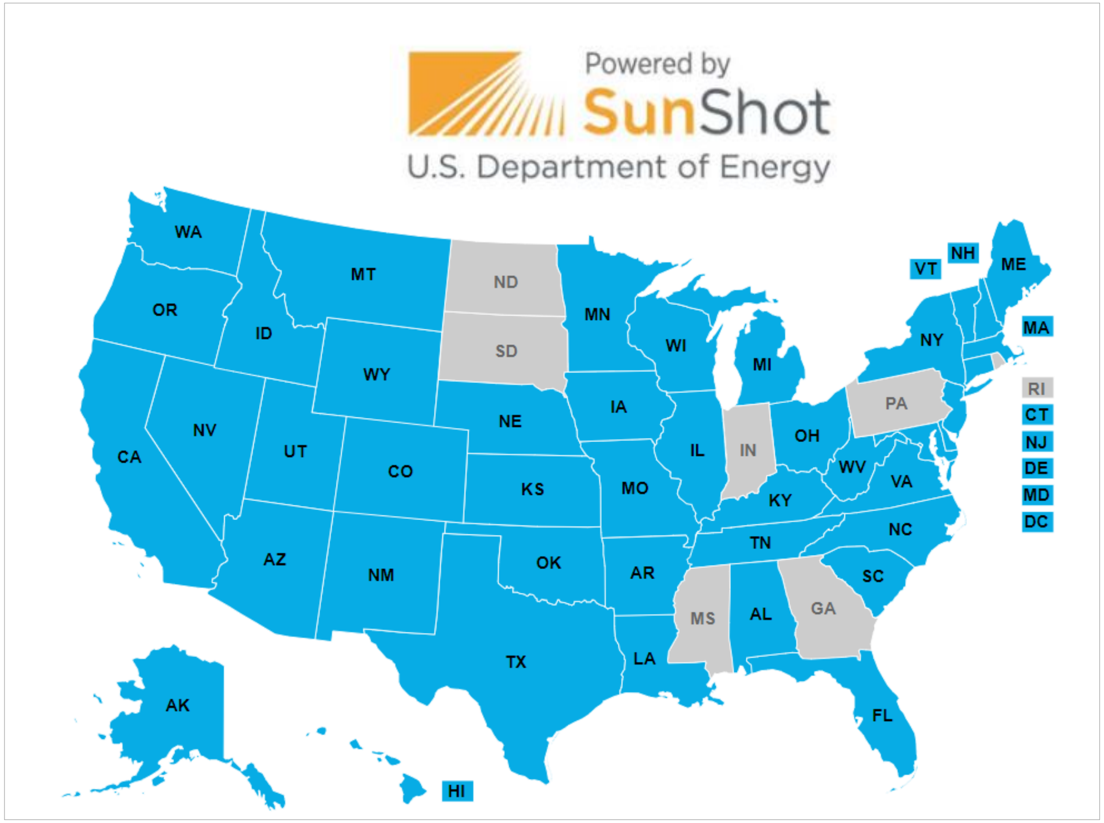

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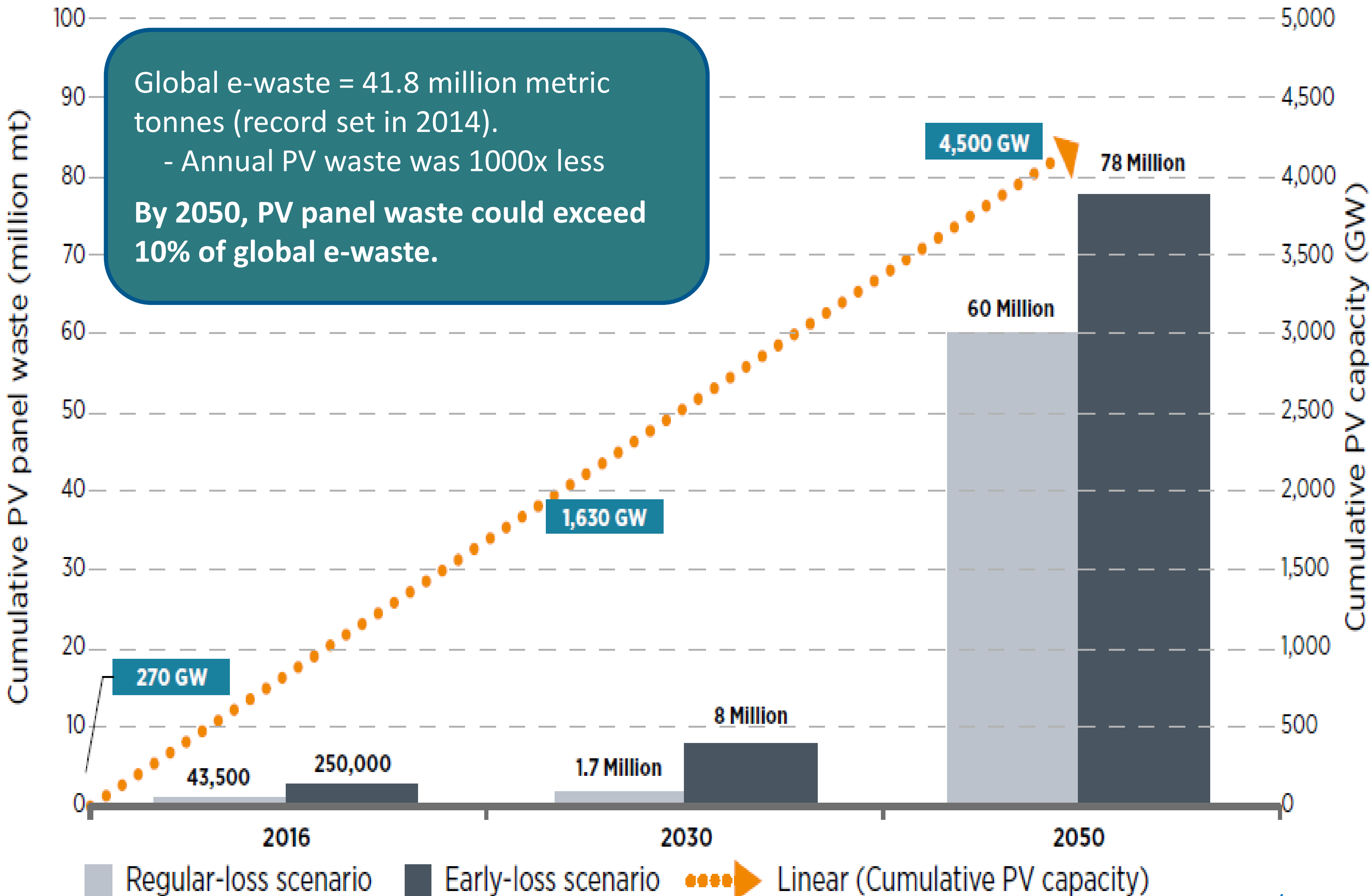
Outline

- Motivation and Need for Recycling of Photovoltaic Modules
- Value Creation and Manufacturing Sector Development Potential
- Challenges to Recycling
- Potential Synergistic Trends Enhancing Recycling
- Some Relevant International Research
- Information Gaps States Could Help to Fill

Low Volumes Now, PV Waste Will be Significant Challenge in Future

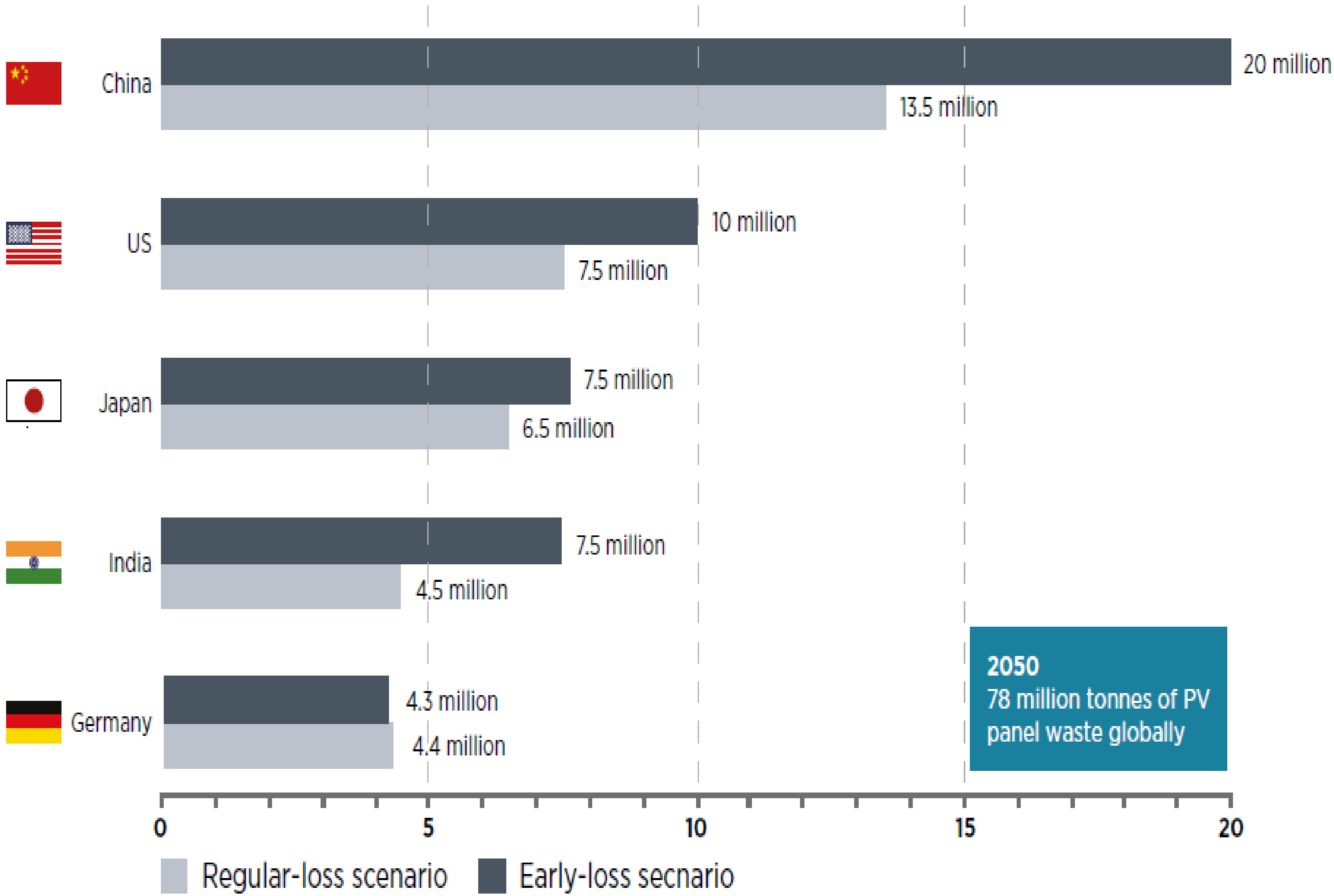
Global e-waste = 41.8 million metric tonnes (record set in 2014).
- Annual PV waste was 1000x less

By 2050, PV panel waste could exceed 10% of global e-waste.



Source: IEA/IRENA, 2016

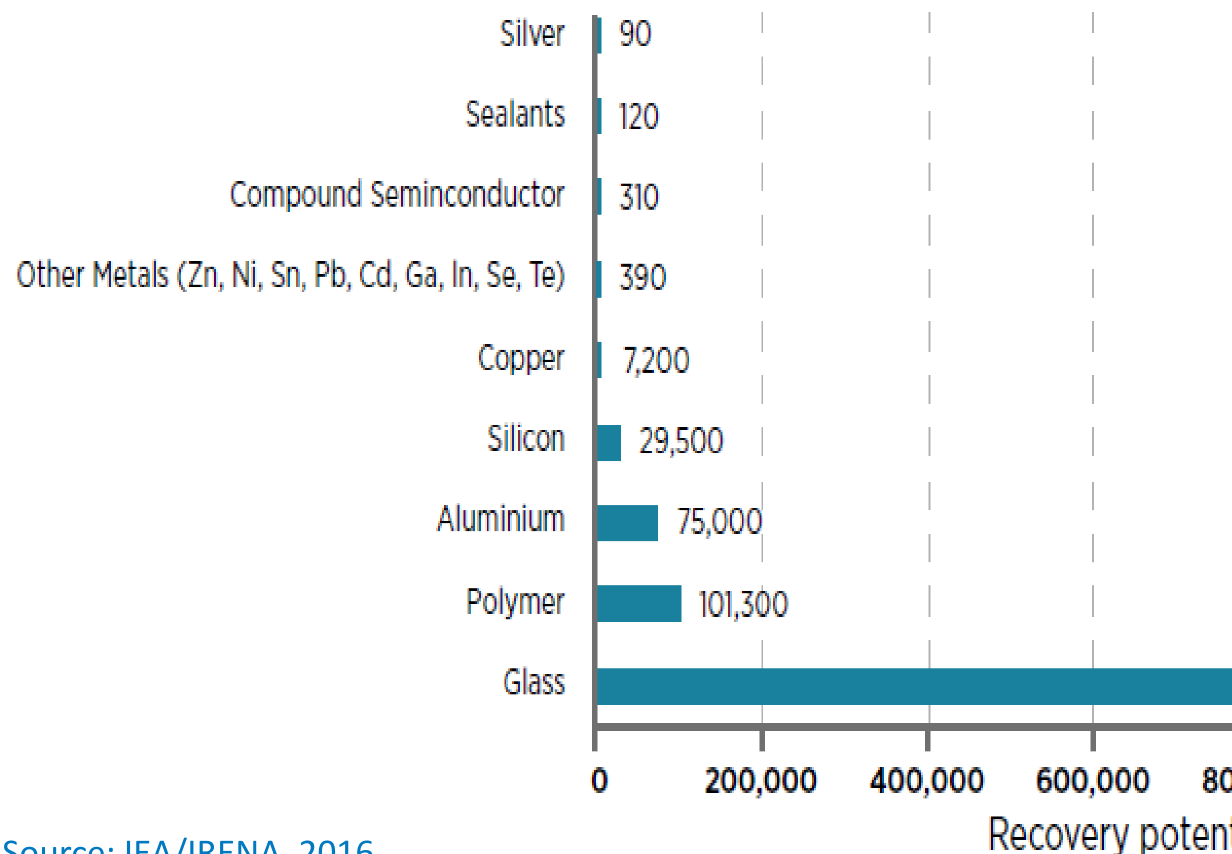
USA Expected As Second Largest PV Waste Volume: Challenge and Opportunity

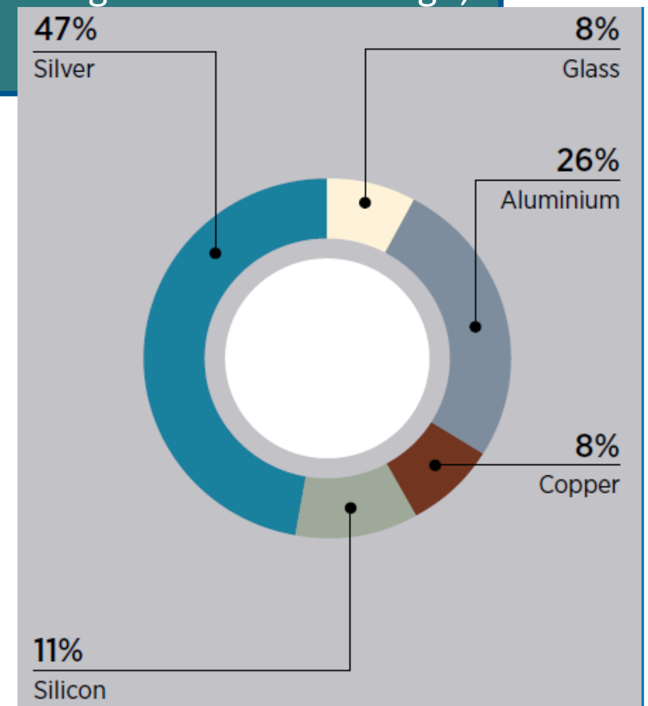


Source: IEA/IRENA, 2016

Why Recycle Modules?
Recovery of Valuable Materials, Preventing Release of Toxic Materials

Cumulative technical potential for end-of-life material recovery (under the regular-loss scenario and considering anticipated changes to module design, like dematerialization)

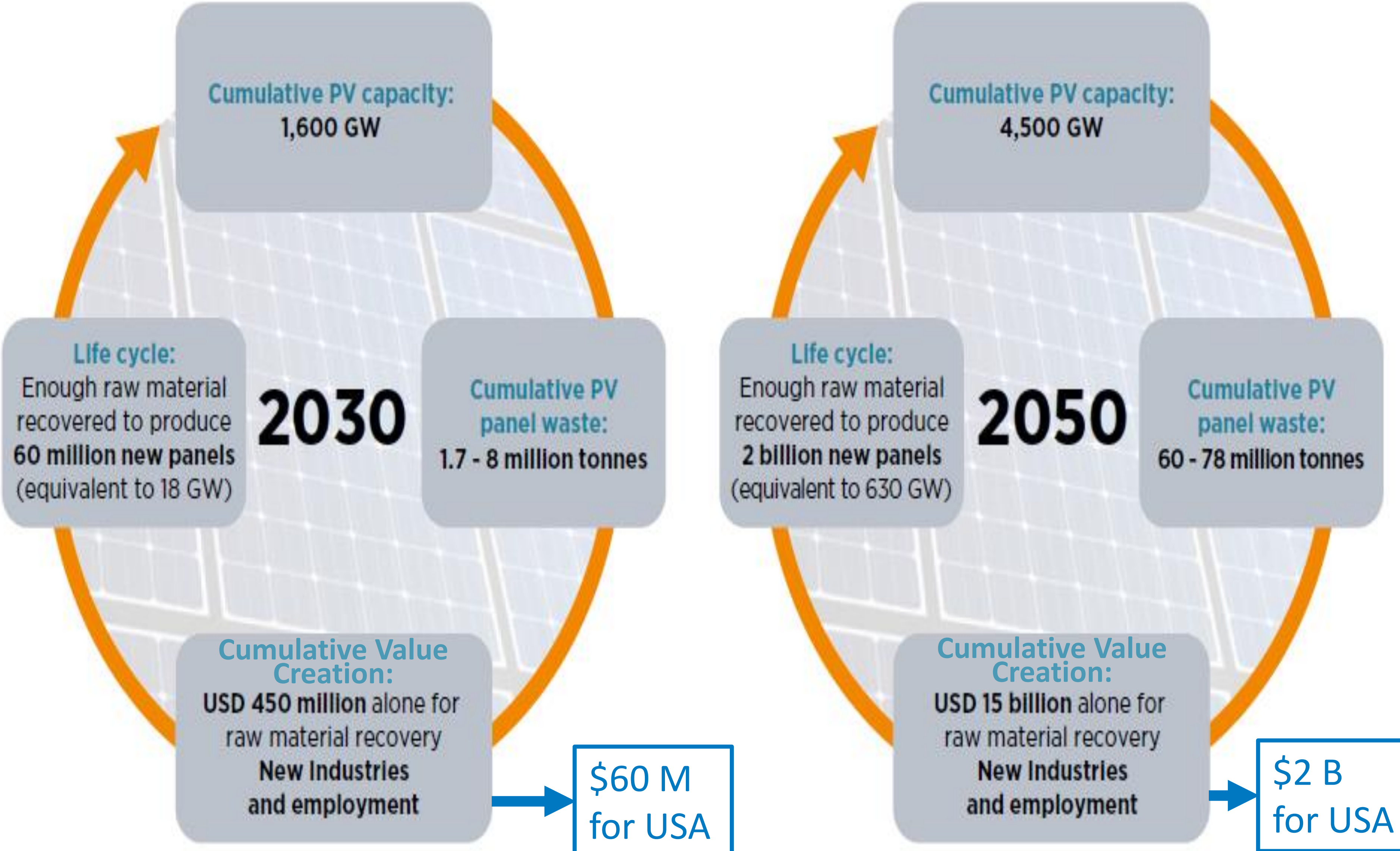




Relative material value of a c-Si Panel
Based on Raithel (2014)

Source: IEA/IRENA, 2016

Potential Value Creation and Circular Economy: A Whole New Waste Management Industry?



Source: IEA/IRENA, 2016

Extending the Value Chain – Cooperation Among New Partners Will Be Important to Create a Vibrant Industry

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

Optimal PV recycling industry will integrate features and actors from energy and waste sectors

Source: IEA/IRENA, 2016

Challenges

Waste Management and Recycling

Challenges are to prepare the technologies, systems and policies to manage decommissioning and disposal of end-of-life modules that can

- Minimize costs and
- Minimize environmental impacts, while
- Maximizing materials recovery.

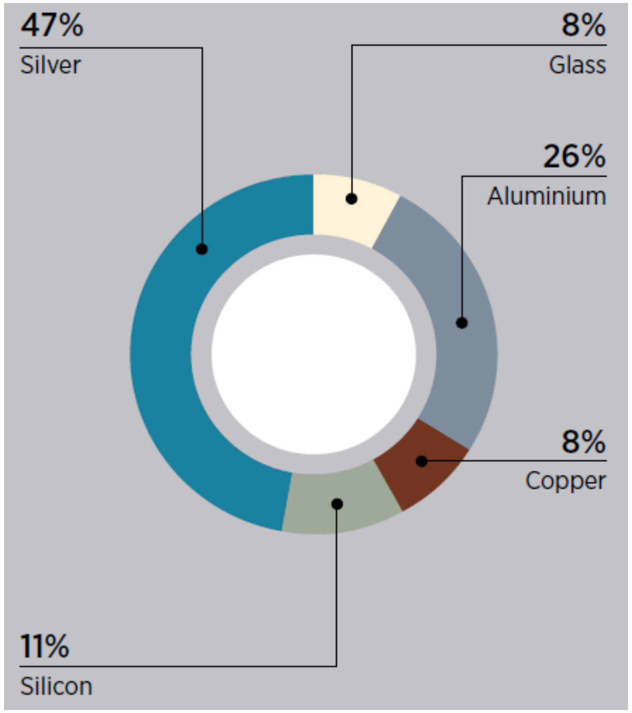
Design for Recycling

Conversely, one way to facilitate economical recycling and maximize material recovery is to design new modules that

- Increase speed and ease of dismantling,
- Improve rate and purity of recovered materials, and
- Reduce waste.

A Challenge to the Value Proposition: Dematerialization

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 the use of silver is a clear manufacturing target, yet significantly affects value of recycled modules.



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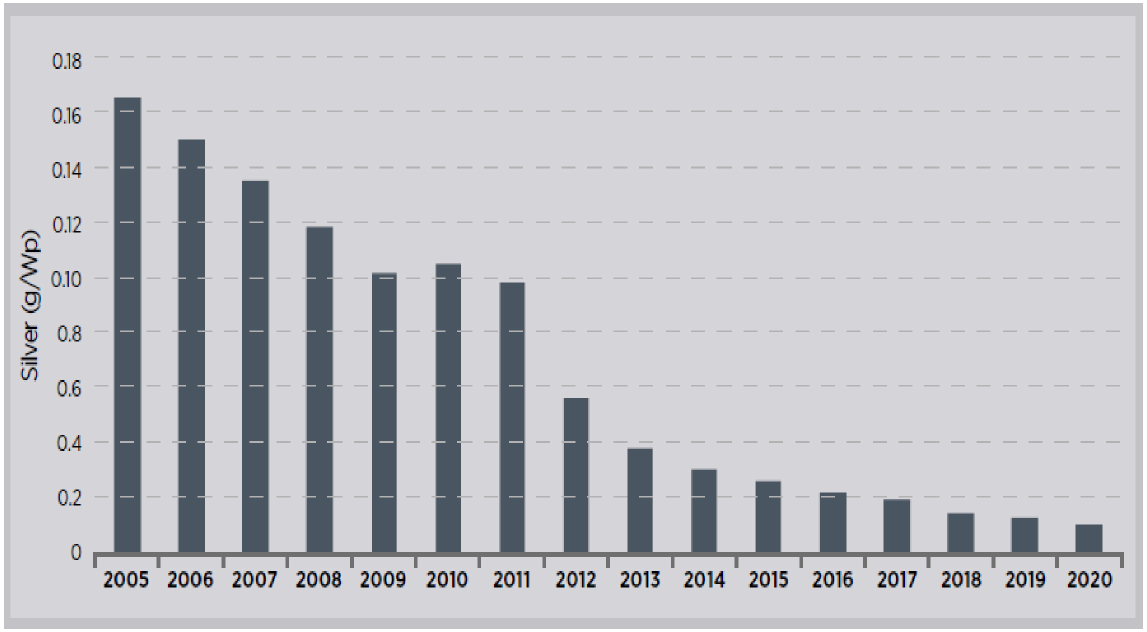


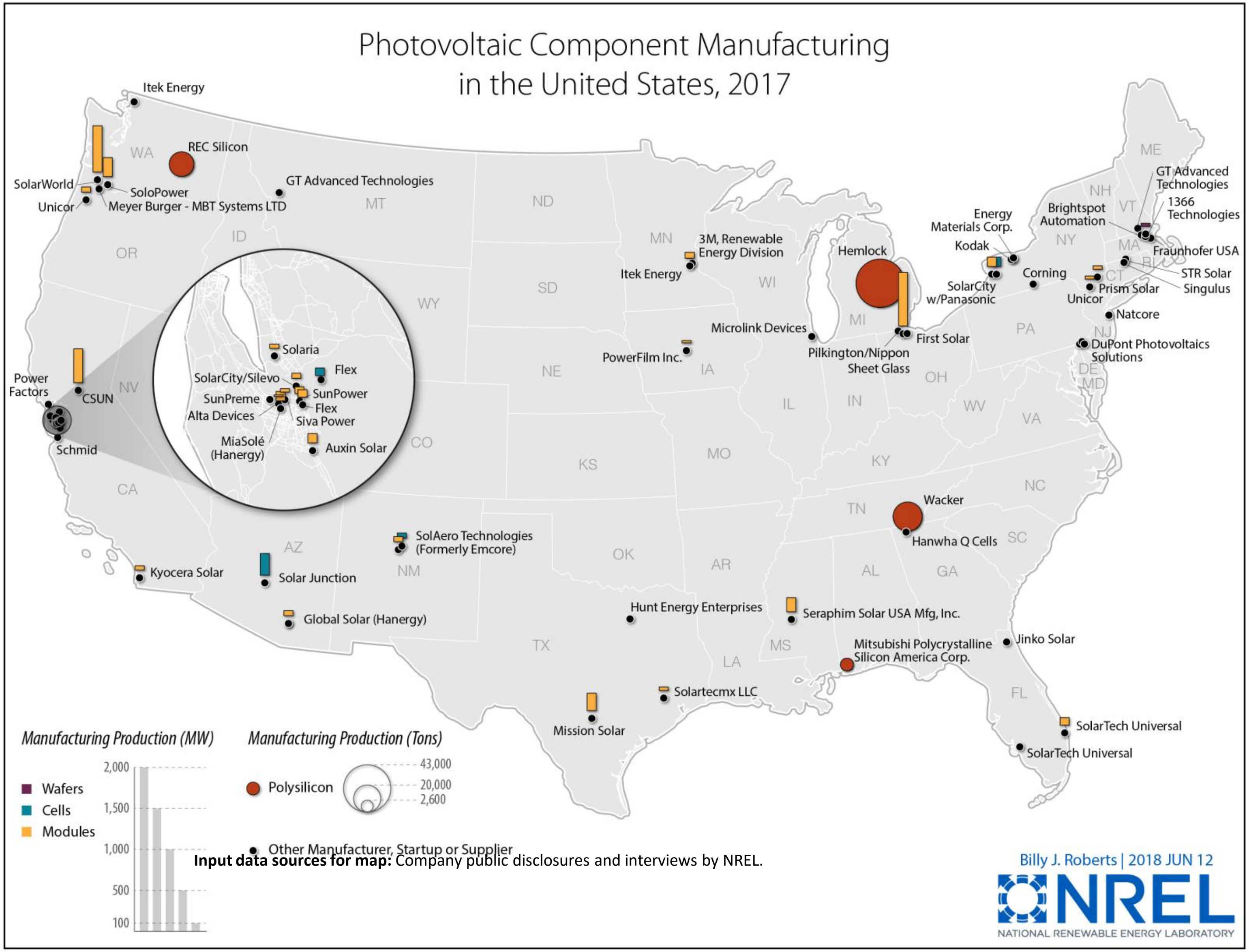
Historic and expected silver consumption per Wp

Based on: Perez-Santalla, M. (2013), Silver Use: Changes & Outlook,

Source: IEA/IRENA, 2016

Growing PV Waste Source: Manufacturing Scrap

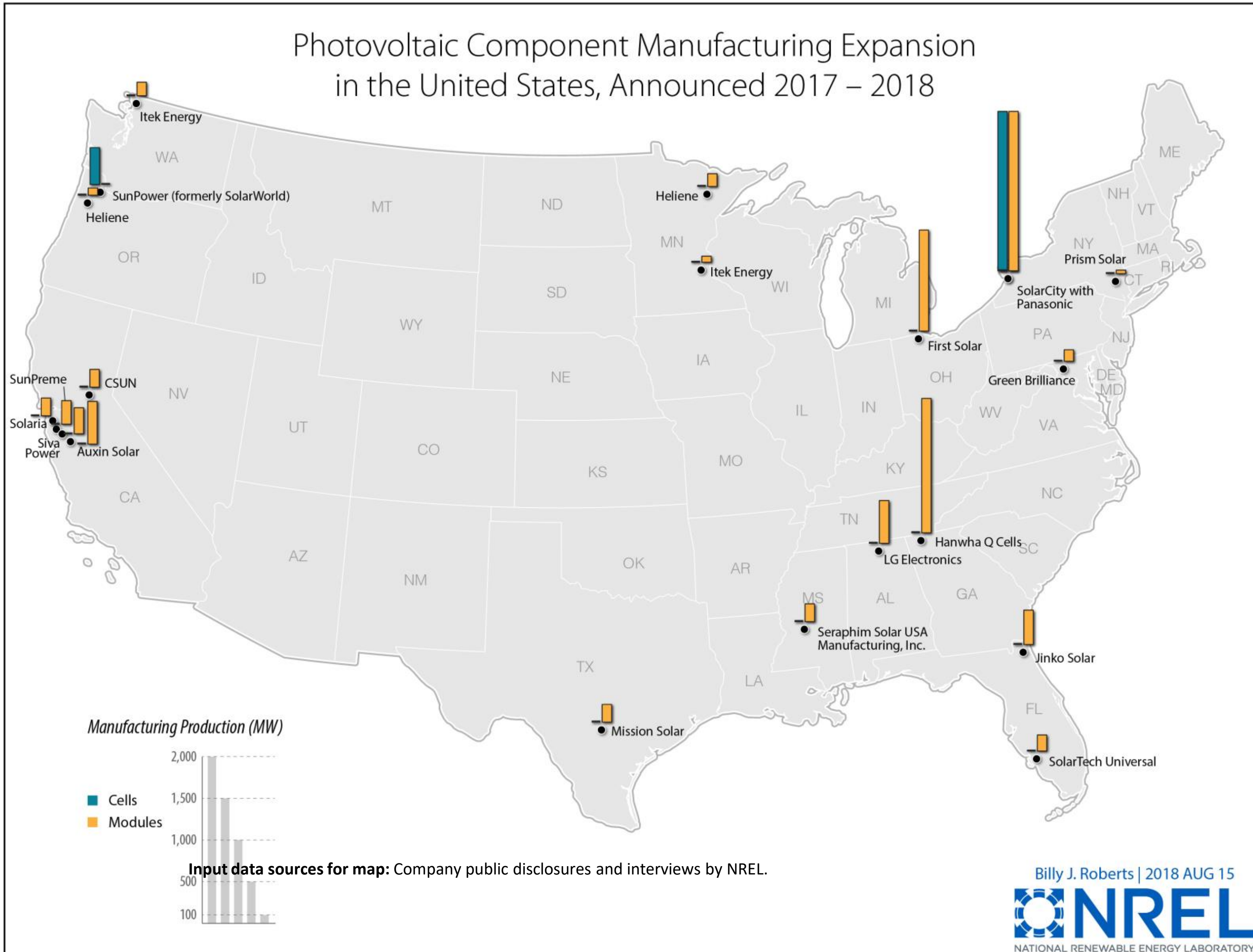
2017 Polysilicon, Wafer, Cell, and Module Capacities. Startup Companies, Materials, and Equipment Suppliers Locations.



Input data sources for map: Company public disclosures and interviews by NREL.

Source: Michael Woodhouse, NREL

New Capacity Announcements Made in 2017 and 2018



Input data sources for map: Company public disclosures and interviews by NREL.

Source: Michael Woodhouse, NREL

A Market Pull for Recycling?
New Sustainability Leadership Standard for PV Modules

- “NSF 457“ – Sustainability Leadership Standard for PV Module Manufacturing (ANSI standard, published December 2017)
  - Comprehensive framework for the establishment of product sustainability performance criteria and corporate performance metrics that exemplify sustainability leadership in the market with third party verification
  - Aims to enable easier specification of high sustainability performance in large purchase contracts of PV modules, alleviating individual purchasers from the arduous and complex task of defining sustainability performance for PV modules
    - Potentially adopted by Green Electronics Council as a new category within the successful EPEAT registry
  - Three tiers of performance: Bronze, Silver, Gold
    - Based on the principle that only leaders – those in the top third of the market – are expected to qualify to the standard at the Bronze level at the date of publication of the standard
    - Very few will qualify for Silver and Gold

(ANSI) NSF 457 Scope

Sustainability Performance Categories

- Substance Management
- Manufacturing Chemicals
- Preferable Materials
- Design for Recycling
- Product Packaging
- Responsible End of Life Management
- Water Use
- Energy Management
- Life Cycle Assessment
- Corporate Environmental Performance
- Corporate Social Performance
- Conflict Mineral Sourcing

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Energy Use and Materials Flows of Current PV Module Recycling Processes in Europe

Introduction and Purpose

- PV module recycling is required in Europe under WEEE regulations
- Few environmental assessments have been published on PV module recycling technologies
- The purpose of this study was to collect energy and material flows (life cycle inventory) for currently operating recycling facilities in Europe that are treating PV modules in order to better understand the process design and support life cycle assessment of their environmental impacts

Approach

- Survey of known recyclers in Europe
  - 9 surveys sent
  - 5 returned

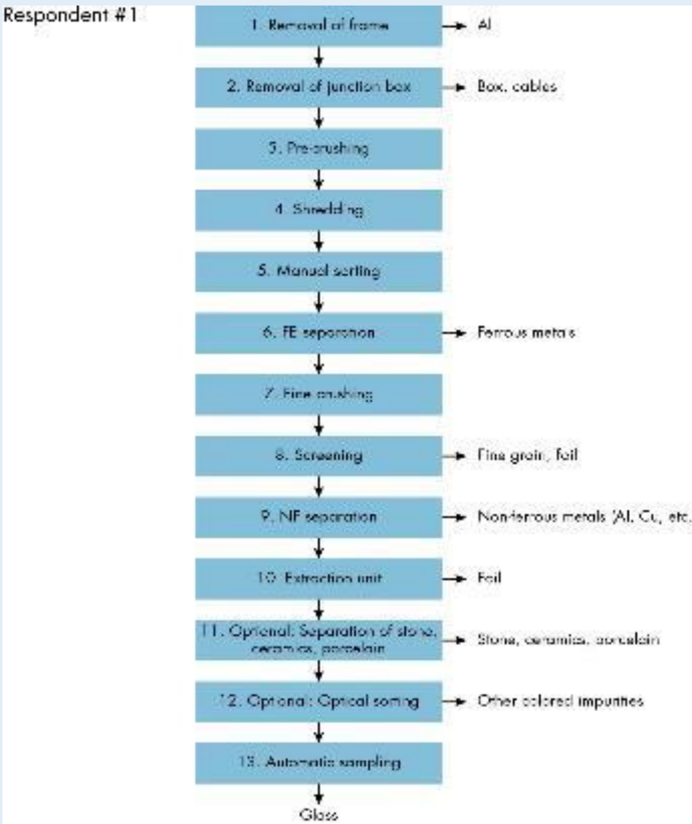
Respondent	Company	Country	Process	Type of Recycler	PV Volume (t/yr)
#1	Anonymous	Germany	Mechanical	Glass	1,200
#2	Exner Trenntechnik GmbH	Germany	Mechanical	Metal	100-250
#3	Maltha	Belgium	Mechanical	Glass	1,000
#4	Nike	Italy	Mechanical	Glass	600
#5	Sasil S.r.l.	Italy	Combination of mechanical, thermal, and chemical	Prototype PV recycling system	(1 t/hr tests)

PVPS

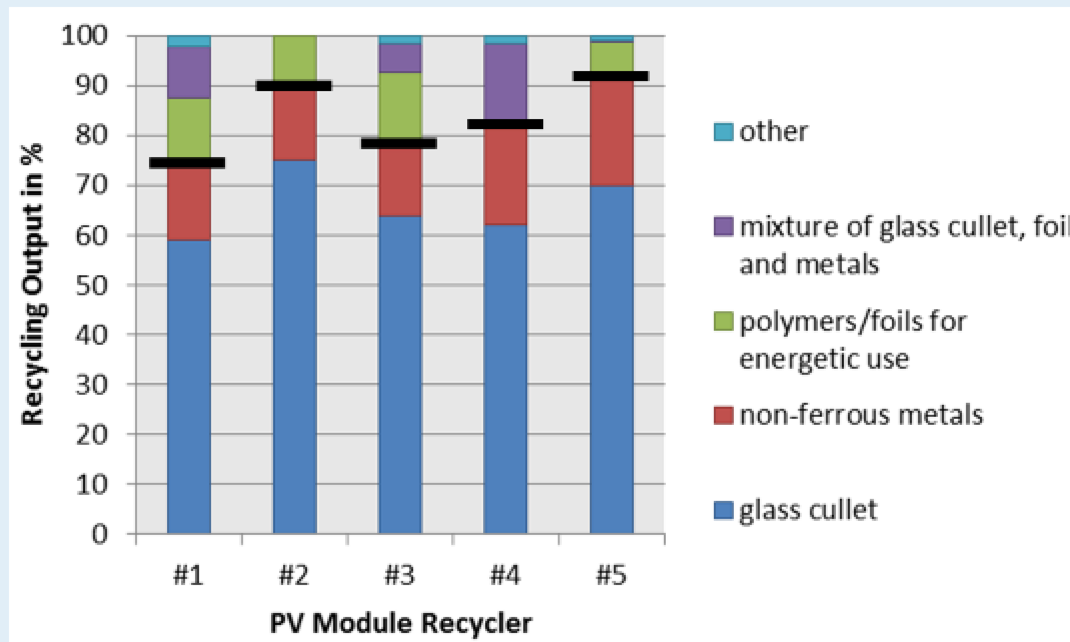
Citation: *Wambach K, Heath G, Libby C. 2018. Life Cycle Inventory of Current Photovoltaic Module Recycling Processes in Europe. IEA-PVPS Task 12 Report T12-12:2017. ISBN 978-3-906042-67-1.*

Synthesis

- Electricity is main energy source for recycling operations, with all but one using 50-100 kWh per tonne of module input
- Higher material recovery rate can be achieved with greater input energy - Respondent #2 used more electricity for a more intense mechanical process; whereas Respondent #5 additionally used thermal energy.



Example of a PV-module recycling process performed as a batch run in a laminated-glass recycling plant, which is considered the reference process of this study since it sets a cost benchmark for PV module recycling in Europe today.



Fraction of recycling output (percent of total output mass) by material category for each of the five respondents. (Polymers are included in mixture for respondent #4.) The bold black lines indicate the total material recovery rate of the process.

End-of-Life Management of Photovoltaic Panels: Trends in PV Module Recycling Technologies

Introduction

- When a product cannot be repaired or reused, recycling is the next best option.
- In the case of PV modules, recycling has become an important emerging topic and various development and research activities have been conducted.
- The purpose of this study was to provide an international survey of trends related to the development of PV module recycling technology.

Approach

1. Patent analysis
    - Database used: online WIPS (worldwide intellectual property service) covering Jan. 6, 1976 – Dec. 9, 2016.
    - Countries covered: EP, DE, FR, GB, US, CN, JP, KR, and the PCT
2. Overview of technology R&D
    - Survey of literature published by firms implementing R&D projects.

Citation: *K. Komoto, J.-S. Lee, J. Zhang, D. Ravikumar, P. Sinha, A. Wade, G. Heath, 2018, End-of-Life Management of Photovoltaic Panels: Trends in PV Module Recycling Technologies, IEA PVPS Task 12, International Energy Agency Power Systems Programme, Report IEA-PVPS T12-10:2018.*

Patent Analysis

• Procedure

Initial search → 6,465 patents → Screening → 178 patents* → analysis (based on targeted components, processing method, and recovered materials)

*directly related to PV recycling

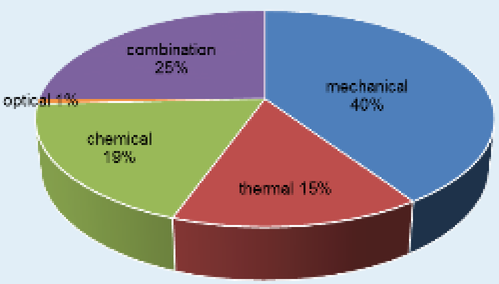
• Analysis results

c-Si – 128 patents

- 45% focusing on module separation
- Mechanical method for 40%
- Many patents for recovery of components, not for recovery of individual materials.

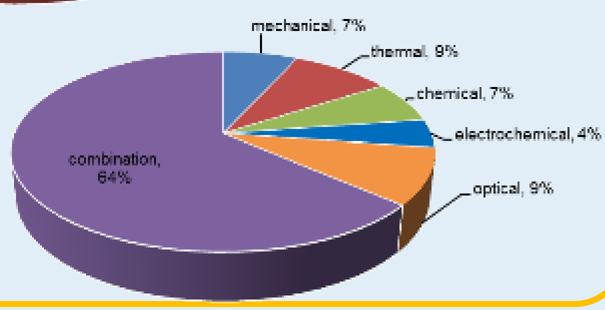
Thin-film compound – 44 patents

- High value recycling recovers higher fraction of the mass
- Combination method for 64%
- Total recycling from module separation to material recovery.



c-Si

Thin-film compound

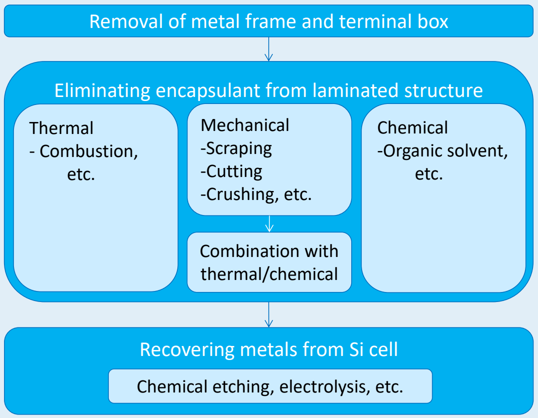


Overview of Technology R&D

Delamination is a key recycling step:

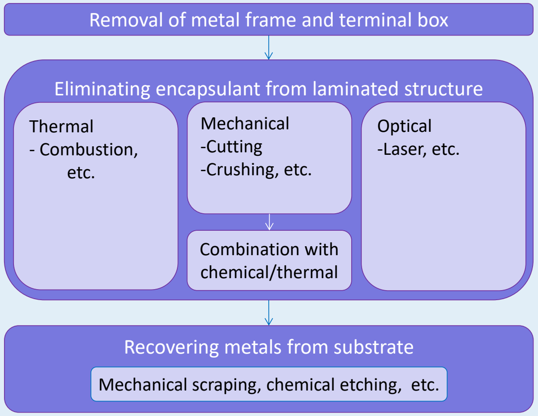
c-Si

- Separation and recovery of glass, Si cells, and other metals
- Thermal, mechanical and chemical approaches can be used.



Thin-film compound

- Recovery of cover and substrate glass with the semiconductor layer
- Thermal, mechanical and optical approaches can be used.



Environmental Assessment of Current Photovoltaic Module Recycling

Introduction

- c-Si PV modules are currently treated in recycling plants designed for glass, metals or electronic waste. Only the bulk materials glass, aluminum and copper are recovered; the cells and other materials are incinerated.
- CdTe PV modules are recycled in dedicated facilities. The semiconductor material (Cd and Te) is recovered in addition to glass and copper.

Approach for Environmental Assessment (LCA)

- Life cycle inventories
  - c-Si PV module recycling based on average of current European recyclers (3 glass recyclers, 1 metal recycler – data from Task 12 LCI report)
  - CdTe PV module recycling by First Solar
- Tested two life cycle inventory modelling approaches: Cut-off / End-of-life
- Followed recognized international procedures for life cycle assessment (LCA)

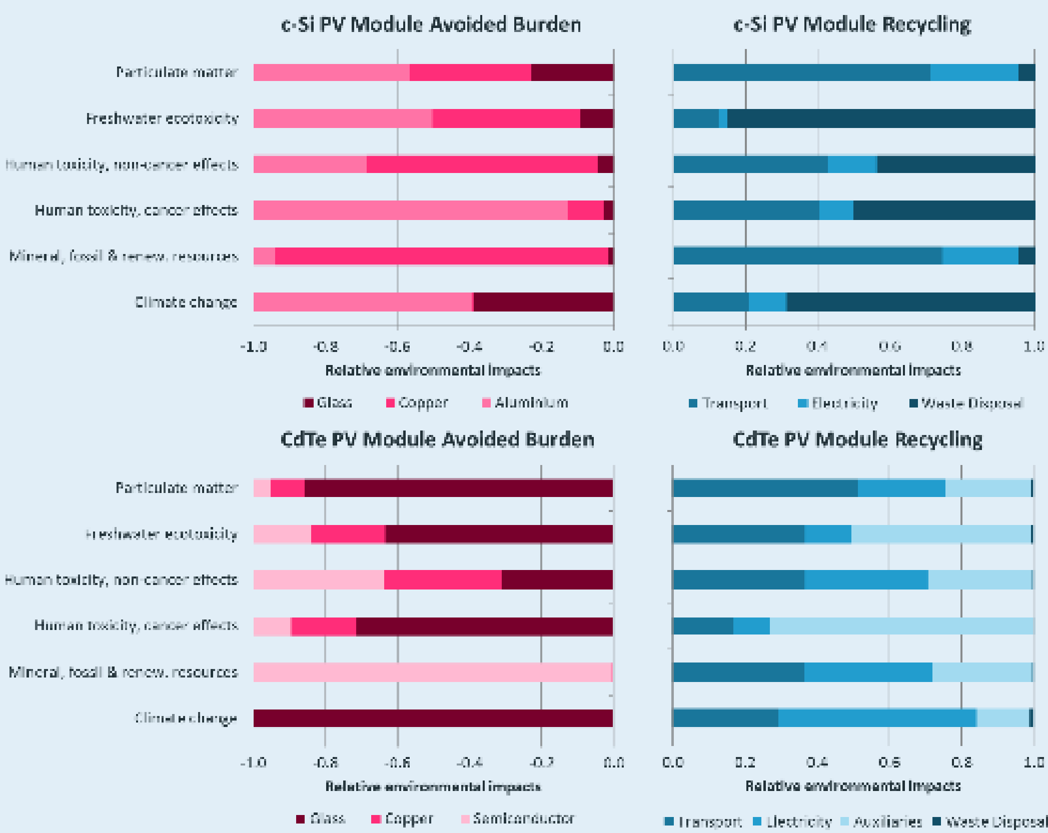
Citation: *P. Stolz, R. Frischknecht, K. Wambach, P. Sinha, G. Heath, 2018, Life Cycle Assessment of Current Photovoltaic Module Recycling, IEA PVPS Task 12, International Energy Agency Power Systems Programme, Report IEA-PVPS T12-13:2018.*

Environmental impacts of end of life of PV modules (cut-off approach)

- Current generation recycling of c-Si and CdTe PV modules causes a small share (<5 %) of the total environmental impacts of residential rooftop PV systems.
- The contribution of PV module recycling is highest in the impact category climate change (from transport, electricity supply, and waste disposal).

Net environmental impacts of PV material recovery (end-of-life approach)

- Recovery of glass, metals, and semiconductor material from PV modules causes lower environmental impacts than the extraction, refinement and supply of the respective materials from primary resources.



Information Gaps States Could Help to Fill

- Market size: how much PV module waste is being generated?
  - This is a very basic information gap critical to enabling investment in recycling infrastructure and industrial R&D.
    - Manufacturing off-spec
    - Warranty issues
    - Other failures – transport, installation, field operation (e.g., extreme weather)
- Current recycling costs are high relative to landfilling or other options
  - R&D and industrial experience is needed to reduce cost, increase material recovery rates, increase purity and decrease contamination
- Analysis of recycling policy design options for cost (owner and administrator), recovery rates, compliance rates, environmental benefits, etc.
  - Collection systems through treatment and disposal
  - Also limitations and challenges given current codes, standards, regulations

Thank you!

Garvin.Heath@nrel.gov

IEA PVPS Task 12:
http://iea-pvps.org/index.php?id=60

Thank you for attending our webinar

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Upcoming Webinar

Community Solar Program Design and Implementation for Low-and Moderate-Income Customers

Thursday, August 30, 1-2pm ET

Guest speakers from NREL will discuss their new report, which reviews existing and emerging LMI community solar programs, discusses key questions related to program design, outlines how states can leverage incentives and finance structures to lower the cost of LMI community solar, and examines marketing and outreach considerations.

Read more and register at www.cesa.org/webinars

PV Waste Management / Recycling – US Status

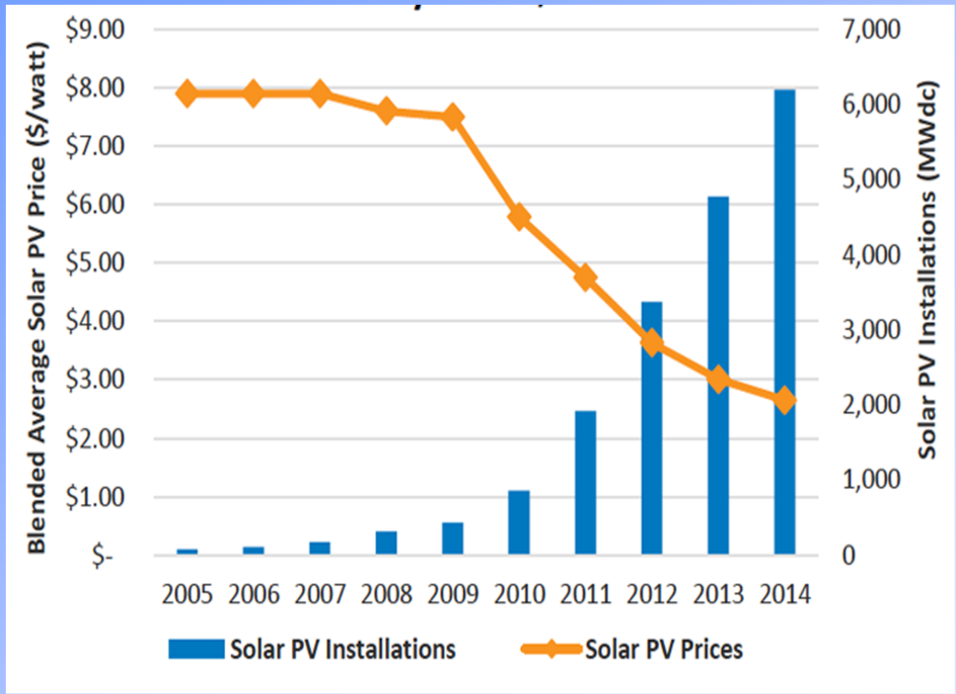
Vasilis Fthenakis

Columbia University and Brookhaven National Laboratory

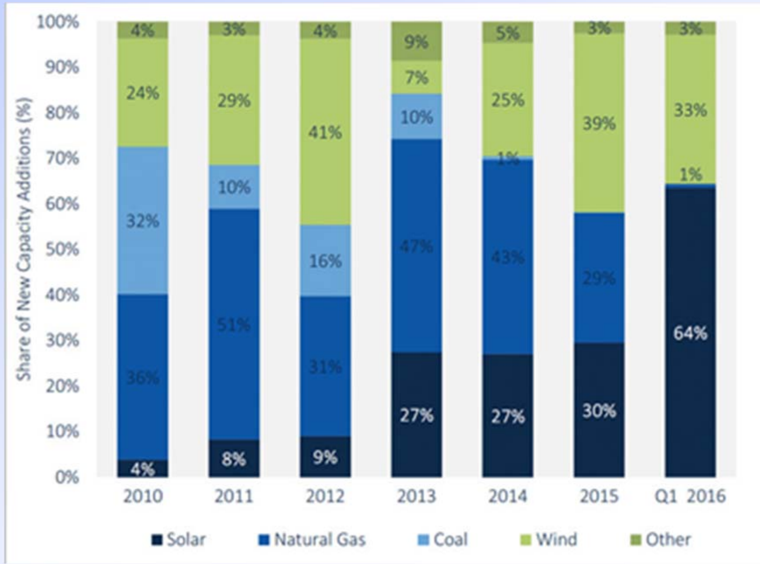
IEA-PVPS / IRENA PV End-of-Life Management Workshop
EUPVSEC, Munich, June 22 2016

PV Deployment in the United States

PV Capacity & Prices

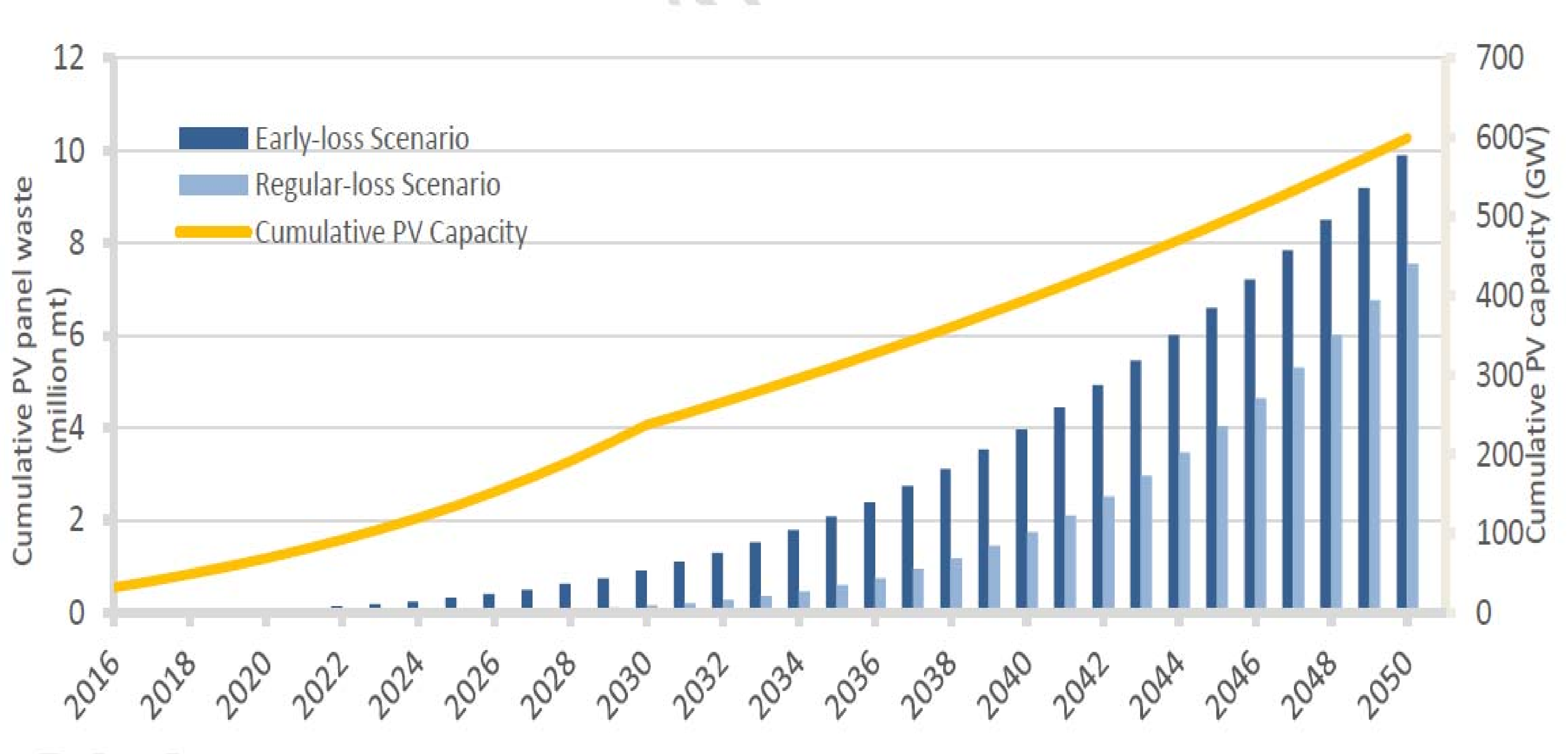


New Power Plants (2010-16)



Source: GTM Research/ SEIA

US End-of-life PV Panel Waste volumes



Source: IEA/IRENA PV End-of-life Management; draft-NOT FOR DISTRIBUTION

PV End-of-Life Management Status in the U.S.

Regulations

- No Federal rules except for general requirements such as RCRA:
  - Spent PV classified Hazardous Waste if they fail the EPA TCLP test (Ag, Cd, Cu, Pb)
- Several states have regulations that go beyond RCRA
  - California (CA) has additional threshold limits for hazardous materials classification
  - CA Senate Bill 489 classifies end-of-life PV panels as Universal Waste, (facilitating easy transport); pending EPA approval

Practices

- Sent to metal/electronics recyclers (Sun Power, Solar City, Sun Run, other?)*
- Hazardous waste landfilling+
- Regular landfilling +
- Refurbishing modules that are in good enough condition +
- Stockpiling in warehouses +
- In-house recycling (First Solar, Ohio)

* source: SEIA PV Recycling Group
\+ own investigation

PV Recycling Status in the US

- Some PV companies have recycling policies and use third-party recyclers, whereas First Solar, runs their own recycling program

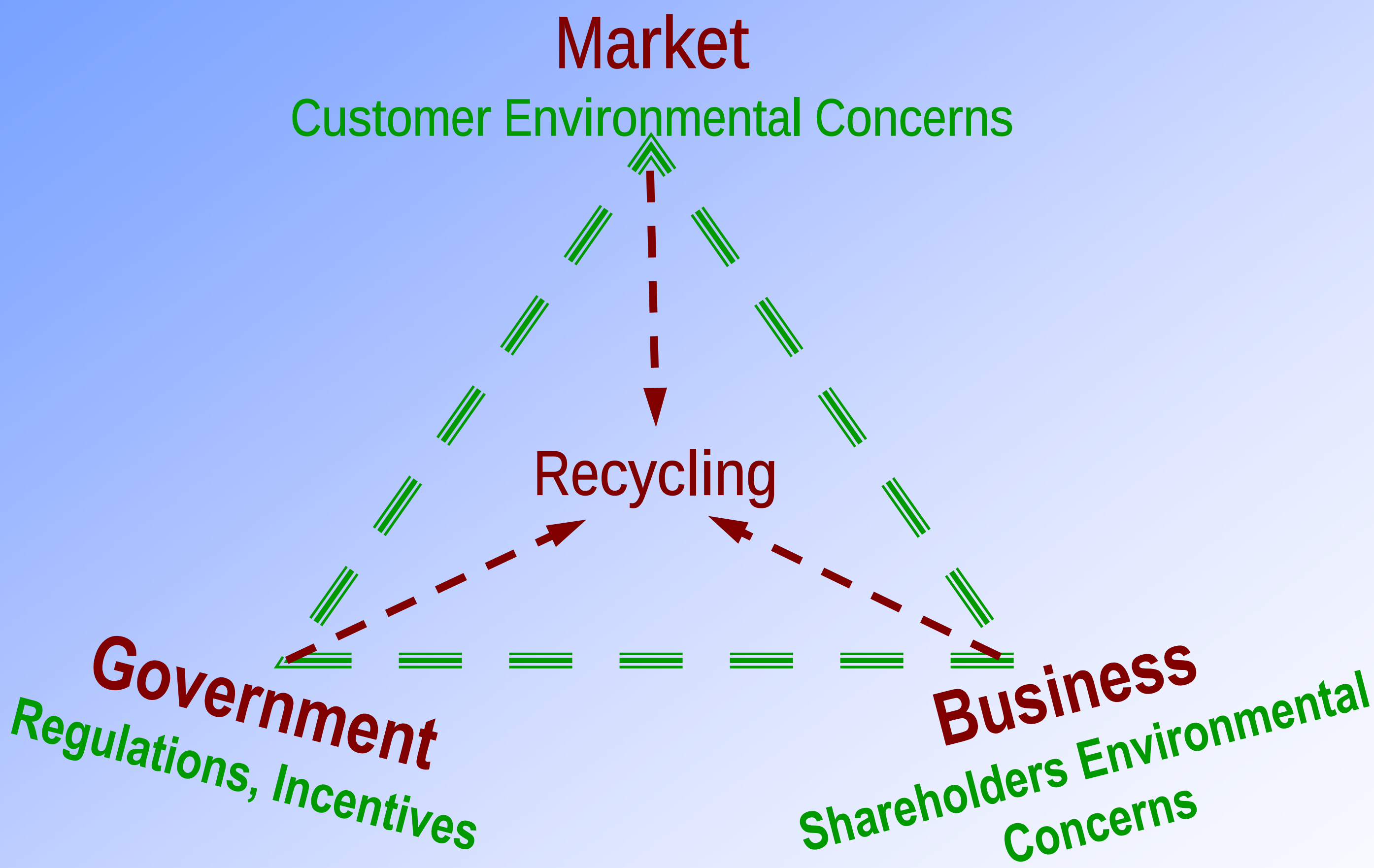
Reasons for lacking and industry-wide recycling program

- Small volume of current waste (up to recently)
- Lack of proactive industry approach/ financial constraints
- The value of recovering materials has not been considered

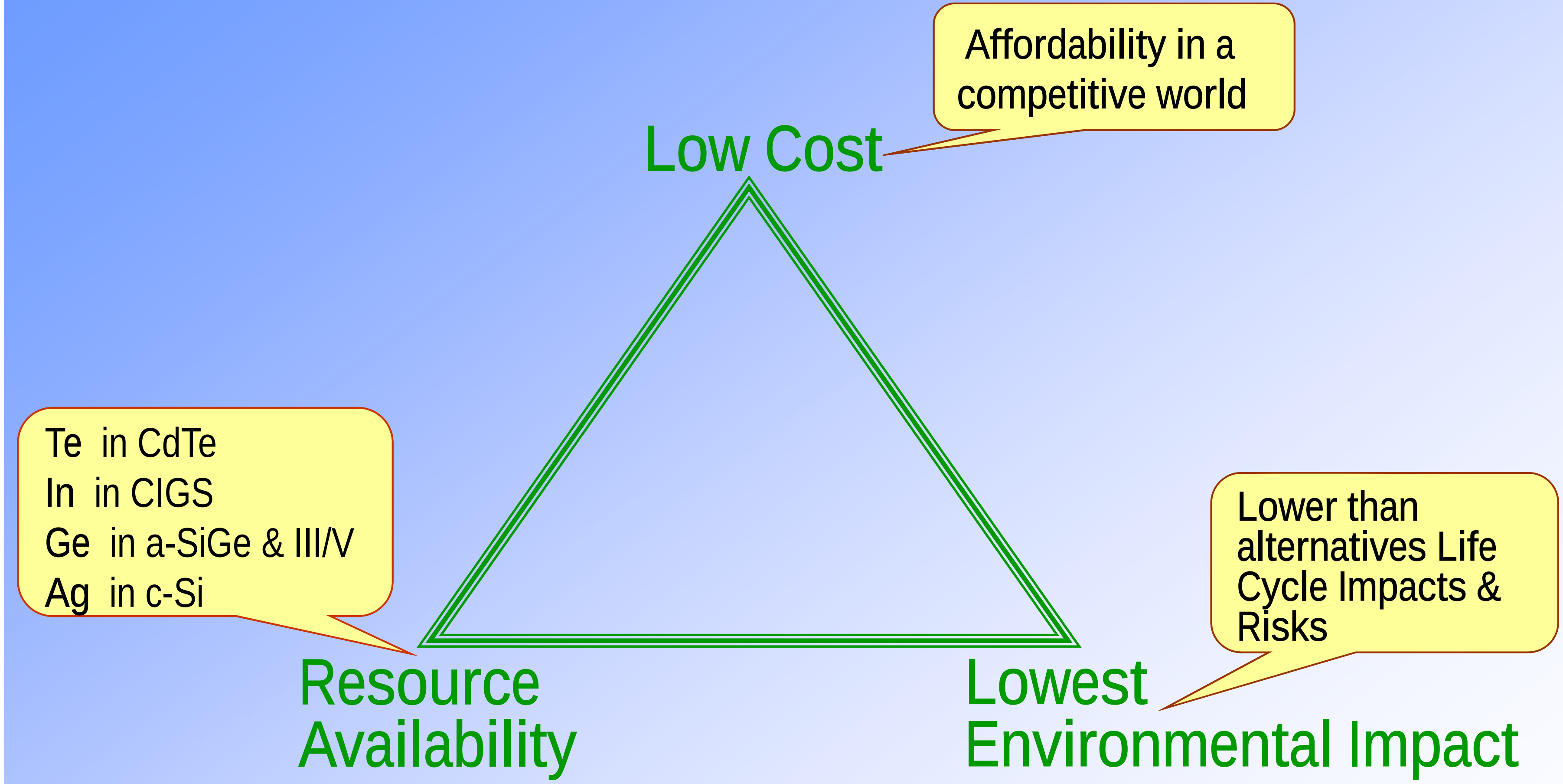
But

- The issue is coming under the radar

Recycling –Addressing Concerns

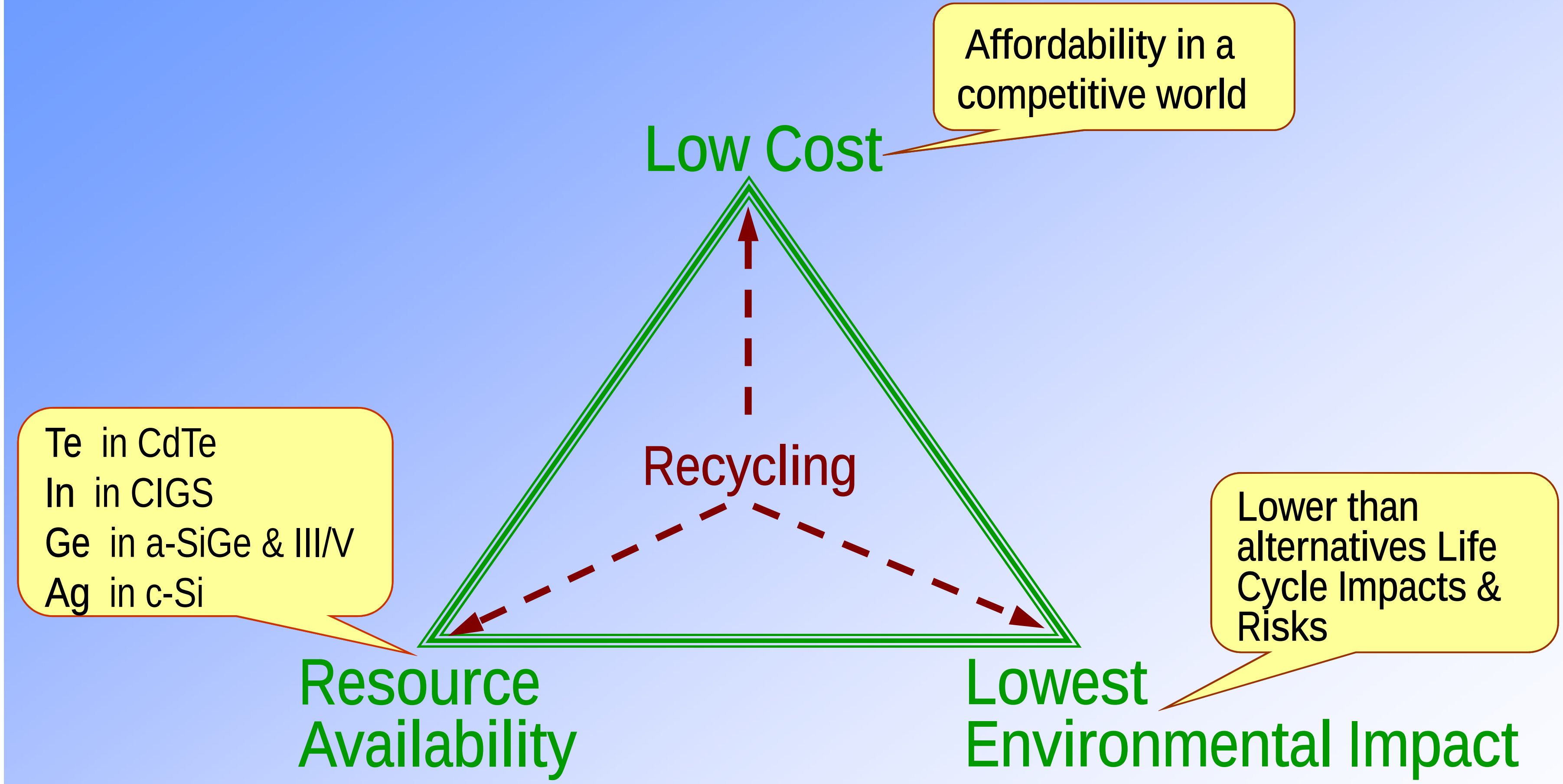


Large Scale PV –Sustainability Criteria



Zweibel, Mason & Fthenakis, A Solar Grand Plan, Scientific American, 2008
Fthenakis, Mason & Zweibel, The technical, geographical and economic feasibility for solar energy in the US, Energy Policy, 2009
Fthenakis, The sustainability of thin-film PV, Renewable & Sustainable Energy Reviews, 2009
Fthenakis, Sustainability metrics for extending thin-film PV to terawatt levels. MRS Bulletin, 2012

Large Scale PV –The Value of Recycling



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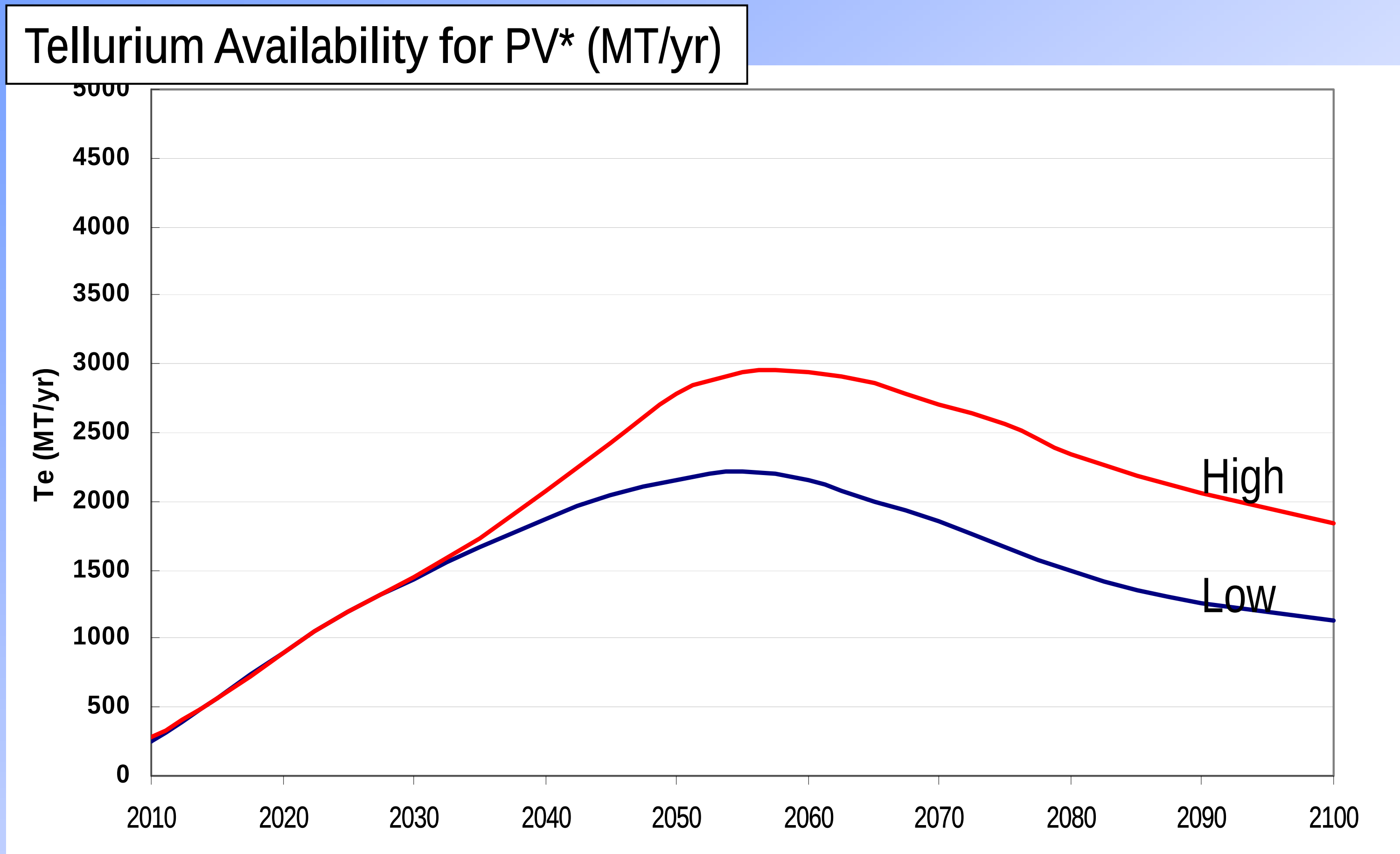
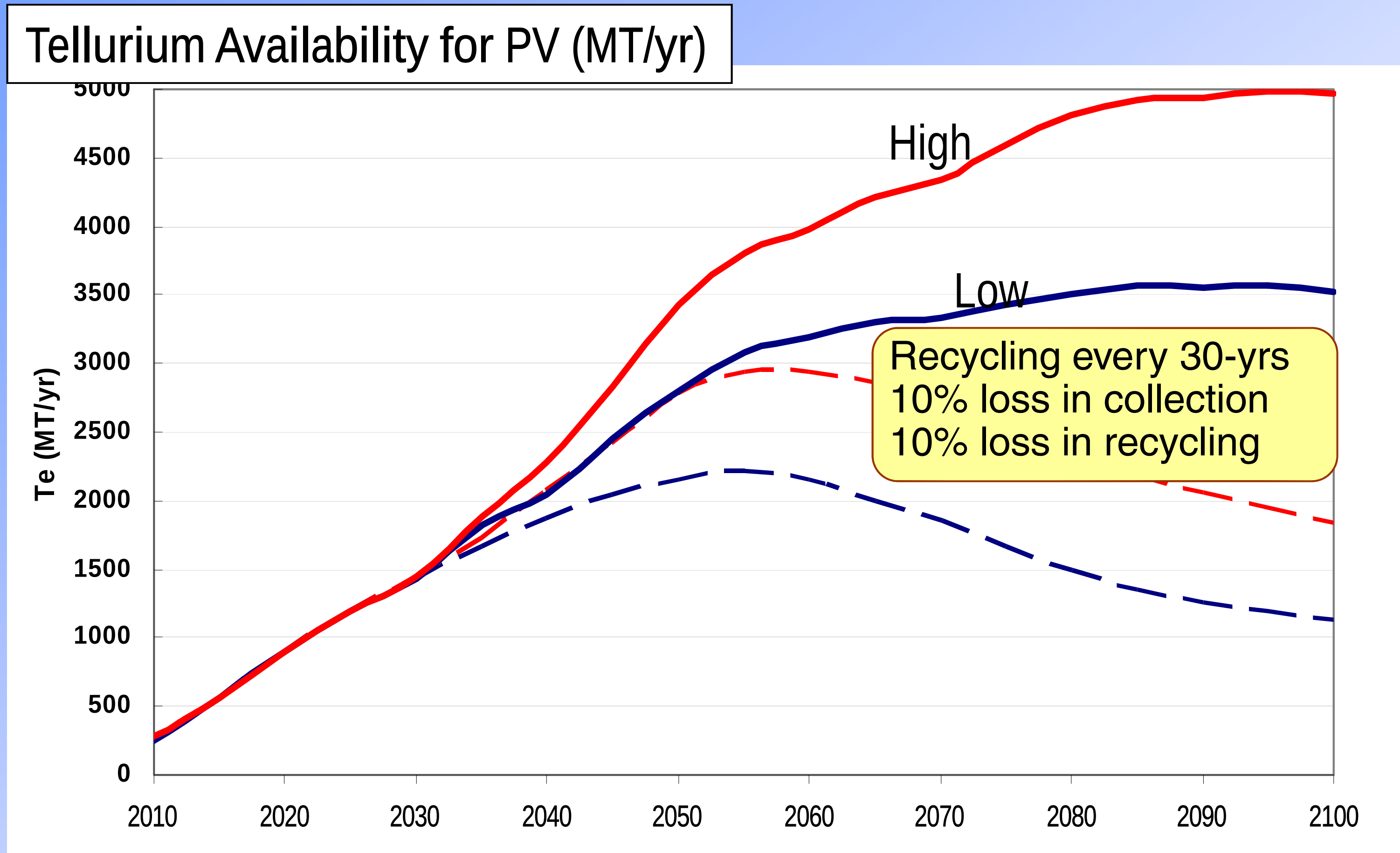
Tellurium for PV* from Copper Smelters



•Global Efficiency of Extracting Te from anode slimes increases to 80% by 2030 (low scenario); 90% by 2040 (high scenario)

* 322 MT/yr Te demand for other uses has been subtracted
All the growth in Te production is allocated to PV

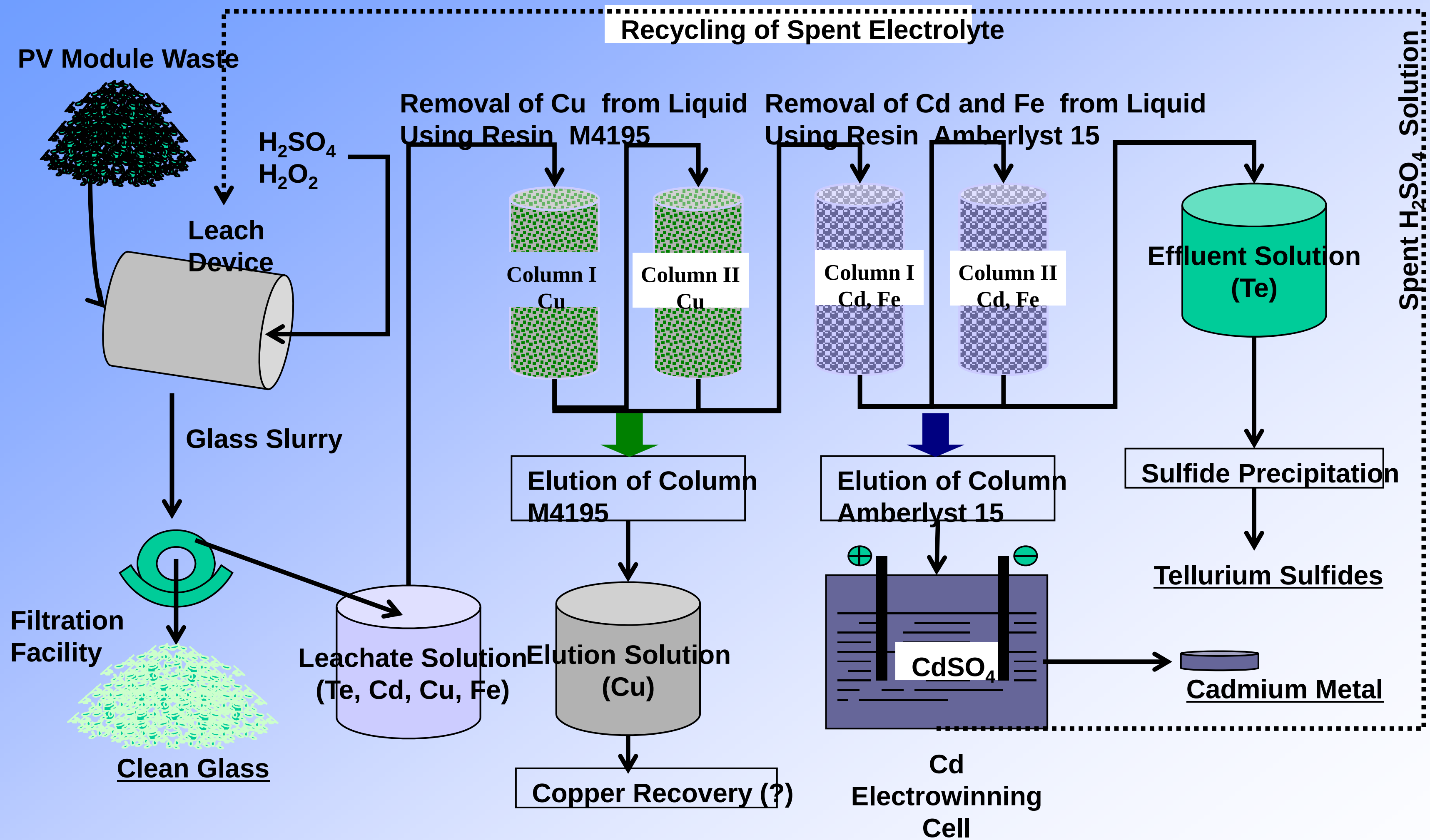
Te Availability for PV:
Primary + Recycled



Fthenakis V., *Renewable & Sustainable Energy Reviews* 13, 2746, 2009

Fthenakis V., *MRS Bulletin*, 37, 425, 2012

Thin-film Recycling R&D at BNL: CdTe PV Modules



Fthenakis V. and Wang W., Separating Te from Cd Waste Patent No 7,731,920, June 8, 2010

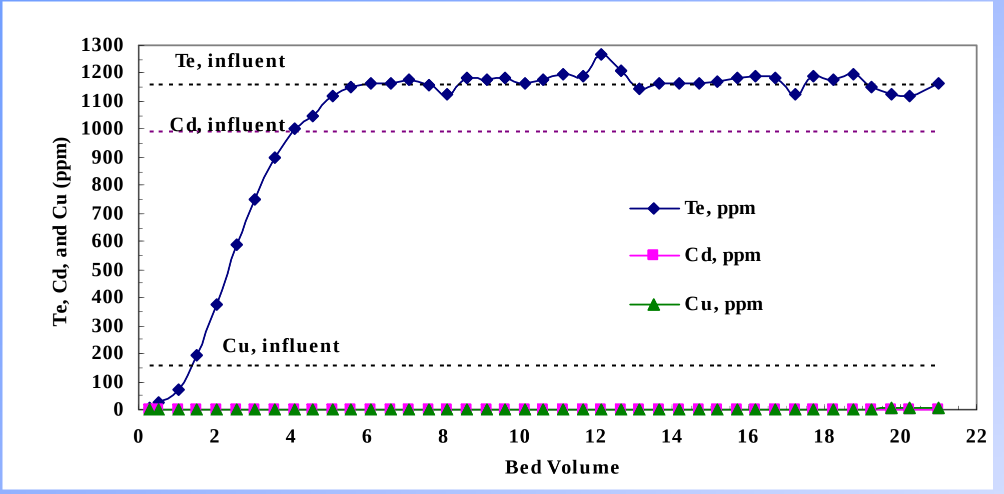
Wang W. and Fthenakis V.M. Kinetics Study on Separation of Cadmium from Tellurium in Acidic Solution Media Using Cation Exchange Resin, Journal of Hazardous Materials, B125, 80-88, 2005

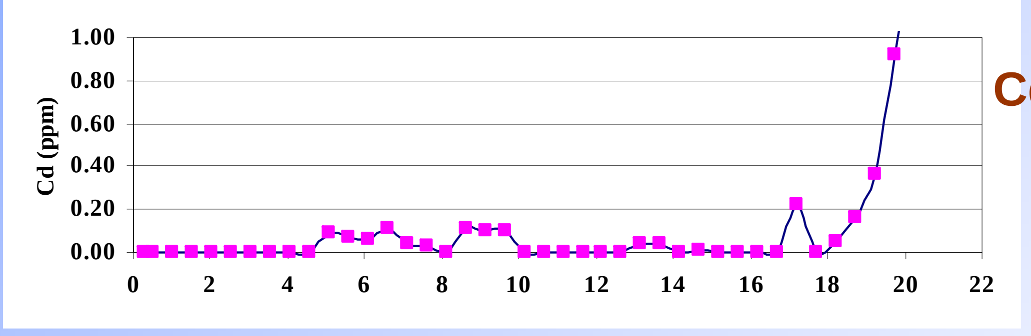
Fthenakis V.M and Wang W., Extraction and Separation of Cd and Te from Cadmium Telluride Photovoltaic Manufacturing Scrap, Progress in Photovoltaics, 14:363-371, 2006.

Research Objectives

- Complete separation of Cd from CdTe modules to produce clean glass and clean effluents
- Recovery of Cd and Te in high purity so that can be re-used in PV manufacturing
- Achieve recycling at a few ¢/W

Separation of Cd and Te from Leaching Solution





Cd separation 99.99%

Cd effluent concentration <0.3 ppm

Cd, Te extraction & separation was completed at a projected cost of 1 ¢/W_p
(~$100/tonne of PV panel)

Fthenakis V. and Wang W., Separating Te from Cd Waste Patent No 7,731,920, June 8, 2010

Pure Material Recovery Challenges & Perspectives

- Sulfuric acid leaching method yields a solution containing several impurities, e.g. Cu, Fe, Al, Na, Ca, Si, Mg, and other.
- Production of high purity cadmium and tellurium products are compromised with the presence of so many contaminants
- The Glass-EVA separation is not complete precluding its reuse in flat glass manufacturing

Remaining R&D Needs

- Glass-polymer separations (to enhance glass value)
- Prevent glass contamination with metals during processing
- Develop recycling methods for multiple PV types
- Assess recyclability of new PV types
- PV recycling system (Collection+Recycling) cost optimization

Motivation for Cost Optimization Model

- Various cell & module production technologies
  - Fluctuation of material quantities & prices
- Evolving environmental legislations

- Must evaluate the trade-offs between different cost and revenue structures
  - Spatial and temporal issues

General Recycling Cost Model

- Maximize:

$$\sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{j=1}^{J}\alpha_{jk}\Omega_{ijkt} - \sum_{t=1}^{T}\sum_{i=1}^{I}\pi_{it}\omega_{it} - \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{k=1}^{K}c_k\tau_{ik}\Psi_{it} - \sum_{t=1}^{T}\sum_{i=1}^{I}\sigma_t\pi_{it}\Lambda_{it}$$

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

- Using GAMS (General Algebraic Modeling System)

J. -K. Choi, and V.M. Fthenakis, "Economic feasibility of recycling photovoltaic modules: Survey and model", *Journal of Industrial Ecology*, 2010.

Conclusion

- Major PV Sustainability metrics include cost, resource availability, and environmental impacts
- These three aspects are closely related; **recycling** spent modules will become increasingly important in resolving cost, resource, and environmental constraints to large scales of sustainable growth
- The technical and economic feasibility of recycling currently commercial PV modules is demonstrated
- Opportunities exist in reducing recycling costs by improving the purity of recovered materials and optimizing system costs

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Recoverable Materials

Value of Materials in PV Products

Material	Avg Price ($/kg)	Peak Price ($/kg)	Products
Indium	700	2000	CIGS*
Gallium	650		CIGS
Silver	600	1600	c-Si
Tellurium	100	220	CdTe
Silicon	12**		c-Si
Cadmium	4***		CdTe
Germanium	1200		III/V, a-Si
Aluminum	2		frame
Glass	0.07+		all

* CIGS also contains valuable molybdenum and selenium
** UMG grade: $12; 6N-8N: $20; Recovered Si wafers: $25-40/kg
***Cadmium has low intrinsic value, but there is value in avoiding hazardous waste disposal costs
+ Glass cullet prices range from $3 to $75/tonne depending on purity

IEA INTERNATIONAL ENERGY AGENCY
PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

IRENA
International Renewable Energy Agency

END-OF-LIFE MANAGEMENT

Solar Photovoltaic Panels

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ABOUT IRENA

IRENA is an intergovernmental organisation that supports countries in their transition to a sustainable energy future and serves as the principal platform for international co-operation, a centre of excellence and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

www.irena.org

ABOUT IEA-PVPS

The IEA, founded in November 1974, is an autonomous body within the framework of the Organisation for Economic Co-operation and Development (OECD) that carries out a comprehensive programme of energy co-operation among its member countries. The European Commission also participates in the work of the IEA. The IEA-PVPS is one of the collaborative research and development (R&D) agreements established within the IEA. Since 1993, participants in the PVPS have been conducting a variety of joint projects in the applications of PV conversion of solar energy into electricity.

www.iea-pvps.org

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END-OF-LIFE MANAGEMENT

Solar Photovoltaic Panels

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GLOSSARY

Amorphous silicon	Non-crystalline form of silicon formed using silicon vapour which is quickly cooled.
Electrical and electronic equipment	The term electrical and electronic equipment (EEE) is defined as equipment designed for use with a voltage rating not exceeding 1,000 Volts (V) for alternating current and 1,500 V for direct current, or equipment dependent on electric currents or electromagnetic fields in order to work properly, or equipment for the generation of such currents, or equipment for the transfer of such currents, or equipment for the measurement of such currents.
Extended Producer Responsibility	Extended Producer Responsibility (EPR) is an environmental policy approach in which a producer's responsibility for a product is extended to the post-consumer stage of a product's life cycle. An EPR policy is characterised by (1) shifting responsibility (physically and/or economically; fully or partially) upstream towards the producers and away from governments and (2) the provision of incentives to producers to take into account environmental considerations when designing their products.
Monocrystalline silicon	Silicon manufactured in such a way that if forms a continuous single crystal without grain boundaries.
Raw material	Basic material which has not been processed, or only minimally, and is used to produce goods, finished products, energy or intermediate products which will be used to produce other goods.
Pay-as-you-go and pay-as-you-put	In a pay-as-you-go (PAYG) approach, the cost of collection and recycling is covered by market participants when waste occurs. By contrast, a pay-as-you-put (PAYP) approach involves setting aside an upfront payment of estimated collection and recycling costs when a product is placed on the market. Last-man-standing-insurance is an insurance product that covers a producer compliance scheme based on a PAYG approach if all producers disappear from the market. In that situation, the insurance covers the costs of collection and recycling. In a joint-and-several liability scheme, producers of a certain product or product group agree to jointly accept the liabilities for waste collection and recycling for a specific product or product group.
Poly- or multicrystalline silicon	Silicon manufactured in such a way that it consists of a number of small crystals, forming grains.
Thin-film	Technology used to produce solar cells based on very thin layers of PV materials deposited over an inexpensive material (glass, stainless steel, plastic).

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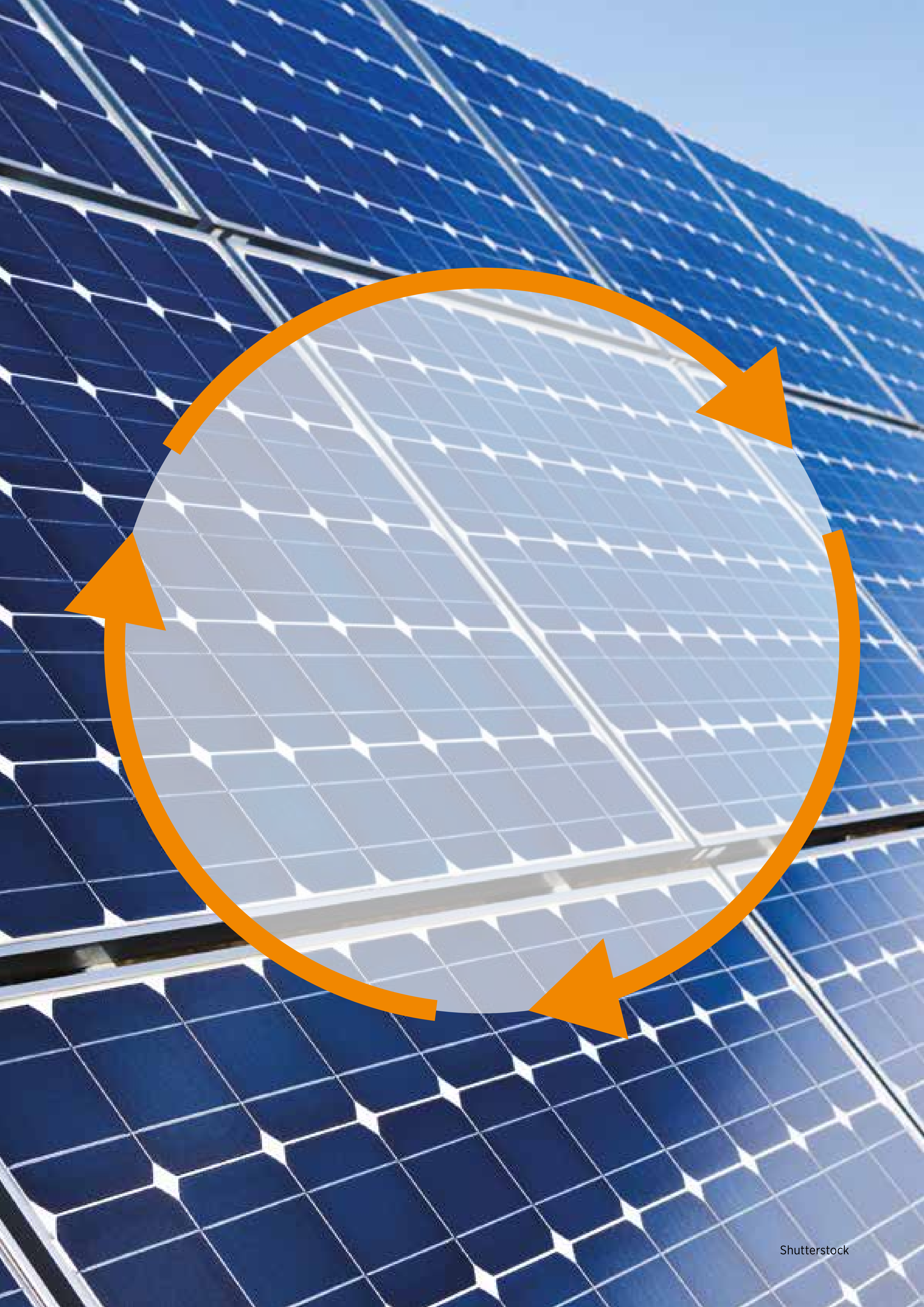
ABBREVIATIONS

a-Si	amorphous silicon
B2B	business-to-business
B2C	business-to-consumer
BIPV	building-integrated PV
c-Si	crystalline silicon
CIGS	copper indium gallium (di)selenide
CdTe	cadmium telluride
CIS	copper indium selenide
CO2	carbon dioxide
CU-PV	Energy Research Centre of the Netherlands and PV CYCLE
EEE	electrical and electronic equipment
EPR	extended producer responsibility
EVA	ethylene vinyl acetate
GW	gigawatts
IEA	International Energy Agency
IEA PVPS	International Energy Agency Photovoltaic Power System Programme
IEE	Institute for Electrical Engineering of the National Academy of Sciences, China
IRENA	International Renewable Energy Agency
ISE	(Fraunhofer) Institute for Solar Energy Systems, Germany
ITRPV	International Technology Roadmap for Photovoltaic
JNNSM	Jawaharlal Nehru National Solar Mission, India
kg	kilogramme
kW	kilowatt
L	litre
METI	Ministry of Economy, Trade and Industry, Japan
mg	milligramme
MOE	Ministry of Environment, Japan
MW	megawatt
NEDO	New Energy and Industrial Technology Development Organization, Japan
NREL	National Renewable Energy Laboratory, US
PAYG	pay-as-you-go
PAYP	pay-as-you-put
PV	photovoltaic
R&D	research and development
t	metric tonne
W	watt
Wp	watt-peak
WEEE	waste electrical and electronic equipment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EXECUTIVE SUMMARY

Solar photovoltaic (PV) deployment has grown at unprecedented rates since the early 2000s. Global installed PV capacity reached 222 gigawatts (GW) at the end of 2015 and is expected to rise further to 4,500 GW by 2050. Particularly high cumulative deployment rates are expected by that time in China (1,731 GW), India (600 GW), the United States (US) (600 GW), Japan (350 GW) and Germany (110 GW).

As the global PV market increases, so will the volume of decommissioned PV panels. At the end of 2016, cumulative global PV waste streams are expected to have reached 43,500-250,000 metric tonnes. This is 0.1%-0.6% of the cumulative mass of all installed panels (4 million metric tonnes). Meanwhile, PV waste streams are bound to only increase further. Given an average panel lifetime of 30 years, large amounts of annual waste are anticipated by the early 2030s. These are equivalent to 4% of installed PV panels in that year, with waste amounts by the 2050s (5.5-6 million tonnes) almost matching the mass contained in new installations (6.7 million tonnes).

Growing PV panel waste presents a new environmental challenge, but also unprecedented opportunities to create value and pursue new economic avenues. These include recovery of raw material and the emergence of new solar PV end-of-life industries. Sectors like PV recycling will be essential in the world's transition to a sustainable, economically viable and increasingly renewables-based energy future. To unlock the benefits of such industries, the institutional groundwork must be laid in time to meet the expected surge in panel waste.

PV panel waste and global e-waste

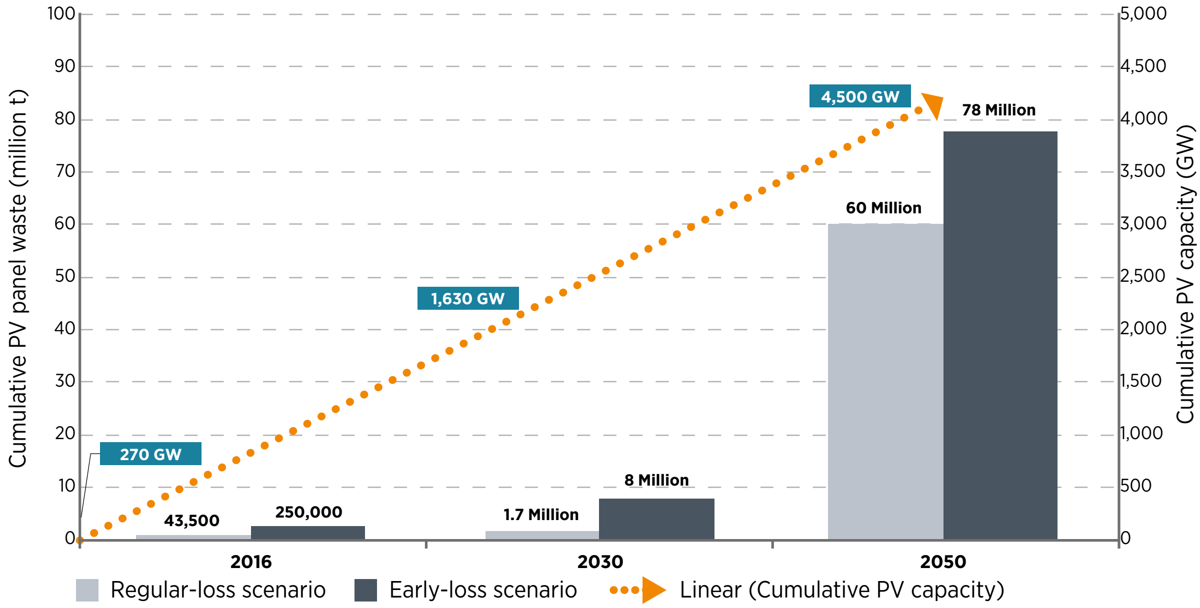
The world's total annual electrical and electronic waste (e-waste) reached a record of 41.8 million metric tonnes in 2014. Annual global PV panel waste was 1,000 times less in the same year. Yet by 2050, the PV panel waste added annually could exceed 10% of the record global e-waste added in 2014.

As the analysis contained in this report shows, the challenges and experiences with e-waste management can be turned into opportunities for PV panel waste management in the future.

This report presents the first global projections for future PV panel waste volumes to 2050. It investigates and compares two scenarios for global PV panel waste volumes until 2050.

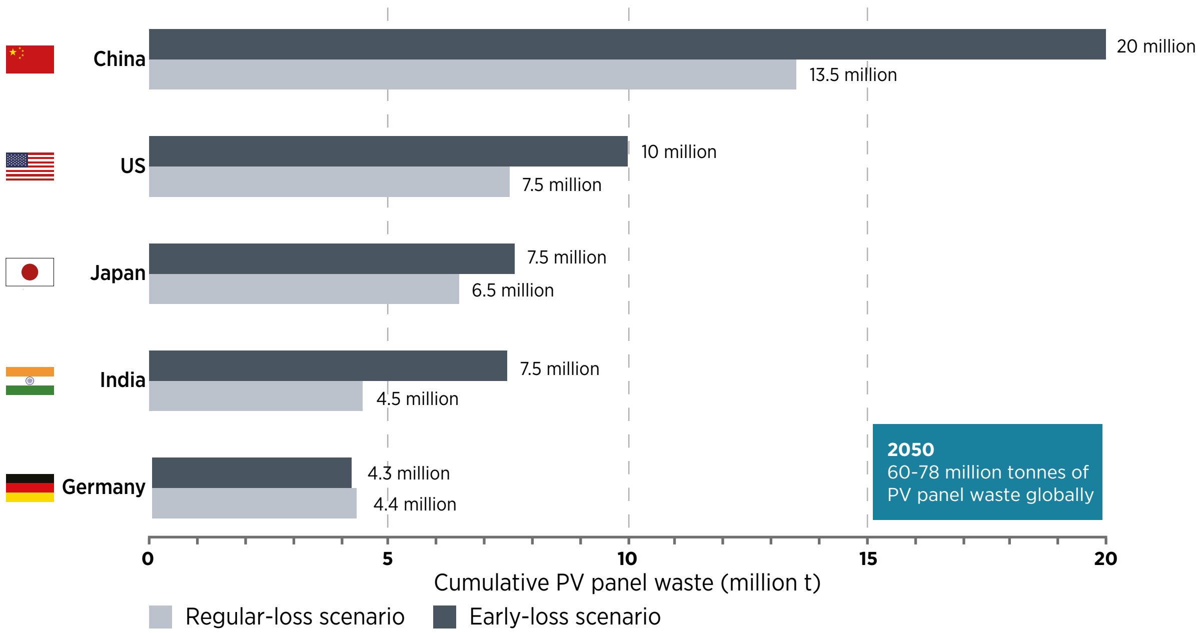
- Regular-loss: Assumes a 30-year lifetime for solar panels, with no early attrition;
- Early-loss: Takes account of "infant", "mid-life" and "wear-out" failures before the 30-year lifespan.

Overview of global PV panel waste projections, 2016-2050



Policy action is needed to address the challenges ahead, with enabling frameworks being adapted to the needs and circumstances of each region or country. Countries with the most ambitious PV targets are expected to account for the largest shares of global PV waste in the future, as outlined by case studies in this report. By 2030 the top three countries for cumulative projected PV waste are projected to include China, Germany and Japan. At the end of 2050 China is still forecast to have accumulated the greatest amount of waste but Germany is overtaken by the United States of America (US). Japan comes next followed by India.

Cumulative waste volumes of top five countries for of end-of-life PV panels in 2050

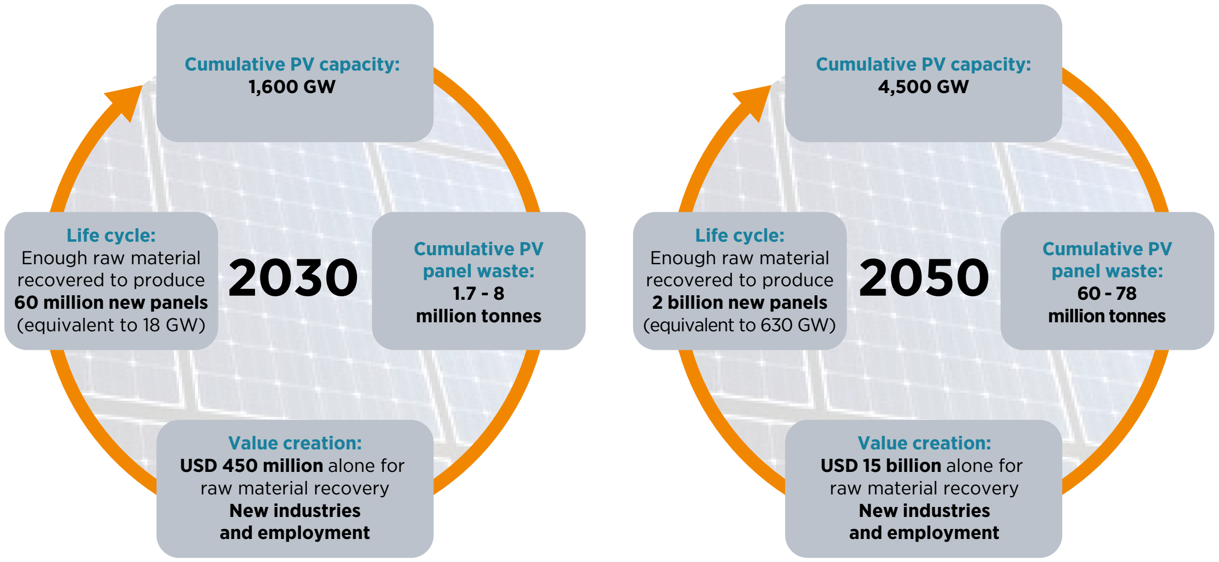


At present, only the European Union (EU) has adopted PV-specific waste regulations. Most countries around the world classify PV panels as general or industrial waste. In limited cases, such as in Japan or the US, general waste regulations may include panel testing for hazardous material content as well as prescription or prohibition of specific shipment, treatment, recycling and disposal pathways. The EU, however, has pioneered PV electronic waste (e-waste) regulations, which cover PV-specific collection, recovery and recycling targets. Based on the extended-producer-responsibility principle, the EU Waste Electrical and Electronic Equipment (WEEE) Directive requires all producers supplying PV panels to the EU market (wherever they may be based) to finance the costs of collecting and recycling end-of-life PV panels put on the market in Europe. Lessons can be learned from the experience of the EU in creating its regulatory framework to help other countries develop locally appropriate approaches.

End-of-life management could become a significant component of the PV value chain.[1] As the findings of the report underline, recycling PV panels at their end-of-life can unlock a large stock of raw materials and other valuable components. The recovered material injected back into the economy can serve for the production of new PV panels or be sold into global commodity markets, thus increasing the security of future raw material supply. Preliminary estimates suggest that the raw materials technically recoverable from PV panels could cumulatively yield a value of up to USD 450 million (in 2016 terms) by 2030. This is equivalent to the amount of raw materials currently needed to produce approximately 60 million new panels, or 18 GW of power-generation capacity. By 2050, the recoverable value could cumulatively exceed USD 15 billion, equivalent to 2 billion panels, or 630 GW.

1. *The value creation in different segments of the solar value chain has been studied in IRENA's publications "The Socio-economic Benefits of Solar and Wind" (2014) and "Renewable Energy Benefits: Leveraging Local Industries" (2016 forthcoming).*

Potential value creation through PV end-of-life management



End-of-life management for PV panels will spawn new industries, can support considerable economic value creation, and is consistent with a global shift to sustainable long-term development. New industries arising from global PV recycling can yield employment opportunities in the public and private sectors. In the public sector, jobs may be created in local governments responsible for waste management, such as municipalities and public waste utilities, but also public research institutes. Solar PV producers and specialised waste management companies may become the main employment beneficiaries in the private sector. Opportunities could also emerge in developing or transitioning economies, where waste collection and recycling services are often dominated by informal sectors. Here, PV waste management systems could generate additional employment, especially in the repair/reuse and recycling/treatment industries, while encouraging better overall PV waste management practices.

PV end-of-life management also offers opportunities relating to each of the 'three Rs' of sustainable waste management:

- **Reduce**

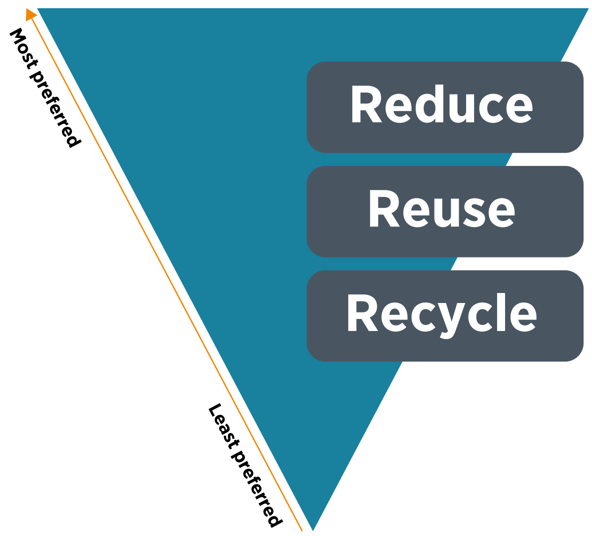
As research and development (R&D) and technological advances continue with a maturing industry, the composition of panels is expected to require less raw material. Today, two-thirds of globally manufactured PV panels are crystalline silicon (c-Si). These are typically composed of more than 90% glass, polymer and aluminium, which are classified as non-hazardous waste. However, the same panels also include such hazardous materials as silver, tin and lead traces. Thin-film panels, by comparison, are over 98% non-hazardous glass, polymer and aluminium, combined with around 2% copper and zinc (potentially hazardous) and semiconductor or other hazardous materials. These include indium, gallium, selenium, cadmium, tellurium and lead. Hazardous materials are typically subject to rigorous treatment requirements with specific classifications depending on the jurisdiction.

By 2030, given current trends in R&D and panel efficiency, the raw material inputs for c-Si and thin-film technologies could be reduced significantly. This would decrease the use of hazardous and rare materials in the production process and consequently improve the recyclability and resource recovery potential of end-of-life panels.

- **Reuse**

Rapid global PV growth is expected to generate a robust secondary market for panel components and materials. Early failures in the lifetime of a panel present repair and reuse opportunities. Repaired PV panels can be resold on the world market at a reduced market price. Even partly repaired panels or components might find willing buyers in a second-hand market. This secondary market presents an important opportunity for buyers in countries with limited financial resources which still want to engage in the solar PV sector.

Preferred options for PV waste management



- **Recycle**

As current PV installations reach the final decommissioning stage, recycling and material recovery will be preferable to panel disposal. The nascent PV recycling industry typically treats end-of-life PV panels through separate batch runs within existing general recycling plants. This allows for material recovery of major components. Examples include glass, aluminium and copper for c-Si panels that can be recovered at cumulative yields greater than 85% of total panel mass. In the long term, dedicated panel recycling plants can increase treatment capacities and maximise revenues owing to better output quality and the ability to recover a greater fraction of embodied materials. PV-specific panel recycling technologies have been researched and implemented to some extent for the past decade. Learning from past, ongoing and future research is important to enable the development of specialised, cost- and material recovery-efficient recycling plants. Technical and regulatory systems, however, need to be established to guarantee that PV panel waste streams are sufficiently large for profitable operation.

THE WAY FORWARD

Industry, governments and other stakeholders need to prepare for the anticipated waste volumes of solar PV panels in the following three main ways:

- **Adopt PV-specific waste regulations**

Sustainable end-of-life management policies for PV panels can be achieved through an enabling regulatory framework, along with the institutions needed to implement it. Addressing the growth of PV waste and enabling related value creation will not be easy in the absence of legally binding end-of-life standards specific to PV panels. The development of PV-specific collection and recycling regulations, including recycling and treatment standards for PV panels, will be crucial to consistently, efficiently and profitably deal with increasing waste volumes. Furthermore, waste regulations or policies can promote more sustainable life cycle practices and improve resource efficiency. Lessons learned from the experiences summarised in this report can help guide the development of regulatory approaches.

More data and analyses are needed at the national level to support the establishment of suitable regulatory and investment conditions. As a first step, accurate assessments of waste panel markets will require better statistical data than is currently available. This should include regular reporting and monitoring of PV panel waste systems, with amounts of waste produced by country and technology; composition of this waste stream; and other aspects of PV waste management. In addition, installed system performance and, in particular, the causes and frequency of system failures should be reported to provide clearer estimates of future end-of-life panel waste. The resulting country-level waste and system performance data would improve the viability of how PV panel waste management is organised, expand knowledge of material recovery potential and provide a foundation for sound regulatory frameworks. Further data to assess the full range of value creation, including socio-economic benefits, will also help to stimulate end-of-life market growth for solar PV.

- **Expand waste management infrastructure**

Management schemes for PV waste should be adapted to the unique conditions of each country or region. As case studies on Germany and the United Kingdom show, different waste management frameworks have emerged from the national implementation of the EU WEEE Directive. These experiences can provide a variety of lessons and best practices from which other PV markets can benefit. Rapidly expanding PV markets such as Japan, India and China still lack specific regulations

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covering PV panel waste. However, they have started preparing for future waste streams through R&D and the establishment of long-term policy goals. In the absence of sufficient waste volumes or country-specific technical know-how, regional markets for waste management and recycling facilities also help to maximise value creation from PV waste.

Co-ordination mechanisms between the energy and waste sectors are essential to supporting PV end-of-life management. A wide array of energy stakeholders is usually involved in the decommissioning stage of a PV project, which includes dismantling, recycling and disposal. These stakeholders include project developers, construction companies, panel producers and others. Traditionally, the waste sector has only been involved in a limited way (e.g. disposal of PV panel waste at landfill sites and/or with general waste treatment). However, with increasing waste volumes and related recycling opportunities, waste management companies will become an important player in PV end-of-life activities. This is already the case in several EU countries. In accordance with the extended-producer-responsibility principle, producers in these countries provide the financing for waste management and delegate the treatment and recycling of PV panels to the waste sector. The development of industrial clusters that promote co-operation across energy and waste sector stakeholders can be effective in stimulating innovation and contributing to spillover effects.

- **Promote ongoing innovation**

R&D and skills development are needed to support additional value creation from PV end-of-life panels. 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. Pressure to reduce PV panel prices is already driving more efficient mass production and material use, material substitutions, and the introduction of new, higher-efficiency technologies. To improve even further, additional skills development is needed. Research and education programmes are critical to not only achieve the technical goals but also train the next generation of scientists, engineers, technicians, managers etc. Such jobs will be required to develop the technical, regulatory, logistics and management systems necessary to maximise value extracted from growing PV waste streams. In addition, specific education and training on PV panel repairs can help to extend the lifetime of PV panels that show early failures. Material recycling for PV panels faces another barrier: recovered raw materials often lack the quality needed to achieve maximum potential value because recycling processes are not fully developed. Increased R&D for PV panel end-of-life treatment technologies and techniques could help close this gap and enable improved and efficient recovery of raw materials and components. Just as importantly, technological R&D must be coupled with prospective techno-economic and environmental analyses to maximise societal returns, minimise detrimental outcomes and avoid unintended consequences.

In the years ahead, policy-makers and PV stakeholders must prepare for the rise of panel waste and design systems to capitalise on the resulting opportunities. Unlocking end-of-life value from PV panels calls for targeted actions like those described above and, most importantly, appropriately designed frameworks and regulations. With the right conditions in place, end-of-life industries for solar PV can thrive as an important pillar of the infrastructure for a sustainable energy future.


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INTRODUCTION

The deployment of PV technology has grown dramatically in recent years, reaching a cumulative global installed capacity of 222 GW at the end of 2015 (IRENA, 2016b). PV offers economic and environmentally friendly electricity production but like any technology it ages and ultimately requires decommissioning (which includes dismantling, recycling and disposal). As PV increasingly becomes a global commodity, and to ensure its sustainable future, stakeholders involved with each step of the product life cycle must implement sound environmental processes and policies, including responsible end-of-life treatment. Regulatory frameworks that support the early development of life cycle management techniques and technologies will foster such processes and policies.

This report aims to look ahead of the curve, projecting future PV panel waste volumes in leading solar markets and distilling lessons from current PV waste management approaches. The intention is that other countries can then move faster up the learning curve with technological and regulatory systems dealing with PV panel waste.

In mature and saturated markets for products like automobiles in Europe or the US, the ratio of waste to new products is more or less constant. By contrast, the ratio of waste panels to new installed panels is currently very low at 0.1% (around 43,500 metric tonnes of waste, and 4 million metric tonnes of new installations estimated by end of 2016).[2] This is because the global PV market is still young, and PV systems typically last 30 years. Findings in this report show that a large increase in PV waste is projected to emerge globally around 2030. Some regions, like the EU, will start generating important waste volumes earlier because of their larger-scale adoption of PV since the 1990s. The proportion of global PV panel waste to new installations is estimated to increase steadily over time, reaching 4%-14% in 2030 and climbing to over 80% in 2050.

End-of-life management with material recovery is preferable to disposal in terms of environmental impacts and resource efficiency as a way to manage end-of-life PV systems. When recycling processes themselves are efficient, recycling not only reduces waste and waste-related emissions but also offers the potential for reducing the energy use and emissions related to virgin-material production. This could be particularly significant for raw materials with high levels of impurities (e.g. semiconductor precursor material), which often require energy-intensive pre-treatment to achieve required purity levels. Recycling is also important for long-term management of resource-constrained metals used in PV.

2. Assuming 80-100 metric tonnes (t) per megawatt (MW). See Chapter 2.

The PV recycling industry is expected to expand significantly over the next 10-15 years. Annual end-of-life PV panel waste is projected to increase to more than 60-78 million metric tonnes cumulatively by 2050 according to this report's model. This increasing scale should improve the cost-effectiveness and energy/resource efficiency of recycling while stimulating the technical innovations needed to handle the wide variety of materials used in fast-evolving PV technologies.

This report highlights and demonstrates the importance and benefit of developing flexible regulatory frameworks. They ensure sustainable PV end-of-life management, and enable economically and environmentally efficient processes and technologies for product and material recovery processes. They stimulate associated socio-economic benefits like recovery of valuable materials, and foster new industries and employment.

As the first region witnessing large-scale PV deployment, the EU started to promote sustainable PV life cycle management in the early 2000s. The voluntary extended-producer-responsibility (EPR)[3] initiative PV CYCLE (PV CYCLE, 2016) was one example. This has led to the development of pilot and industrial-scale recycling facilities as well as the first comprehensive legal framework on PV panels: the Waste Electrical and Electronic Equipment (WEEE) Directive of 2012 (European Parliament and Council, 2012).[4] In other parts of the world, little specific legislation for handling end-of-life PV panels yet exists, and waste is handled under each country's legislative and regulatory framework for general waste treatment and disposal.

3. The OECD defines EPR as an environmental policy approach in which a producer's responsibility for a product is extended to the post-consumer stage of a product's life cycle. An EPR policy is characterised by (1) shifting responsibility (physically and/or economically; fully or partially) upstream towards the producers and away from governments and (2) the provision of incentives to producers to take into account environmental considerations when designing their products (OECD, 2015).

4. In the context of the WEEE Directive, PV panels have been clearly defined as pieces of electrical equipment designed with the sole purpose of generating electricity from sunlight for public, commercial, industrial, rural, and residential applications—the definition excludes balance-of-system components (such as inverters, mounting structures, and

The purpose of this joint IRENA and IEA-PVPS Task 12 report is to communicate existing technological and regulatory knowledge and experience, including best practice related to PV panel end-of-life waste management. The report also identifies opportunities for value creation from end-of-life PV by analysing potential environmental and socio-economic benefits based on novel projections of PV panel waste to 2050. The report consists of five main chapters.

Chapter 2 provides predictions of global PV growth which act as the baseline for quantifying future PV panel waste streams (globally and for specific countries). These results provide the context and motivation for the waste management policies and recycling technologies described in the remainder of the report.

Chapter 3 characterises the materials embodied in the different types of PV panels along with corresponding regulatory waste classification considerations that determine required treatment and disposal pathways for PV panels.

Chapter 4 describes general PV waste management options, explaining general waste management principles and the difference between voluntary and legal approaches. This is followed by summaries of country-specific current approaches to waste management in **Chapter 5**, including case studies of major current and future PV markets. These are Germany, the UK, the US, Japan, China and India.

Chapter 6 covers value creation from end-of-life PV by analysing opportunities to reduce, reuse and recycle, as well as resulting socio-economic benefits.

Finally, **Chapter 7** outlines the conclusions and way forward.


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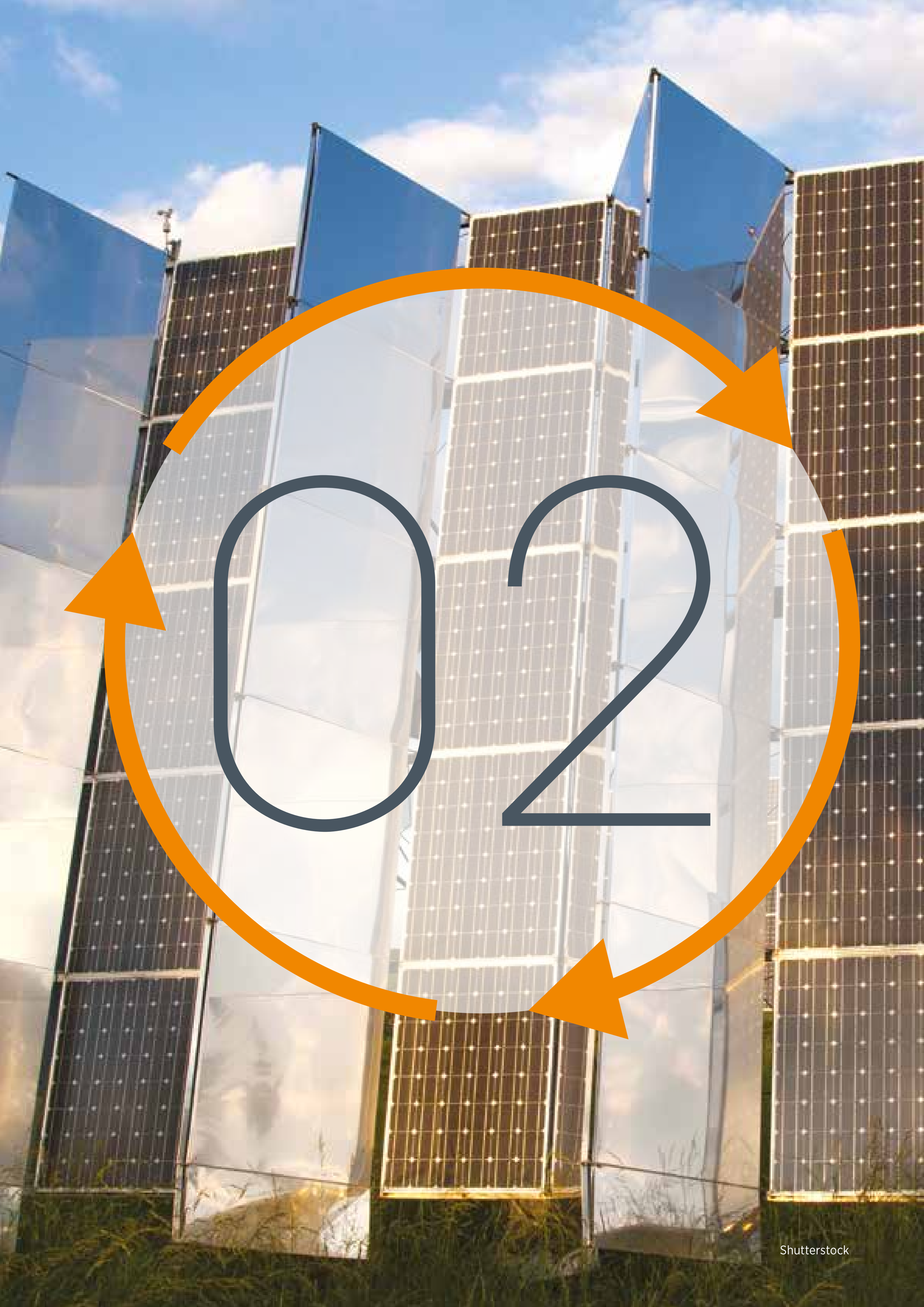

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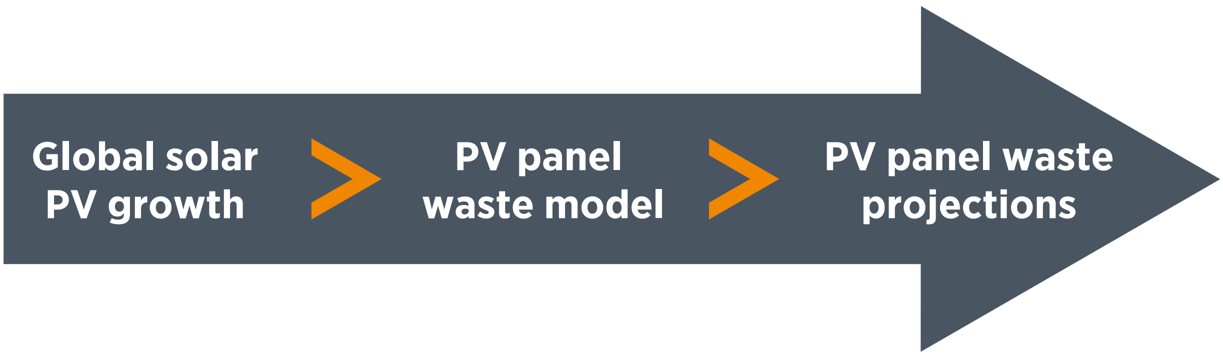
SOLAR PV PANEL WASTE PROJECTIONS

PV panel waste streams will increase alongside worldwide PV deployment. This publication is the first to quantify potential PV panel waste streams in the period until 2050.

As outlined in Figure 1, a three-step approach is used to quantify PV panel waste over time. First, this chapter analyses trends and future global solar PV growth rates from 2010 to 2050, which is a main input to waste volume estimation. Next, the PV panel waste model and main methodology used in this report are explained. The last section summarises the findings and provides PV panel waste predictions globally and by country.

Figure 1 Approach to estimating PV panel waste



2.1 GLOBAL SOLAR PV GROWTH

In 2015 capacity to generate renewable energy increased by 8.3% or 152 GW, the highest annual growth rate on record (IRENA, 2016b). Global solar PV capacity added in 2015 made up 47 GW of this increase, cumulatively reaching 222 GW at the end of 2015, up from 175 GW in 2014 (IRENA, 2016b). The bulk of these new installations was in non-traditional PV markets, consolidating the shift in major PV players. Traditional PV markets such as Europe and North America grew 5.2% and 6.3% in 2015 respectively. By contrast, Latin America and the Caribbean grew at a rate of 14.5%, and Asia at a rate of 12.4%. Asia alone thereby witnessed a 50% increase in solar PV capacity in 2015, with 15 GW of new PV capacity installed in China and another 10 GW in Japan. Main global PV leaders today include China (43 GW of cumulative installed capacity), Germany (40 GW), Japan (33 GW) and the US (25 GW).

To account for current and future waste streams for solar PV, global PV growth rates were projected until 2050. These rely on results from previous work on PV forecasts by both IRENA and the IEA. For projections to 2030, *REmap* (see Box 1), IRENA's roadmap for doubling the global share of renewables, was used (IRENA, 2016a). For 2030-2050, the projections are based on IEA's *Technology Roadmap on Solar Photovoltaic Energy* (see Box 2) (IEA, 2014).

Box 1 An overview of IRENA's REmap – a global renewable energy roadmap

IRENA's roadmap shows feasible, cost-effective ways to double renewables from 18% to 36% in the world's total final energy consumption by 2030. This is based on an in-depth analysis of the energy transition in 40 economies, representing 80% of global energy use. For each technology, including solar PV, power capacity deployment is calculated from the reference year 2010 in five-year increments to 2030. This takes into consideration existing technologies, their costs and the available timeframe.

The REmap analysis finds that doubling the renewables share is not only feasible but cheaper than not doing so once health and environmental factors are taken into account. The accelerated energy transition can boost economic growth, save millions of lives and combined with energy efficiency helps limit the global temperature increase to 2° Celsius in line with the Paris Agreement. To meet that goal, however, renewable energy deployment needs to happen six times faster. For decision-makers in the public and private sectors alike, this roadmap sends out an alert on the opportunities at hand and the costs of not taking them (IRENA, 2016a).

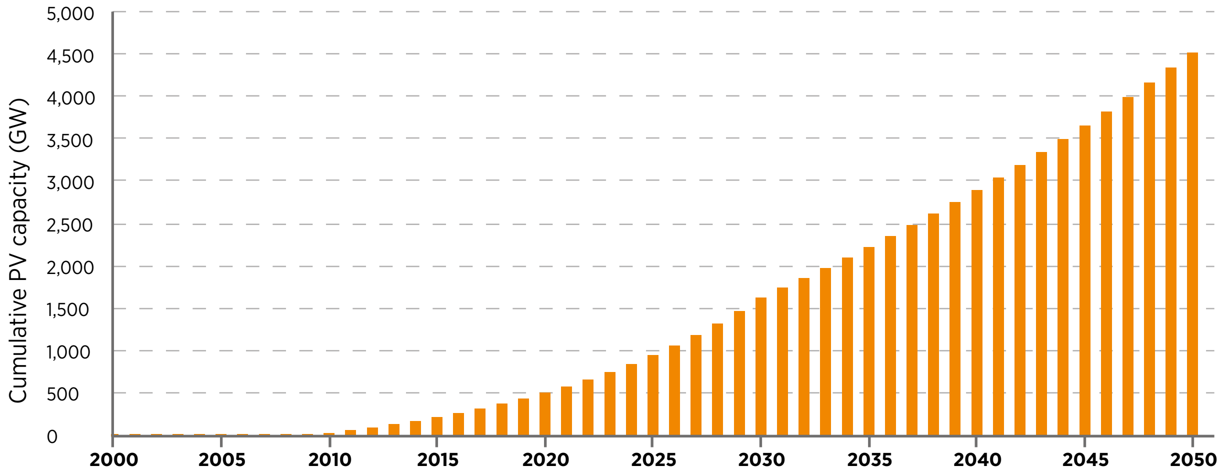
Box 2 An overview of the IEA's PV Technology Roadmap to 2050

To achieve the necessary reductions in energy-related CO_2 emissions, the IEA has developed a series of global technology roadmaps under international guidance and in close consultation with industry. The overall aim is to advance global development and uptake of key technologies to limit the global mean temperature increase to 2° Celsius in the long term. The roadmaps are not forecasts. Instead, they detail the expected technology improvement targets and the policy actions required to achieve that vision by 2050.

The PV Technology Roadmap is one of 21 low-carbon technology roadmaps and one of nine for electricity generation technologies. Based on the IEA's *Energy Technology Perspectives* (2014), this roadmap envisages the PV contribution to global electricity reaching 16% by 2050. This is an increase from 135 GW in 2013 to a maximum of 4,674 GW installed PV capacity in 2050. The roadmap assumes that the costs of electricity from PV in different parts of the world will converge as markets develop. This implies an average cost reduction of 25% by 2020, 45% by 2030 and 65% by 2050, leading to USD 40-160 per megawatt-hour, assuming a cost of capital of 8%. To achieve the vision in this roadmap, the total PV capacity installed each year needs to rise rapidly from 36 GW in 2013 to 124 GW per year on average. It would peak to 200 GW per year between 2025 and 2040. The vision is consistent with global CO_2 prices of USD 46/t CO_2 in 2020, USD 115/t CO_2 in 2030 and USD 152/t CO_2 in 2040 (IEA, 2014).

As shown in Figure 2, global cumulative PV deployment accelerated after 2010 and is expected to grow exponentially, reaching 1,632 GW in 2030 and about 4,512 GW in 2050.

Figure 2 Projected cumulative global PV capacity



Based on IRENA (2016) and IEA (2014)

To develop annual estimates of PV capacity between 2016 and 2030, an interpolation was made between IRENA's *REmap* estimates for 2015, 2020 and 2030. To achieve this, an average annual growth rate was calculated between each five-year period, amounting to 8.92%. In some selected countries, the individual growth rates may be adjusted higher or lower due to political and economic uncertainties foreseen. To extend the model projection to 2050, more conservative growth projections were assumed for 2030-2050 with annual growth rate of about 2.5%. This extrapolation was matched with the forecast of the IEA's PV Technology Roadmap.

The final projections of global PV growth to 2050 are shown in Table 1 and were used to model global waste streams in the next chapter.

Table 1 Projected cumulative PV capacity, 2015-2050, based on IRENA (2016) and IEA (2014)

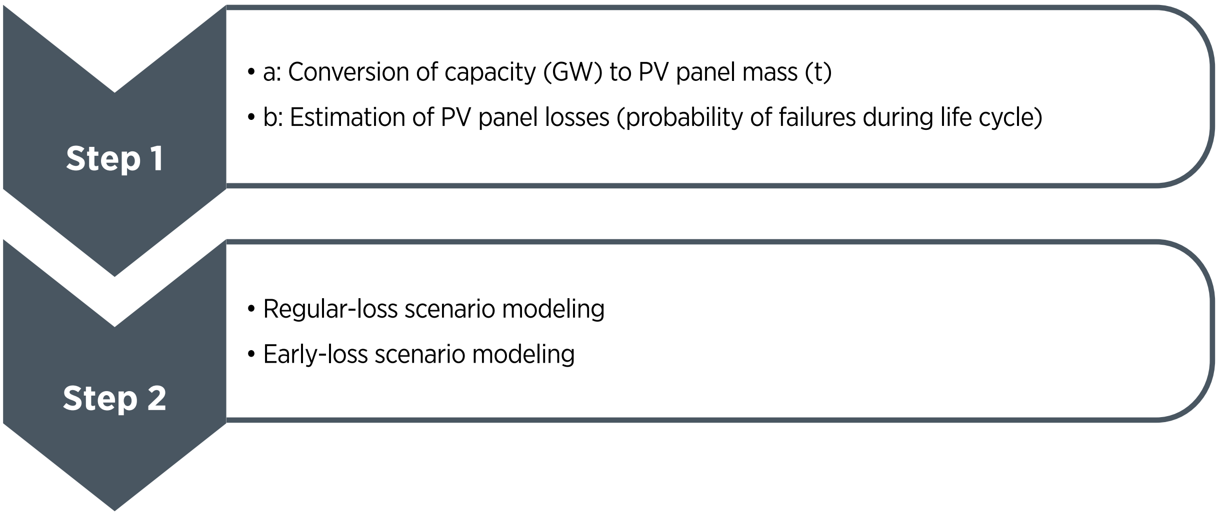
Year	2015	2020	2025	2030	2035	2040	2045	2050
Cumulative installed PV capacity (GW)	222	511	954	1,632	2,225	2,895	3,654	4,512

2.2 PV PANEL WASTE MODEL

The objective of this report is to quantify future PV panel waste streams. Most waste is typically generated during four primary life cycle phases of any given PV panel. These are 1) panel production 2) panel transportation 3) panel installation and use, and 4) end-of-life disposal of the panel. The following waste forecast model covers all life cycle stages except production. This is because it is assumed that production waste is easily managed, collected and treated by waste treatment contractors or manufacturers themselves and thus not a societal waste management issue.

Future PV panel waste streams can be quantified according to the model described in Figure 3. The two main input factors are the conversion and probability of losses during the PV panel life cycle (step 1a and 1b). They are employed to model two waste stream scenarios using the Weibull function, the regular-loss and the early- loss scenario (step 2).

Figure 3 Two-step PV panel waste model



The next section provides a step-by-step guide showing details of the methodology and underlying assumptions.

Step 1a: Conversion of capacity to PV panel mass (from gigawatts to metric tonnes)

Table 2 PV panel loss model methodology for step 1a

Model	Data input and references
• The model's exponential regression function converts gigawatts of PV capacity to metric tonnes of panel mass. • For each year, the annual conversion factor is calculated.	• Standard panel 1990-2013 data sheets (Photon, 2015) are used to extract supporting data for the exponential fit. Typical panel data were used in five-year periods from the biggest producers (Arco Solar, BP Solar, Kyocera, Shell Solar, Sharp, Siemens Solar, Solarex, Solarworld, Trina and Yingli). • Standard panel data are predicted using the 2014 International Technology Roadmap for Photovoltaic (ITRPV) as a baseline (Raithel, 2014) as well as other literature (Berry, 2014; IEA, 2014; IRENA, 2014; Marini *et al.*, 2014; Lux Research, 2013 and Schubert, Beaucarne and Hoornstra, 2013).

To estimate PV panel waste volumes,[5] installed and projected future PV capacity (megawatts or gigawatts-MW or GW) was converted to mass (metric tonnes-t), as illustrated in Table 2. An average ratio of mass of PV per unit capacity (t/MW) was calculated by averaging available data on panel weight and nominal power. For past PV panel production, the nominal power and weight of representative standard PV panel types was averaged from leading producers over five-year intervals (Photon, 2015). The panel data sheets of Arco, Siemens, BP, Solarex, Shell, Kyocera, Sharp, Solarworld and Trina were considered.

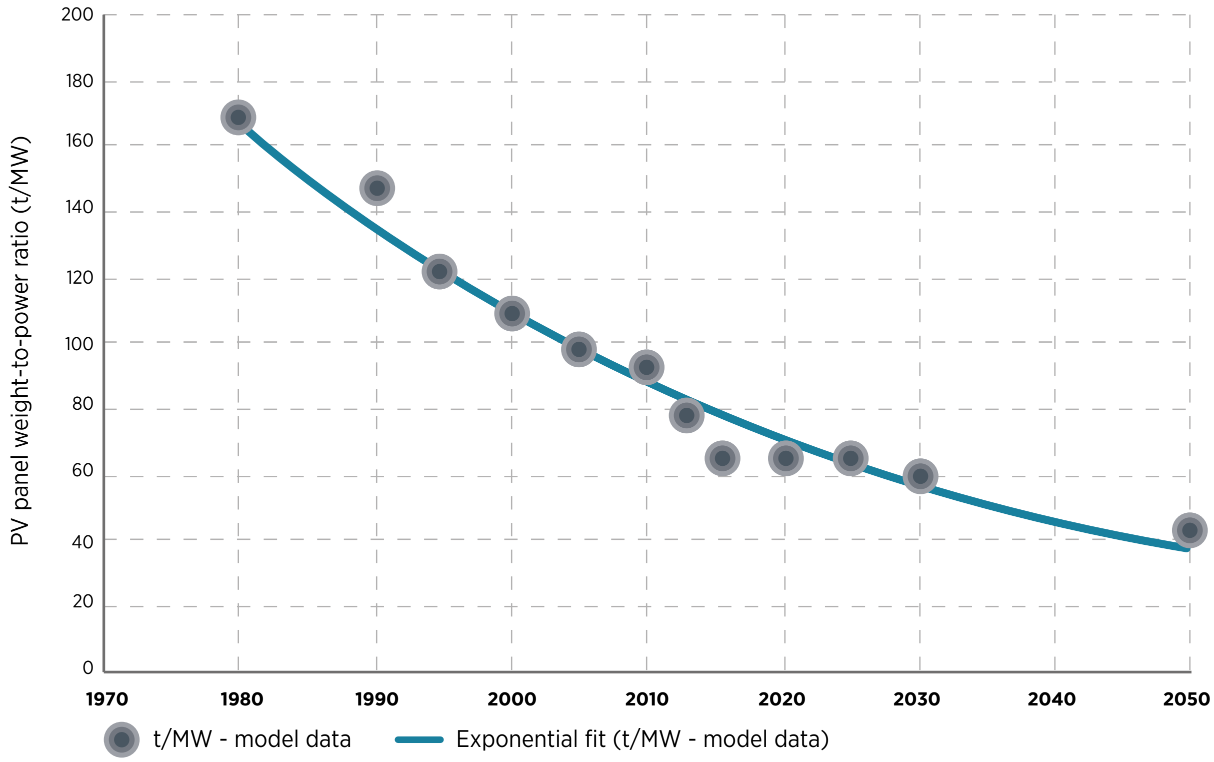
5. Note that 'volume' is used interchangeably in this report with the more accurate metric 'mass' despite the incongruence of units.

For future PV panel production, the data are based on recent publications (Berry, 2014; IEA, 2014; IRENA, 2014; Marini, 2014; Raithel, 2014; Lux Research, 2013 and Schubert, Beaucarne and Hoornstra, 2013).

This report's model includes a correction factor to account for panels becoming more powerful and lighter over time. This is due to optimisation of cell and panel designs as well as weight reductions from thinner frames, glass layers and wafers. The correction factor is based on an exponential least-square fit of weight-to-power ratio for historic and projected future panels.[6] Figure 4 shows how the weight-to-power ratio is continuously reduced over time due to further developments in PV technologies such as material savings and improved solar cell efficiencies.

6. In previous studies a constant factor of 100 t/MW was used as a first approximation (Sander et al., 2007). This report's approach is thus more reflective of expected panel weight per capacity change.

Figure 4 Exponential curve fit of projection of PV panel weight-to-power ratio (t/MW)



Step 1b: Probability of PV panel losses

Table 3 PV panel loss model methodology for step 1b

Model	Data input and references
• Infant failure • Midlife failure • Wear-out failure	• Assumptions on early losses were based on reports by TÜV, Dupont, SGS and others (IEA-PVPS, 2014a; Padlewski, 2014; Vodermeyer, 2013; DeGraaff, 2011).

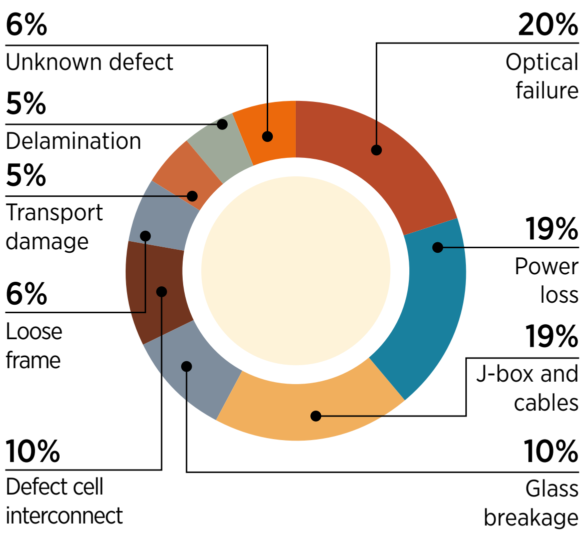
The potential origin of failures for rooftop and ground-mounted PV panels was analysed independently from PV technology and application field to estimate the probability of PV panels becoming waste before reaching their estimated end-of-life targets. The three main panel failure phases detected are shown in Table 3 (IEA-PVPS, 2014a):

- Infant failures defined as occurring up to four years after installation (average two years);
- Midlife failures defined as occurring about five to eleven years after installation;
- Wear-out failures defined as occurring about 12 years after installation until the assumed end-of-life at 30 years.

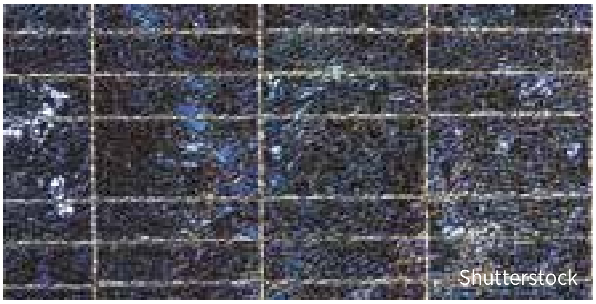
Empirical data on causes and frequency of failures during each of the phases defined above were obtained from different literature (IEA-PVPS, 2014a; Padlewski, 2014; Vodermayer, 2013 and DeGraaff, 2011). Independent of those phases, Figure 5 provides an overview of the main causes of PV panel failure.

7. C-Si panels constituted the largest share of surveyed technologies. The weight-to-power ratio was continuously reduced during the development of the PV technology by material savings and improved solar cell efficiencies (Photon, 2015).

Figure 5 Failure rates according to customer complaints



Based on IEA-PVPS (2014a)



The main infant failure causes include light-induced degradation (observed in 0.5%-5% of cases), poor planning, incompetent mounting work and bad support constructions. Many infant failures have been reported within the electrical systems such as junction boxes, string boxes, charge controllers, cabling and grounding.

Causes of midlife failures are mostly related to the degradation of the anti-reflective coating of the glass, discoloration of the ethylene vinyl acetate, delamination and cracked cell isolation.

Causes of frequently observed failures within all phases in the first 12 years - after exposure to mechanical load cycles (e.g. wind and snow loads) and temperatures changes - include potential induced degradation, contact failures in the junction box, glass breakage, loose frames, cell interconnect breakages and diode defects.

In the wear-out phase, failures like those reported in the midlife phase increase exponentially in addition to the severe corrosion of cells and interconnectors. Previous studies with statistical data on PV panel failures additionally observe that 40% of PV panels inspected suffered from at least one cell with microcracks. This defect is more commonly reported with newer panels manufactured after 2008 due to the thinner cells used in production.

These failures and probability of loss findings, alongside data from step 1a (conversion factors) are used to estimate PV panel waste streams (step 2).

On the basis of step 1a and 1b, two PV waste scenarios were defined (see Table 4) – the regular-loss scenario and early-loss scenario.

Step 2: Scenarios for annual waste stream estimation (regular-loss and early-loss scenarios)

Table 4 PV panel loss model methodology for step 2

Model	Data input and references

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)
	• 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).

Both scenarios are modelled using the Weibull function as indicated in the formula below. The probability of losses during the PV panel life cycle is thereby determined by the shape factor α that differs for the regular-loss and early-loss scenario.

The formula is:

$$F(t) = 1 - e^{-(t/T)^{\alpha}}$$

where

t = time in years

T = average lifetime

α = shape factor, which controls the typical S shape of the Weibull curve

Both scenarios assume a 30-year average panel lifetime and a 99.99% probability of loss after 40 years. A 30-year panel lifetime is a common assumption in PV lifetime environmental impact analysis (e.g. in life cycle assessments) and is recommended by the IEA-PVPS (Frischknecht *et al.*, 2016). The model assumes that at 40 years at the latest PV panels are dismantled for refurbishment and modernisation. The durability of PV panels is thus assumed to be in line with average building and construction product experiences such as façade elements or roof tiles. These also traditionally have a lifetime of 30-40 years.

Neither initial losses nor early losses were included in the **regular-loss scenario.** The results from Kuitsche (2010) are used directly, assuming an **alpha shape factor in this scenario of 5.3759** (see Table 5).

In the **early-loss scenario**, the following loss assumptions are made based on an analysis of the literature and expert judgement (IEA-PVPS, 2014a; Padlewski, 2014; Vodermayer, 2013 and DeGraaff, 2011):

- 0.5% of PV panels (by installed PV capacity in MW) is assumed to reach end-of-life because of damage during transport and installation phases[8];
- 0.5% of PV panels will become waste within two years due to bad installation;
- 2% will become waste after ten years;
- 4% will become waste after 15 years due to technical failures.

The early-loss scenario includes failures requiring panel replacement such as broken glass, broken cells or ribbons and cracked backsheet with isolation defects. However, only panels with serious functional or safety defects requiring entire replacement are included, while other defects that, for example, reduce power output or create panel discoloration are ignored.

In the early-loss scenario, the shape factor was calculated by a regression analysis between data points from literature and also considered early failures (see Table 5). The resulting **alpha shape factor of 2.4928 for the early-loss scenario** is lower than literature values presented. This is because it includes early defects that yield higher losses in the first 30 years and lower losses in later life should a panel last longer.

For each scenario (regular-loss and early-loss), the probability of failure value (alpha) is multiplied according to the Weibull function by the weight of panels installed in a given year. Since a bigger alpha value is used in the regular-loss scenario, the curve ascends smoothly and intersects with the early-loss scenario curve at the nominal lifetime point of 30 years. In line with the Weibull function and due to the different assigned alpha parameters, regular-loss and early-loss scenarios have the opposite effect after 30 years. Hence, the regular-loss scenario indicates a higher probability of loss from 30 years on (see Figure 6).

8. Most PV system installers might have to purchase excess panels to compensate for potential losses during transport and installation, which was accounted for in this model. The model assumes that 0.5% of panels are lost in the initial period and is lower than the rate assumed in Sander's model (2007).

Table 5 Overview of Weibull shape factors reported in the literature for modelling PV panel loss probability alongside baseline values selected for use in this study

Weibull shape factors	Kumar & Sarkan (Kumar, 2013)	Kuitsche (2010)	Zimmermann (2013)	Marwede (2013)	This study
Lower	9.982	3.3		8.2	
Upper	14.41	8.7484		12.8	
Baseline		5.3759 (represents regular-loss scenario)	5.3759		2.4928 (represents early-loss scenario)

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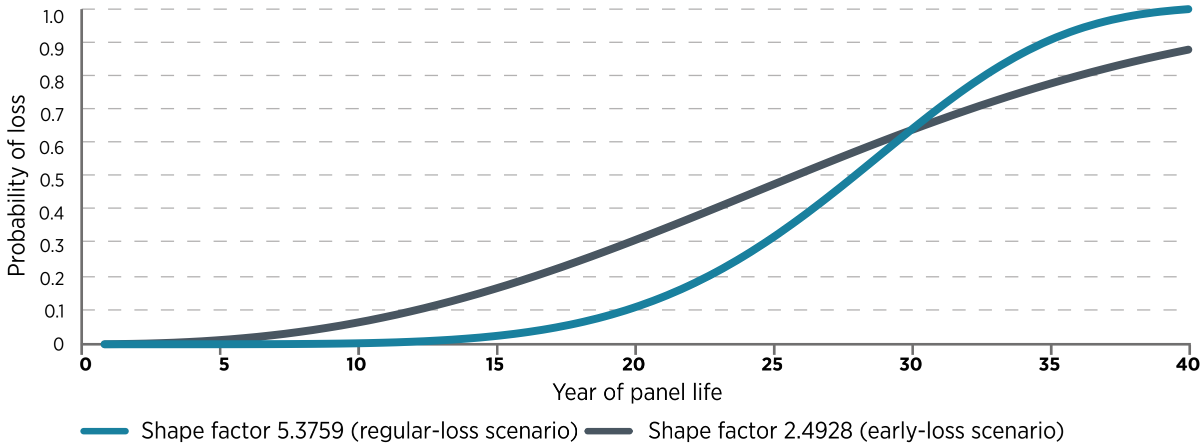
Figure 6 Example of Weibull curve with two different shape factors from Table 5



Box 3 Uncertainty analysis

This study is the first to quantify PV panel waste at a global scale and across different PV technologies. This means 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. Further, they stimulate the need for more assessments. This box gives a short overview of the three main areas of uncertainty that could affect the results and conclusions of the study. The uncertainty related to the cumulative installed PV capacity to 2050 is an input factor for the model and therefore not further considered here.

First and foremost, the data available on PV panel failure modes and mechanisms is only a small fraction of the full number of panels installed worldwide. This means the baseline assumptions bear some uncertainties and will need to be refined as more data become available. The rapid evolution of PV materials and designs adds another level of complexity and uncertainty to estimates.

Moreover, failure does not necessarily mean that a panel will enter the waste stream at the given year of failure. This is because some failures might not be detected right away or may be tolerated for years. For example, if a PV panel still produces some output, even if lower than when initially commissioned, replacement may not be financially justified. Hence, data available on the different determinants of the end of a PV panel's lifetime are often interlinked with non-technical and system aspects that are very difficult to predict.

The last major uncertainty relates to key assumptions used to model the probability of PV panel losses versus the life cycle of the panels using the Weibull function. To calculate the Weibull shape factors for this study's regular-loss and early-loss scenarios, existing literature was reviewed. The results of the analysis are presented in Table 5. It is assumed that the early losses in the early-loss scenario are constant into the future. In other words, no learning to reduce premature losses is taken into account. The model also excludes repowering PV plants.

In summary, this study develops two scenarios – regular-loss and early-loss – to account for the above uncertainties about the mechanisms and predicted timing of panel failures. To better estimate potential PV panel waste streams in the future, national and regional decisions on PV waste stream regulation must include a monitoring and reporting system. This will yield improved statistical data to strengthen waste stream forecasts and enable a coherent framework for policy regulations.

The above modelling produces PV panel waste projections by country up to 2050. The next section summarises the findings of the model.

2.3 PV PANEL WASTE PROJECTIONS

Global PV panel waste outlook

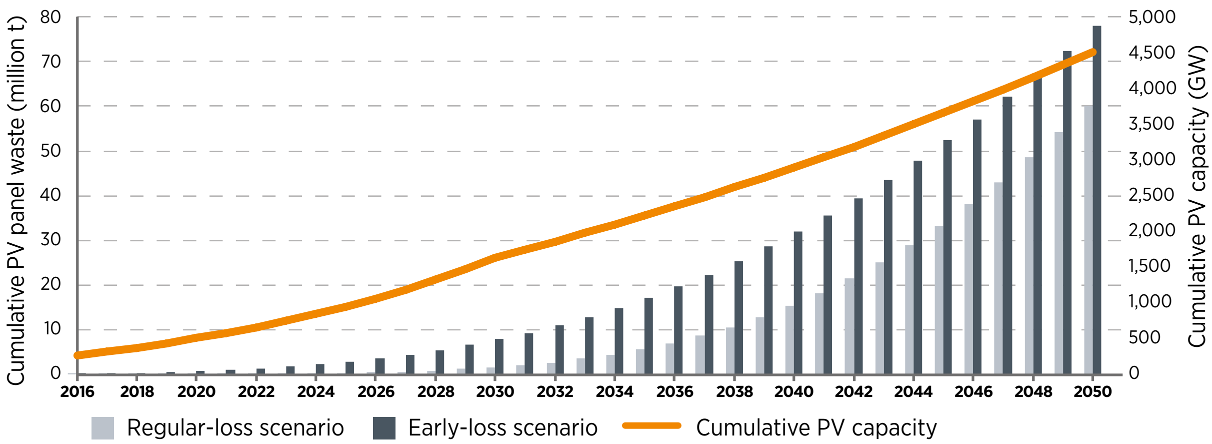
Total annual e-waste in the world today accounts for 41.8 million t (Baldé, 2015). By comparison, cummulative PV panel waste will account for no more than 250,000 t by the end of 2016 according to the early-loss scenario modelled in this report. This represents only 0.6% of total e-waste today but the amount of global waste from PV panels will rise significantly over the next years.

Figure 7 displays **cumulative PV panel waste results** up to 2050.

- In the regular-loss scenario, the PV panel waste accounts for 43,500 t by end 2016 with an increase projected to 1.7 million t in 2030. An even more drastic rise to approximately 60 million t could be expected by 2050.
- The early-loss scenario projection estimates much higher total PV waste streams, with 250,000 t alone by the end of 2016. This estimate would rise to 8 million t in 2030 and total 78 million t in 2050. This is because the early-loss scenario assumes a higher percentage of early PV panel failure than the regular-loss scenario.

Based on the best available information today, this report suggests the actual future PV panel waste volumes will most likely fall somewhere between the regular-loss and early-loss values.

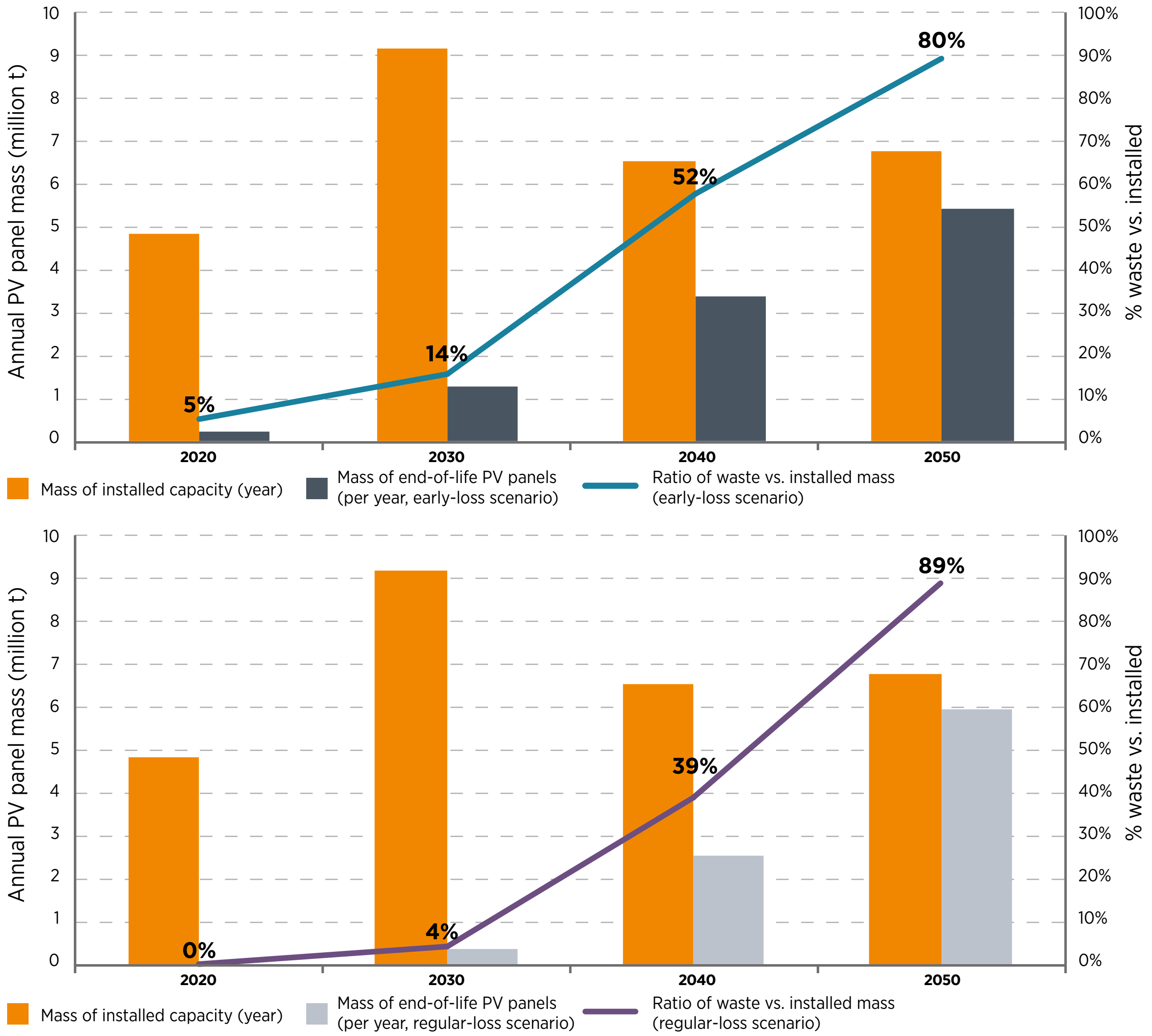
Figure 7 Estimated cumulative global waste volumes (million t) of end-of-life PV panels



Annual PV panel waste up to 2050 is modelled in Figure 8 by illustrating the evolution of PV panel end-of-life and new PV panel installations as a ratio of the two estimates. This ratio starts out low at 5% at the end of 2020, for instance (i.e. in the early-loss scenario, annual waste of 220,000 t compared to 5 million t in new installations). However, it increases over time to 4%-14% in 2030 and 80%-89% in 2050. At that point, 5.5-6 million t of PV panel waste (depending on scenario) is predicted in comparison to 7 million t in new PV panel installations.

A feature of the Weibull curve shape factors for the two modelled scenarios is that the estimated waste of both scenarios intersects. The scenario predicting greater waste panels in a given year then switches. The intersection is projected to take place in 2046. This modelling feature can be observed in Figure 8 which shows the volume of PV panel waste amounting to over 80% of the volume of new installations as a result of the early-loss scenario in 2050. The comparable figure for the regular-loss scenario exceeds 88% in the same year.

Figure 8 Annually installed and end-of-life PV panels 2020-2050 (in % waste vs. t installed) by early-loss scenario (top) and regular-loss scenario (bottom)



Waste projections by country

Detailed PV panel waste estimates by selected countries are displayed in Table 6 from 2016 up to 2050. The countries were chosen according to their regional leadership when it comes to PV deployment and expected growth.

The projections are modelled using the same Weibull function parameters as the global estimates of the previous section. Projected waste volumes of PV panels in individual countries are based on existing and future annual installations and rely on input data available for each country. The historic cumulative installed PV capacity was used as benchmark in each country alongside future projections to 2030 using IRENA's *REmap* and for 2030 to 2050 IEA's *PV Technology Roadmap*, with a simple interpolation.

Table 6 Modelled results of estimated cumulative waste volumes of end-of-life PV panels by country (t)

Year	**2016**		**2020**		**2030**		**2040**		**2050**	
Scenario (regular-loss/early-loss)	**regular loss**	**early loss**	**regular loss**	**early loss**	**regular loss**	**early loss**	**regular loss**	**early loss**	**regular loss**	**early loss**
Asia										
China	5,000	15,000	8,000	100,000	200,000	1,500,000	2,800,000	7,000,000	13,500,000	19,900,000
Japan	7,000	35,000	15,000	100,000	200,000	1,000,000	1,800,000	3,500,000	6,500,000	7,600,000
India	1,000	2,500	2,000	15,000	50,000	325,000	620,000	2,300,000	4,400,000	7,500,000
Republic of Korea	600	3,000	1,500	10,000	25,000	150,000	300,000	820,000	1,500,000	2,300,000
Indonesia	5	10	45	100	5,000	15,000	30,000	325,000	600,000	1,700,000
Malaysia	20	100	100	650	2,000	15,000	30,000	100,000	190,000	300,000
Europe										
Germany	3,500	70,000	20,000	200,000	400,000	1,000,000	2,200,000	2,600,000	4,300,000	4,300,000
Italy	850	20,000	5,000	80,000	140,000	500,000	1,000,000	1,200,000	2,100,000	2,200,000
France	650	6,000	1,500	25,000	45,000	200,000	400,000	800,000	1,500,000	1,800,000
United Kingdom	250	2,500	650	15,000	30,000	200,000	350,000	600,000	1,000,000	1,500,000
Turkey	30	70	100	350	1,500	11,000	20,000	100,000	200,000	400,000
Ukraine	40	450	150	2,500	5,000	25,000	50,000	100,000	210,000	300,000
Denmark	80	400	100	2,000	4,000	22,000	40,000	70,000	130,000	125,000
Russian Federation	65	65	100	350	1,000	12,000	20,000	70,000	150,000	200,000
North America										
United States of America	6,500	24,000	13,000	85,000	170,000	1,000,000	1,700,000	4,000,000	7,500,000	10,000,000
Mexico	350	800	850	1,500	6,500	30,000	55,000	340,000	630,000	1,500,000
Canada	350	1,600	700	7,000	13,000	80,000	150,000	300,000	650,000	800,000
Middle East										
United Arab Emirates	0	10	50	100	3,000	9,000	20,000	205,000	350,000	1,000,000
Saudi Arabia	200	250	300	1,000	3,500	40,000	70,000	220,000	450,000	600,000
Africa										
South Africa	350	550	450	3,500	8,500	80,000	150,000	400,000	750,000	1,000,000
Nigeria	150	200	250	650	2,500	30,000	50,000	200,000	400,000	550,000
Morocco	0	25	10	100	600	2,000	4,000	32,000	50,000	165,000
Oceania										
Australia	900	4,500	2,000	17,000	30,000	145,000	300,000	450,000	900,000	950,000
Latin America and Caribbean										
Brazil	10	10	40	100	2,500	8,500	18,000	160,000	300,000	750,000
Chile	150	200	250	1,500	4,000	40,000	70,000	200,000	400,000	500,000
Ecuador	10	15	15	100	250	3,000	5,000	13,000	25,000	35,000
Total World	**43,500**	**250,000**	**100,000**	**850,000**	**1,700,000**	**8,000,000**	**15,000,000**	**32,000,000**	**60,000,000**	**78,000,000**
Sum of Leading Countries	**28,060**	**187,255**	**72,160**	**668,500**	**1,352,850**	**6,442,500**	**12,252,000**	**26,105,000**	**48,685,000**	**67,975,000**
Rest of the World	**15,440**	**62,745**	**27,840**	**181,500**	**347,150**	**1,557,500**	**2,748,000**	**5,895,000**	**11,315,000**	**10,025,000**

PV panel waste projections until 2030

The results modelled indicate that the highest expected PV panel waste streams by 2030 are in Asia with up to 3.5 million t accumulated, depending on the scenario. Regional Asian champions in renewable energy deployment will therefore also experience the highest waste streams. For example, China will have an estimated installed PV capacity of 420 GW in 2030 and could accumulate between 200,000 t and 1.5 million t in waste by the same year. Japan and India follow, with projections of between 200,000 t and 1 million t, and 50,000-325,000 t in cumulative PV-waste by 2030 respectively.

Europe is predicted to present the second largest PV waste market with projected waste of up to 3 million t by 2030. Germany, with an anticipated 75 GW of PV capacity, is forecasted to face between 400,000 and 1 million t of PV panel waste by 2030. Other future significant PV waste markets are projected to include Italy and France.

With an expected cumulative 240 GW in deployed PV by 2030, the US will lead in terms of total installed PV capacity in North America. It is projected to generate waste between 170,000 and 1 million t by then. Countries such as Canada (up to 80,000 t) and Mexico (up to 30,000 t) will also experience rising PV waste streams by 2030.

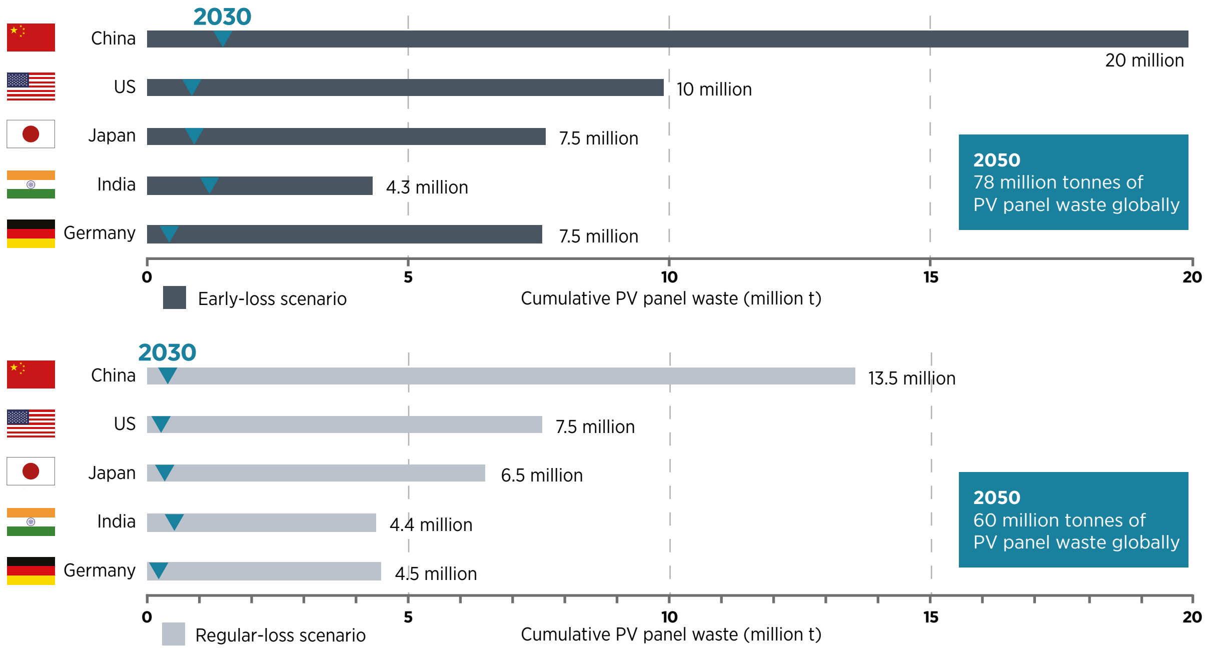
By 2030 Africa and Latin America are predicted to also see expanding PV-waste volumes. South Africa (8,500-80,000 t by 2030) and Brazil (2,500-8,500 t by 2030) will be regional leaders in this respect. Other significant PV-waste markets by 2030 will include the Republic of Korea with cumulative waste of 25,000-150,000 t and Australia with 30.000-145,000 t.

Waste volume surge in 2030-2050

Given the worldwide surge in PV deployment since 2010 and average lifetime and failure rates for panels, waste volumes are certain to increase more rapidly after 2030. Whereas in 2030 the top three PV panel waste countries are expected to include China, Germany and Japan, the picture slightly changes by 2050. By then, China is still predicted to have accumulated the greatest amount of waste (13.5-20 million t). However, Germany is overtaken by the US (7.5-10 million t), Japan is next (6.5-7.5 million t) and India follows (4.4-7.5 million t). The regular-loss and early-loss waste estimates by top five countries in 2030 and 2050 are displayed in Figure 9.

The analysis presented in this chapter develops quantitative estimates for PV panel waste streams until 2050 by country and region as well as on a global scale. At the same time, PV panels and consequently their waste differ in composition and regulatory classification, which will be discussed in the next chapter.

Figure 9 Estimated cumulative waste volumes of end-of-life PV panels by top five countries in 2050 by early-loss scenario (top) and regular-loss scenario (bottom)



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PV PANEL COMPOSITION AND WASTE CLASSIFICATION

PV panels create unique waste-management challenges along with the increasing waste streams forecast in Chapter 2. Apart from in the EU, end-of-life treatment requirements across the world for PV panels are set by waste regulations applying generically to any waste rather than dedicated to PV.

Waste regulations are based on the classification of waste. This classification is shaped according to the waste composition, particularly concerning any component deemed hazardous.

Waste classification tests determine permitted and prohibited shipment, treatment, recycling and disposal pathways. A comprehensive overview of the widely varying global PV waste classification is beyond the scope of this report. Instead, this chapter characterises the materials contained in PV panels and corresponding waste-classification considerations. These determine the required treatment and disposal pathways for PV panels when other more specific waste classifications and regulations are not applicable.

Table 7 Market share of PV panels by technology groups (2014-2030)

<table>
<tr><th>Technology</th><th></th><th>2014</th><th>2020</th><th>2030</th></tr>
<tr><td rowspan="4">Silicon-based (c-Si)</td><td>Monocrystalline</td><td rowspan="4">92%</td><td rowspan="4">73.3%</td><td rowspan="4">44.8%</td></tr>
<tr><td>Poly- or multicrystalline</td></tr>
<tr><td>Ribbon</td></tr>
<tr><td>a-Si (amorph/micromorph)</td></tr>
<tr><td rowspan="2">Thin-film based</td><td>Copper indium gallium (di)selenide (CIGS)</td><td>2%</td><td>5.2%</td><td>6.4%</td></tr>
<tr><td>Cadmium telluride (CdTe)</td><td>5%</td><td>5.2%</td><td>4.7%</td></tr>
<tr><td rowspan="4">Other</td><td>Concentrating solar PV (CPV)</td><td rowspan="4">1%</td><td>1.2%</td><td>0.6%</td></tr>
<tr><td>Organic PV/dye-sensitised cells (OPV)</td><td>5.8%</td><td>8.7%</td></tr>
<tr><td>Crystalline silicon (advanced c-Si)</td><td>8.7%</td><td>25.6%</td></tr>
<tr><td>CIGS alternatives, heavy metals (e.g. perovskite), advanced III-V</td><td>0.6%</td><td>9.3%</td></tr>
</table>

Based on Fraunhofer Institute for Solar Energy Systems (ISE) (2014), Lux Research (2013) and author research

3.1 PANEL COMPOSITION

Technology trends

To achieve optimal waste treatment for the distinct PV product categories, the composition of PV panels needs to be taken into consideration. PV panels can be broken down according to the technology categories shown in Table 7. The different technology types typically differ in terms of materials used in their manufacturing and can contain varying levels of hazardous substances that must be considered during handling and processing.

C-Si PV is the oldest PV technology and currently dominates the market with around 92% of market share (ISE, 2014). Multicrystalline silicon panels have a 55% and monocrystalline silicon panels a 45% share of c-Si technology respectively. Due to low efficiency ratios, a-Si products have been discontinued in recent years, and the market share nowadays is negligible.

The two thin-film PV panel technologies make up 7% of the PV market, 2% for CIGS panels, and 5% for CdTe panels. The following analysis will not pay any more attention to CPV and other technologies because it only has a low market share at less than 1%.

Although the market share of novel devices is predicted to grow, mainstream products are expected to retain market dominance up to 2030, especially c-Si panels (Lux Research, 2013). As shown in Table 7, silicon technology has great potential for improvement at moderate cost if new process steps are implemented into existing lines. For example, an increase in usage of hetero-junction cells is predicted, providing higher efficiencies and performance ratios. According to Lux Research (2013 and 2014), CIGS technology has great potential for better efficiencies and may gain market share while CdTe is not expected to grow. In the long term, CIGS alternatives (e.g. replacing indium and gallium with zinc and tin), heavy metal cells including perovskite structures, and advanced III-V cells, might take nearly 10% of market share. The same can be said of OPV and dye-sensitised cells (Lux Research, 2014). Recent reports indicate OPV has reached efficiencies of 11% and dye-sensitised cells 12% (IEA, 2014).

In line with a PV market heavily dominated by c-Si PV, all the main panel manufacturers except for First Solar rely on silicon-based PV panel technologies. In 2015, the top ten manufacturers for PV panels represented 32 GW per year of manufacturing capacity, which is around two-thirds of the global PV market, estimated at 47 GW (see Table 8).

Table 8 Top ten PV panel manufacturers in 2015

	Thin-film	Silicon-based	Annual manufacturing capacity (MW)
Trina Solar		x	≤5,500
Canadian Solar		x	≤4,500
Jinko Solar		x	≤4,500
JA Solar		x	≤3,500
Hanwha Q CELLS		x	≤3,000
First Solar	x		≤3,000
Yingli		x	≤2,500
GCL System			≤2,000
Suntech Power		x	≤2,000
Renesola		x	≤1,500
Sum of top 10 PV panel manufacturers			**≥32,000**

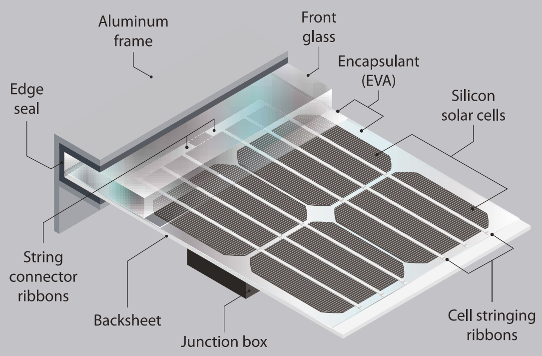
IRENA/IEA-PVPS estimates, 2016[9]

9. Uncertainty is a core characteristic of PV manufacturing capacity data due to inaccurate or incomplete manufacturing and export data on manufactuers discussed.

Component trends

The various components of major PV panel technologies will influence material and waste characterisation as well as the economics of treatment pathways. As shown in Boxes 4 and 5, the design of silicon-based and thin-film panels differs, affecting their composition accordingly.

Box 4 c-Si PV panel components



c-Si (monocrystalline) panel, National Renewable Energy Laboratory (NREL), 2016

c-Si technology consists of slices of solar-grade silicon, also known as wafers, made into cells and then assembled into panels and electrically connected.

The standard cell consists of a p-doped wafer with a highly doped pn-junction. The surface is usually textured and may show pyramid structures (monocrystalline silicon) or random structures (polycrystalline silicon) and an anti-reflective layer to minimise the reflection of light.

c-Si (monocrystalline) panel, National Renewable Energy Laboratory (NREL), 2016

To form an electric field, the front and back of the cell are contacted using grid-pattern printed silver and aluminium pastes. During a thermal process known as firing, the aluminium diffuses into the silicon and forms the back surface field. Advanced cell concepts add further layers to the wafer and utilise laser structuring and contacting to optimise the efficiencies of the cell (Raithel, 2014).

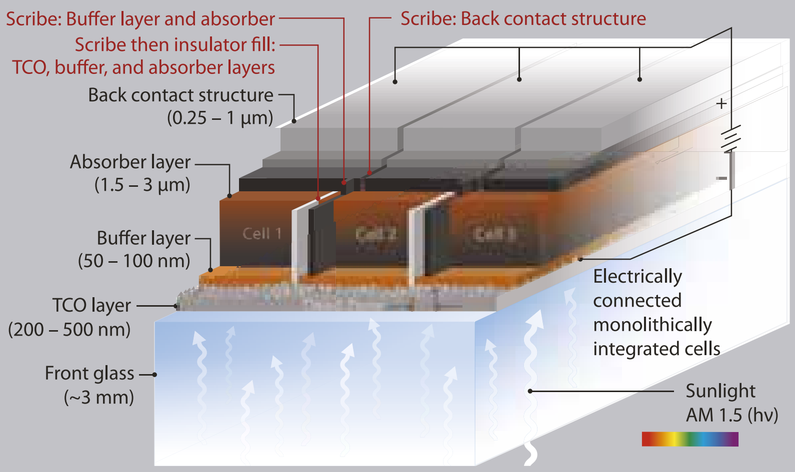
PV CYCLE

PV CYCLE

Box 5 Thin-film PV panel components

Thin-film panels consist of thin layers of semiconducting material deposited onto large substrates such as glass, polymer or metal.

Thin-film PV panel technologies can be broken down to two main categories, CIGS and CdTE.



Thin-film (monolithic integration) panel, NREL, 2016

CIGS panels use high light absorption as a direct semiconductor. Adjustment to the light spectrum is made by varying the ratios of the different elements in the compound semiconductor (e.g. indium, gallium and selenium). The compound has very good light absorption properties so much thinner semiconductor layers are needed to achieve similar efficiencies with C-Si panels (hence the term thin-film). CIGS cells are deposited on a metal back-contact (which can be composed of different metals and alloys) on glass substrates. Deposits on a steel carrier or polymer foil are also possible, producing flexible designs and high throughputs in roll-to-roll productions.

To form the junction needed for the PV effect, thin layers of cadmium sulfide usually form the hetero-transfer layers. Zinc oxide or other transparent conducting oxides are used as a transparent front contact, which may contain traces of other elements for better conductivity. Owing to the deposition of the cell layers on the substrate, the surface requires an encapsulation layer and front glass layer usually made of solar glass. This mainly protects the layers from long-term oxidation and degradation through water ingress, for example. Cadmium sulfide is needed as a buffer layer but it can be replaced by cadmium-free materials like zinc, zinc oxide, zinc selenide, zinc indium selenide or a chemical dependent of indium selenide (Bekkelund, 2013).

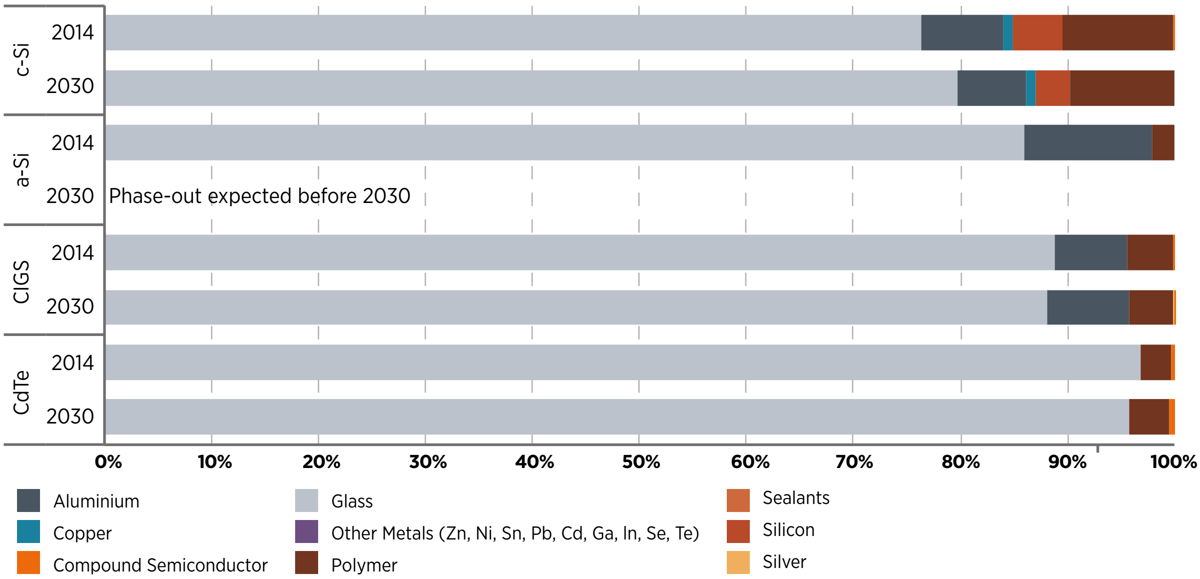
Furthermore, CIGS panels contain cell absorbers made of 'chalcopyrite,' a crystalline structure, with the general formula $Cu(In,Ga)(S,Se)_2$. Most frequently, a mixed crystal compound copper indium diselenide with various additions of gallium (either copper indium selenide or CIGS) is used in the manufacturing process. The substitution of other materials such as aluminium for indium, or silver for copper is currently under investigation. However, these variations will not be commercialised for several years (Pearce, 2014).

Though **CdTe panels** may be grown both in substrate and superstrate configurations, the superstrate configuration is preferred for better efficiencies (up to more than 17%). The transparent conductive oxide, intermediate cadmium sulphide (CdS) and CdTe layers, are deposited on the glass superstrate. The typical thickness of the CdTe layer today is 3 microns, which has the potential to be reduced to one micron in the future. The back layer can consist of copper/aluminium, copper/graphite or graphite doped with copper. An encapsulation layer laminates the back glass to the cell.

A typical crystalline PV panel with aluminium frame and 60 cells has a capacity of 270 watt-peak (Wp) and weighs 18.6 kilogrammes (kg) (e.g. Trina Solar TSM-DC05A.08). For a standard CdTe panel, 110 Wp can be assumed on average for 12 kg weight (e.g. First Solar FS-4100). A CIGS panel usually holds a capacity of 160 Wp and 20 kg (e.g. Solar Frontier SF160-S).

Research on the PV components concludes that progress in material savings and panel efficiencies will drive a reduction in materials use per unit of power and the use of potentially hazardous substances (Marini *et al.* (2014); Pearce (2014); Raithel (2014); Bekkelund (2013); NREL (2011) and Sander *et al.*, (2007)). On this basis, Figure 10 compares the materials employed for the main PV panel technologies between 2014 and 2030.

Figure 10 Evolution to 2030 of materials used for different PV panel technologies as a percentage of total panel mass



Based on Marini et al., (2014); Pearce (2014); Raithel (2014); Bekkelund (2013); NREL (2011) and Sander et al., (2007)

Crystalline silicon PV panels

By weight, typical **c-Si PV panels** today contain about 76% glass (panel surface), 10% polymer (encapsulant and backsheet foil), 8% aluminium (mostly the frame), 5% silicon (solar cells), 1% copper (interconnectors) and less than 0.1% silver (contact lines) and other metals (mostly tin and lead) (Sander *et al.*, 2007 and Wambach and Schlenker, 2006).

Industry trend studies such as the International Technology Roadmap for Photovoltaic (ITRPV) suggest new process technologies will prevail, encouraging thinner and more flexible wafers as well as more complex and manifold cell structures. These will require new interconnection and encapsulation techniques. For example, bifacial cell concepts offer high efficiencies in double glass panels made of two glass panes each two millimetres thick. An encapsulant layer reduction of up to 20% is possible owing to thinner wafers. Cells with back-contacts and metal wrap-through technologies that reduce shadow and electrical losses (known as hetero-junction concept cells) are equally expected to gain significant market share (Raithel, 2014).

By 2030 the glass content of c-Si panels is predicted to increase by 4% to a total of 80% of the weight's panel. The main material savings will include a reduction in silicon from 5% down to 3%, a 1% decrease in aluminium and a very slight reduction of 0.01% in other metals. Specific silver consumption is expected to be further decreased by better metallisation processes and replacements with copper or nickel/copper layers (Raithel, 2014).

In today's market, the most efficient panels with back junction-interdigitated back-contacts have shown efficiencies of about 21%. Hetero-junction technologies have achieved 19%. The average efficiency of a c-Si panel has grown by about 0.3% per year in the last ten years (Raithel, 2014).

a-Si PV panels have lost significant market share in recent years and do not contain significant amounts of valuable or hazardous materials (see Figure 10). Thus, they will most likely not require special waste treatment in the future. This section and the rest of the report therefore does not cover a-Si panels.

In **multi-junction cell design**, two (tandem) or more cells are arranged in a stack. In all cases the upper cell(s) have to be transparent in a certain spectrum to enable the lower cells to be active. By tailoring the spectrum sensitivity of the individually stacked cells, a broader range of sunlight can be absorbed, and the total efficiency maximised. Such cell types are used in a-Si, c-Si and concentrator cells. The low cost of c-Si today allows cost-efficient mass production of high-efficiency multi-junction cells. This can be combined, for example, with III-V alloys, chalcogenides and perovskites expected to perform extremely well even in non-concentrating tracker applications (Johnson, 2014).

Thin-film panels

Thin-film panels are technologically more complex than silicon-based PV panels. Glass content for c-Si panels is likely to increase by 2030. By contrast, it is likely to decrease for thin-film panels by using thinner and more stable glass materials. This in turn will encourage a higher proportion of compound semiconductors and other metals (Marini *et al.*, 2014 and Woodhouse *et al.*, 2013).

CIGS panels are today composed of 89% of glass, falling 1% to 88% in 2030. They contain 7% aluminium, rising 1% in 2030, and 4% polymer remaining stable. They will experience a slight reduction of 0.02% in other metals but a 0.2% increase in semiconductors. Other metals include 10% copper, 28% indium, 10% gallium and 52% selenium (Pearce, 2014; Bekkelund, 2013 and NREL, 2011).

CIGS panel efficiency is currently 15% and targeted at 20% and above in the long term (Raithel, 2014).

By 2030 the proportion of glass as total panel mass in **CdTe panels** is expected to decrease by 1% from 97% to 96%. However, their polymer mass is expected to increase by 1% from 3% to 4% compared to today. In comparison to CIGS panels, material usage for semiconductors as a proportion of panel usage will decline almost by half from 0.13% to 0.07%. However, the share of other metals (e.g. nickel, zinc and tin) will grow from 0.26% to 0.41% (Marini *et al.*, 2014; Bekkelund, 2013 and NREL, 2011). The main reason for this increase in other metals is the further reduction in CdTe layer thickness (which brings down the semiconductor content of the base semiconductor). However, the efficiency improvements of the past couple of years were also related to 'bandgap' grading effects, which can be achieved by doping the semiconductor layer with other components. The addition of other components to the mix is reflected in the rise in other metals. Another reason for the increase in the proportion of other metals is the addition of a layer between back-contact metals and the semiconductor package. This reduces copper diffusion into the semiconductor and thus long-term degradation and leads to the thickening of the back-stack of metals (Strevel *et al.*, 2013).

The PV industry is aiming for 25% efficiency for CdTe panel research cells and over 20% for commercial panels in the next three years. This is substantially higher than the 15.4% achieved in 2015. New technologies are also expected to reduce the performance degradation rate to 0.5%/year (Strevel *et al.*, 2013).

Chapter 6 provides additional details on panel composition, the function of various materials and potential future changes in panel design and composition.

3.2 WASTE CLASSIFICATION

Background

PV panel waste classification follows the basic principles of waste classification. This also considers material composition by mass or volume and properties of the components and materials used (e.g. solubility, flammability, toxicity). It accounts for potential mobilisation pathways of components and materials for different reuse, recovery, recycling and disposal scenarios (e.g. materials leaching to groundwater, admission of particulate matter into the soil). The overall goal of these classification principles is to identify risks to the environment and human health that a product could cause during end-of-life management. The aim is to prescribe disposal and treatment pathways to minimise these threats. The risk that materials will leach out of the end-of-life product or its components to the environment is very significant, and assessment of this threat helps define necessary containment measures. However, this is just one possible risk. Other examples assessed through waste characterisation include flammability, human exposure hazards through skin contact or inhalation. Risks assessed may differ by country and jurisdiction.

Depending on national and international regulations such as the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal (UN, 2016), waste can be classified into various categories such as inert waste, non-hazardous waste and hazardous waste. To some extent, the origin of the waste is also taken into consideration, defining subcategories such as industrial waste, domestic waste and specific product-related categories such as e-waste, construction waste and mixed solid wastes. The different categories of classified waste then determine permitted and prohibited shipment, treatment, recycling and disposal pathways.

In 2015 two-thirds of PV panels installed across the world were c-Si panels. Typically, more than 90% of their mass is composed of glass, polymer and aluminium, which can be classified as non-hazardous waste. However, smaller constituents of c-Si panels can present recycling difficulties since they contain silicon, silver and traces of elements such as tin and lead (together accounting for around 4% of the mass). Thin-film panels (9% of global annual production) consist of more than 98% glass, polymer and aluminium (non-hazardous waste) but also modest amounts of copper and zinc (together around 2% of the mass), which is potentially environmentally hazardous waste. They also contain semiconductor or hazardous materials such as indium, gallium, selenium, cadmium tellurium and lead. Hazardous materials need particular treatment and may fall under a specific waste classification depending on the jurisdiction.

Key criterion for PV panel waste classification: Leaching tests

Table 9 summarises typical waste characterisation leaching test methods in the US, Germany and Japan. The overview provides one of the most important characterisation metrics used in PV waste classification across the world at this time.

Table 9 PV waste characterisation: Leaching test methods in the US, Germany and Japan

	US	Germany	Japan
Leaching test	US Environment Protection Agency method 1311 (TCLP)	DIN EN German Institute for Standardization standard 12457-4:01-03	Ministry of Environment Notice 13/JIS K 0102:2013 method (JLT-13)
Sample size (centimetres)	1	1	0.5
Solvent	Sodium acetate/ acetic acid (pH 2.88 for alkaline waste; pH 4.93 for neutral to acidic waste)	Distilled water	Distilled water
Liquid:solid ratio for leaching test (*e.g.* amount of liquid used in relation to the solid material)	20:1	10:1	10:1
Treatment method	End-over-end agitation (30±2 rotations per minute)	End-over-end agitation (5 rotations per minute)	End-over-end agitation (200 rotations per minute)
Test temperature	23±2˚C	20˚C	20˚C
Test duration	18±2 hr	24 hr	6 hr

Based on Sinha and Wade (2015)

The key criterion for determining the waste classification is the concentration of certain substances in a liquid which has been exposed to fragments of the broken PV panels for a defined period of time in a particular ratio. This leachate typically dissolves some of the materials present in the solid sample and hence can be analysed for the mass concentration of certain hazardous substances. Different jurisdictions, such as Germany, the US or Japan provide different threshold values for the allowable leachate concentrations for a waste material to be characterised as non-hazardous waste. For instance, the threshold for leachate concentration for lead allowing a panel to be classified as hazardous is 5 milligrammes per litre (mg/l) in the US and 0.3 mg/l in Japan. For cadmium, the hazardous threshold is 1 mg/l in the US, 0.3 mg/l in Japan and 0.1 mg/l in Germany. These compare to publicly available leaching test results in the literature (summarised in Sinha and Wade, 2015) for c-Si and CdTe PV panels. They range from non-detect to 0.22 mg/l for cadmium and non-detect to 11 mg/l for lead. Thus, in different jurisdictions, CdTe and c-Si panels could be considered either non-hazardous or hazardous waste on the basis of these test results.

Regulatory classification of PV panel waste

From a regulatory point of view, PV panel waste still largely falls under the general waste classification.

An exception exists in the EU where PV panels are defined as e-waste in the WEEE Directive. The term 'electrical and electronic equipment' or EEE is defined as equipment designed for use with a voltage rating not exceeding 1,000 V for alternating current and 1,500 V for direct current, or equipment dependent on electric currents or electromagnetic fields in order to work properly, or equipment for the generation of such currents, or equipment for the transfer of such currents, or equipment for the measurement of such currents (EU, 2012).

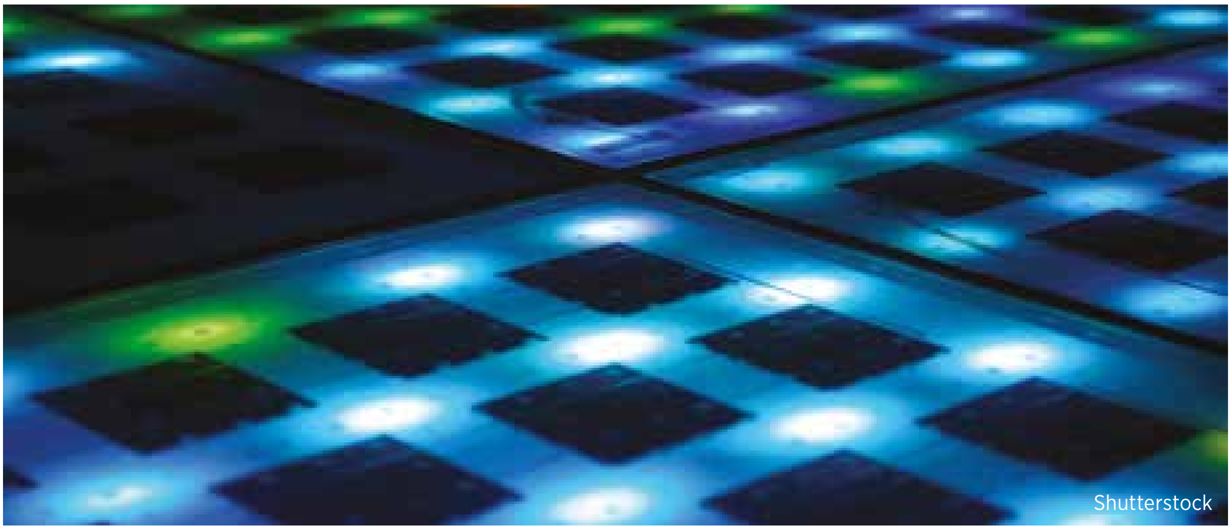
Hence, the waste management and classification for PV panels is regulated in the EU by the WEEE Directive in addition to other related waste legislation (e.g. Waste Framework Directive 2008/98/EC). This comprehensive legal framework also ensures that potential environmental and human health risks associated with the management and treatment of waste are dealt with appropriately. By establishing a List of Wastes (European Commission, 2000), the EU has further created a reference nomenclature providing a common terminology throughout the EU to improve the efficiency of waste management activities. It provides common coding of waste characteristics for classifying hazardous versus non-hazardous waste, transport of waste, installation permits and decisions about waste recyclability as well as supplying a basis for waste statistics.

Some codes from the EU's List of Wastes applicable to PV panels are given in Table 10.

Table 10 Examples of waste codes relevant to PV panels from the EU List of Wastes

Type	Waste code	Remark
All types	160214	Industrial waste from electrical and electronic equipment
	160213*	Discarded equipment containing hazardous components
	200136	Municipal waste, used electrical and electronic equipment
	200135*	Discarded electrical and electronic equipment containing hazardous components
In special cases also: *e.g.* amorphous-silicon (a-Si) panels	170202	Construction and demolition waste – glass

** Classified as hazardous waste, depending on the concentration of hazardous substances. Table 10 portrays leaching test methods commonly used for hazardous waste characterisation.*
Based on European Commission, (2000)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PV PANEL WASTE MANAGEMENT OPTIONS

Beyond general waste regulations, various approaches have been developed specifically for managing end-of-life PV panel waste. The following sections summarise the general principles of panel waste management as well as examples portraying voluntary, public-private-partnership and regulated approaches.

4.1. WASTE MANAGEMENT PRINCIPLES FOR PV PANELS

Life cycle methodology

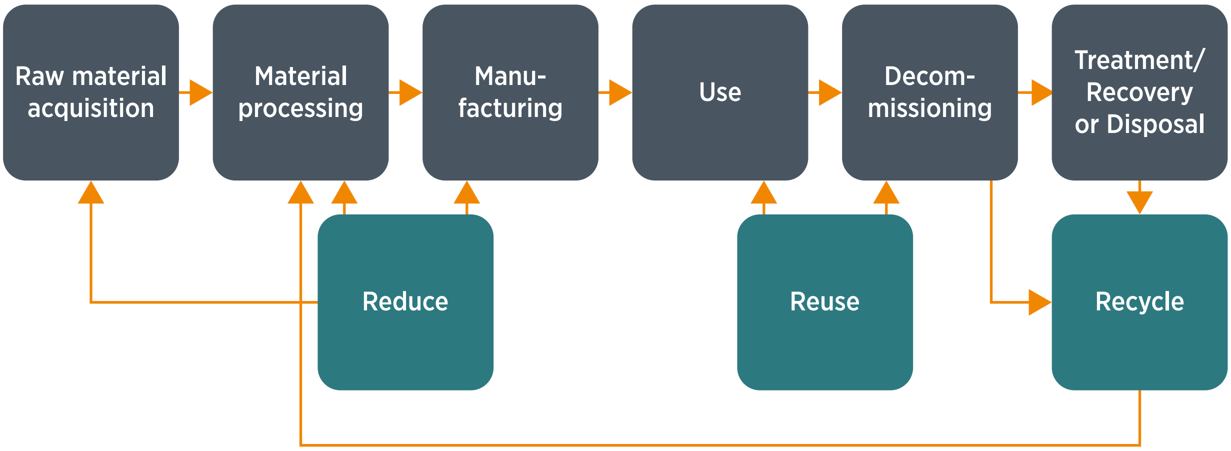
All waste management approaches follow the life cycle stages of a given product.

Figure 11 displays how for PV panels the life cycle starts with the extraction of raw materials (cradle) and ends with the disposal (grave) or reuse, recycling and recovery (cradle).

Chapter 6 will provide more information on the cradle-to-cradle and recovery opportunities to:

- Reduce;
- Reuse;
- Recycle.

Figure 11 Process flow diagram of the life cycle stages for PV panels and resulting opportunities for reducing, reusing or recycling



Adapted from Fthenakis (2000)

Stakeholders and responsibilities

The responsibility for end-of-life waste-management activities downstream (waste generation, collection, transport, treatment and disposal) are typically covered by the following three main stakeholders:

- **Society.** End-of-life management is supported by society, with government organisations controlling and managing operations, financed by taxation. This could create revenue for municipalities and eliminate the fixed costs of building a new collection infrastructure while providing economies-of-scale benefits. Drawbacks could include a lack of competition and slower cost optimisation.

- **Consumers.** The consumer that produces panel waste is responsible for end-of-life management, including the proper treatment and disposal of the panel. The consumer may try to minimise costs, which can have a negative effect on the development of sound waste collection and treatment. Since the producer is not involved, there may be less motivation to produce recyclable and 'green' products. This approach currently remains the dominant framework in most countries for end-of-life PV panel management.

- **Producers.** End-of-life management is based on the extended-producer-responsibility (EPR) principle. This holds producers physically and financially responsible for the environmental impact of their products through to end-of-life and provides incentives for the development of greener products with lower environmental impacts. This principle can also be used to create funds to finance proper collection, treatment, recycling and disposal systems. Although producers finance the waste management system, the added cost can be passed through to consumers in the form of higher prices.

Costs and financing

A decision needs to be made on which of the three stakeholders mentioned (society, consumers and producers) is to take financial responsibility for end-of-life management. All waste management approaches, including e-waste, involve incurring costs. That is equally true for end-of-life PV panel management. The costs can be broken down into three interconnected systems outlined below:

1. **A physical system of collection, storage/aggregation, treatment, recovery, recycling and disposal.** This system collects PV panels, for instance, from separate waste generation points and transfers them to a more central location where first-level treatment can start. After this first treatment step, which usually separates the waste product into material groups (e.g. metals, mixed plastics, glass etc.), further processing of the different material streams is required for recovery and recycling. This step removes potentially hazardous materials and impurities from recycling materials because they prevent recycling. Finally, the disposal of non-recoverable, non-recyclable fractions also needs to be taken care of in the physical system. The costs of operating these physical system are a function of several factors. These include the geographical and economic context, the chosen number of collection and processing points and the complexity of dismantling and separation processes (first-level treatment). A final factor is the value/costs associated with final processing of the different material streams for recycling or disposal.

2. **A financial processing system.** This system counts the amounts of various materials recovered from the recycling process and the associated revenues and costs to the system.

3. **A management and financing system.** This system accounts for the overhead costs of operating an e-waste system for PV panels, for example.

To provide the financial basis for recycling end-of-life products, several fee models have been developed and implemented worldwide. Part of these fees is set aside to finance the waste treatment system when end-of-life products are dropped off at collection points operated by municipalities, dealers, wholesalers, producers or their service providers. The fees are typically structured to follow several principles to ensure they are fair, reasonable, based on actual programme costs and include regular revisions:

- The funds generated from the fees collected should cover the system costs and achieve clear environmental goals.
- The fees should be a function of the return on investment, technical and administrative costs. The revenues generated from the collection, recycling and treatment fees should be sufficient to cover the costs of implementation.
- The fee structure should be implemented without rendering the PV sector uncompetitive with international markets. Special care should be taken to avoid free riders.
- The fee structure should be simple to implement.
- The fee structure should be viable for the PV products covered by the regulation.

Box 6 Financing models for collection, treatment, recovery, recycling and disposal of PV panels

Producer-financed compliance cost
Under this model, the producer finances the activities of the waste management system by joining a compliance scheme and paying for its takeback system or stewardship programme. It covers two types of wastes. The first is orphan waste (from products placed on the market after implementation of the waste management system by producers that no longer exist and cannot be held liable). The second is historic waste (waste from products placed on the market before the waste management system was established). The costs are usually shared between producers. All costs are revised regularly and charged per panel or weight based on the actual recycling costs and estimates of future costs.

Consumer-financed upfront recycling fee
This fee is paid to collect funds for the future end-of-life treatment of the product. Consumers pay the fee at the time of the purchase of the panel. The fee is set according to estimates for future recycling costs but may also be used to offset current recycling costs.

Consumer-financed end-of-life fee (disposal fee)
The last owner pays a fee for the collection and recycling costs to the entity in charge of the recycling of the end-of-life product.

The implementation of these different financial approaches can vary considerably from country to country owing to different legal frameworks, waste streams, levels of infrastructure maturity, and logistical and financial capabilities. In most countries with e-waste management systems, a combination of the consumer-based and producer-based approaches is incorporated into the compliance scheme (e.g. in the EU). However, each such scheme should be adapted to the unique conditions of each country or region.

Enabling framework

Adjusting or developing an end-of-life management scheme for PV panel waste requires the balancing of a number of factors such as collection, recovery and recycling targets. These three targets become the main driver of waste management policies.

Waste management approaches or schemes need to take into account different options for collection systems (e.g. pick-up versus bring-in systems). They also need to consider the nature and design of products to manage end-of-life and recycling processes adequately (e.g. PV panels are often classified as e-waste). Hence, waste management leads naturally also to a motivation to change the design of products themselves in favour of easier waste treatment, for instance (Atasu, 2011).

- **Voluntary approach.** Producers often rely on their internal environmental management systems to manage all their company's environmental responsibilities, including the end-of-life of their products or services. One example is found in the International Standards Organisation ISO 14000 family of international standards on environmental management. ISO 14040: 2006 specifically deals with the principles and framework for life cycle assessment of a company's products and operations (ISO, 2006). Within this or other frameworks, some PV panel manufacturers have established individual voluntary takeback or product stewardship programmes that allow defective panels to be returned for recycling on request. The management of such programmes can be borne directly by the company or indirectly through a recycling service agreement outlined in more detail below:

1. **Direct management:** the manufacturer operates its own recycling infrastructure and refurbishment or recycling programmes to process its own panels, enabling it to control the entire process (e.g. First Solar, 2015b).

2. **Indirect management:** the manufacturer contracts service providers to collect and treat its panels. Different levels of manufacturer involvement are possible depending on the contract details.[10]

10. For example, manufacturers could decide to operate part of the collection and recycling infrastructure. They could contract out the other parts, as in a business-to-business (B2B) environment in which the panel owner is contractually required to bring the panel to a centralised logistic hub. At that point the manufacturer takes over the bulk logistics and treatment processes.

In the option on indirect programmes, producers could outsource part or the entire management and operation of their recycling programmes to a third party. The members of such an organisation may be entirely producers or may also include a network of government entities, recyclers or collectors. Alternatively, it may be a single entity created by the government to manage the system. The activities carried out by third-party organisations and other compliance schemes can vary from country to country and depend on specific legislative requirements and the services offered to members.

- **Public-private approach.** Set up in 2007, PV CYCLE is an example of a voluntary scheme that includes both a 'bring-in' and 'pick-up' system based on the principle of a public-private-partnership between industry and European regulators. The association was established by leading PV manufacturers and is fully financed by its member companies so that end-users can return member companies' defective panels at over 300 collection points around Europe. PV CYCLE covers the operation of the collection points with its own receptacles, collection, transport, recycling and reporting. Large quantities of panels (currently more than 40) can be picked up by PV CYCLE on request. In some countries, PV CYCLE has established co-operatives and it encourages research on panel recycling. PV CYCLE is being restructured to comply with the emerging new regulations for end-of-life PV in the different EU member states (see next chapter on the EU) (PV CYCLE, 2016).

- **Regulatory approach.** The EU is the only jurisdiction that has developed specific regulations and policies addressing the end-of-life management of PV. The next section examines in more detail the regulatory approach taken by the EU.

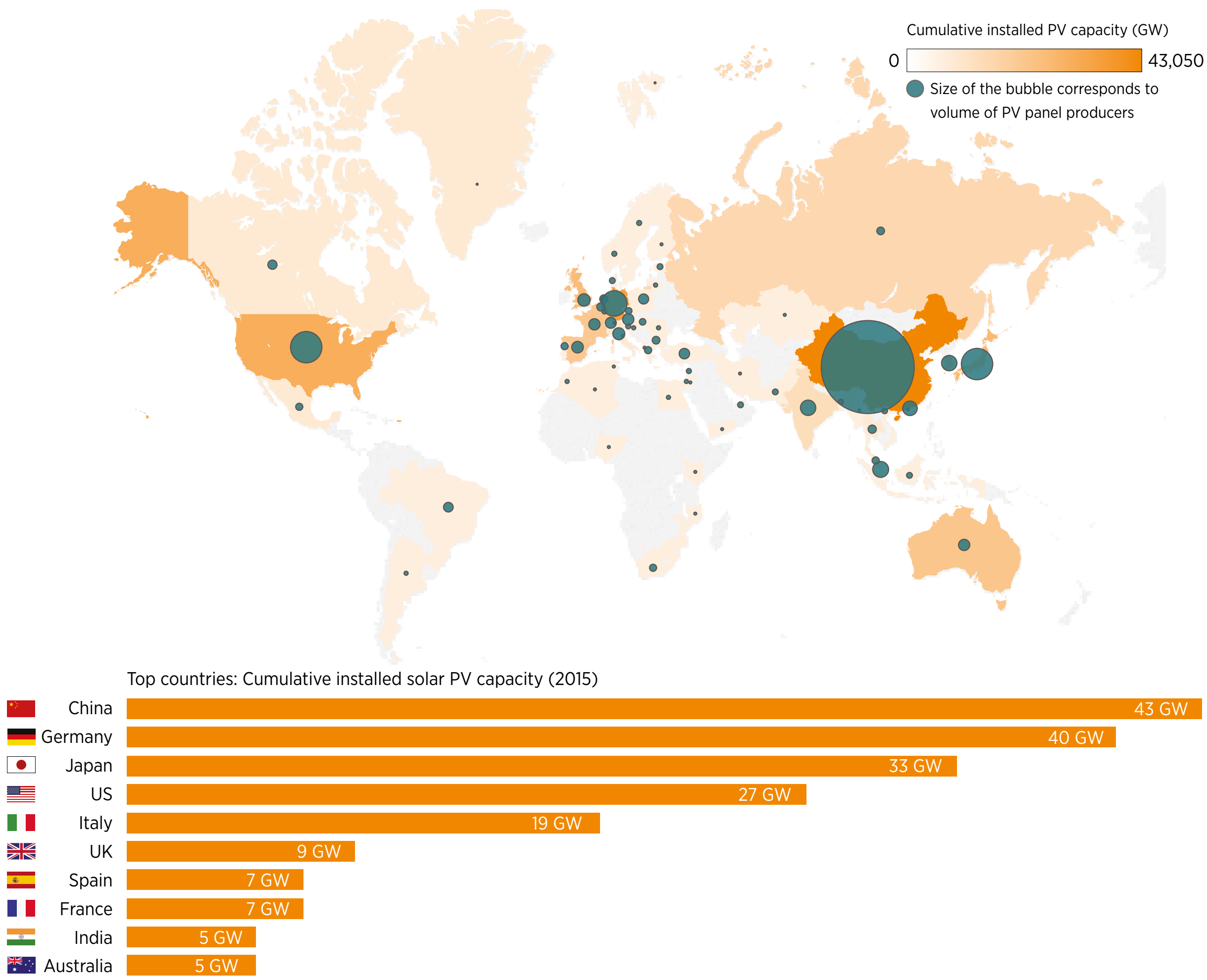
4.2. REGULATORY APPROACH: EUROPEAN UNION

Background

Since the late 1990s, the EU has led PV deployment with significant volumes installed between 2005 and 2011, prompting an increase from 2.3 GW to 52 GW over that period (IRENA, 2016b). Manufacturers selling into the EU thus also started to devise early PV life cycle management concepts, the most prominent example being the previously mentioned pan-European PV CYCLE initiative (PV CYCLE, 2015). The resulting increases in PV production triggered PV recycling technology development since production scrap recycling offered direct economic benefits and justified investments in such technologies in the short term.

High deployment rates, growing manufacturing capacities and increasing demand for PV globally led to a rapid internationalisation and commoditisation of supply chains. This made it very difficult to implement pan-European voluntary initiatives for long-term producer responsibility (see Figure 12 for global overview of PV panel producers and cumulative installed PV capacity). This resulted in the need for regulation to ensure a level playing field for all market participants and secure the long-term end-of-life collection and recycling for PV waste (European Commission, 2014).

Figure 12 World overview of PV panel producers and cumulative installed PV capacity



WEEE Directive

Balancing the advantages and disadvantages of different approaches to addressing e-waste management – including waste PV panels - is at the core of the EU regulatory framework set up through the WEEE Directive. This framework effectively addresses the complex EEE waste stream[11] in the 28 EU member states and the wider economic area, placing the **extended-producer-responsibility principle** at its core. The directive has a global impact, since producers which want to place products on the EU market are legally responsible for end-of-life management, no matter where their manufacturing sites are located (European Commission, 2013).

This combination of producer legal liability for product end-of-life, EEE dedicated collection, recovery and recycling targets, and minimum treatment requirements ensuring environment and human health protection may be a reference point for PV waste management regulation development globally.

The original WEEE Directive (Directive 2002/96/EC) entered into force in February 2003 but proved to be insufficient to tackle the quickly increasing and diverse waste stream (European Parliament and Council, 2002). In 2012, following a proposal by the EU Commission, the directive was revised (2012/19/EU). For the first time it included specifics on end-of-life management of PV panels. The revised WEEE Directive entered into force on 13 August 2012, was to be implemented by the EU member states by 14 February 2014 and thus introduced a new legal framework for PV panel waste. Each one of the 28 EU member states is now responsible for establishing the regime for PV panel collection and treatment in accordance with the directive (European Parliament and Council, 2012).

As the revised WEEE Directive is based on the extended-producer-responsibility principle, producers (see Box 7) are liable for the costs of collection, treatment and monitoring. They must fulfil a certain number of requirements and responsibilities (European Commission, 2015; European Commission, 2014; European Commission 2013; European Parliament and Council, 2008 and 2008b).

- **Financing responsibility.** Producers are liable through a financial guarantee to cover the cost of collection and recycling of products likely to be used by private households. They are responsible for financing public collection points and first-level treatment facilities. They also need to become a member of a collective compliance scheme or may develop an individual scheme.

- **Reporting responsibility.** Producers are obliged to report monthly or annually on panels sold, taken back (through individual or collective compliance schemes) and forwarded for treatment. Within this reporting scheme, producers equally need to present the results from the waste treatment of products (tonnes treated, tonnes recovered, tonnes recycled, tonnes disposed by fraction e.g. glass, mixed plastic waste, metals).

- **Information responsibility.** Producers are accountable for labelling panels in compliance with the WEEE Directive. They must inform buyers that the panels have to be disposed of in dedicated collection facilities and should not be mixed with general waste, and that takeback and recycling are free (European Parliament and Council, 2008b). They are also responsible for informing the buyer of their PV panel end-of-life procedures. Specific collection schemes might go beyond legal requirements, with the producer offering pick-up at the doorstep, for example. Lastly, producers are required to give information to waste treatment companies on how to handle PV panels during collection, storage, dismantling and treatment. This information contains specifics on hazardous material content and potential occupational risks. In the case of PV panels, this includes information on electrocution risks when handling panels exposed to light.

Box 7 Definition of producers under the WEEE Directive

'Producers' include a range of parties involved in bringing a product to market — not just the original equipment manufacturer. The WEEE Directive defines the producer in Article 3:

'Producer' means any natural or legal person who, irrespective of the selling technique used, including distance communication within the meaning of Directive 97/7/EC (European Commission, 1997) of the European Parliament and of the Council of 20 May 1997 on the protection of consumers in respect of distance contracts (19):

i. is established in a Member State and manufactures EEE under his own name or trademark, or has EEE designed or manufactured and markets it under his name or trademark within the territory of that Member State;

ii. is established in a Member State and resells within the territory of that Member State, under his own name or trademark, equipment produced by other suppliers, a reseller not being regarded as the 'producer' if the brand of the producer appears on the equipment, as provided for in point (i);

iii. is established in a Member State and places on the market of that Member State, on a professional basis, EEE from a third country or from another Member State; or

iv. sells EEE by means of distance communication directly to private households or to users other than private households in a Member State, and is established in another Member State or in a third country.

Whoever exclusively provides financing under or pursuant to any finance agreement shall not be deemed to be a 'producer' unless he also acts as a producer within the meaning of points (i) to (iv).

WEEE Directive targets

The WEEE Directive follows the staggered approach to collection and recovery targets outlined in Table 11. Collection targets rise from 45% (by mass) of equipment 'put on the market'[12] in 2016 to 65% of equipment 'put on the market' or 85% of waste generated as from 2018. Recovery targets rise from 75% recovery/65% recycling to 85% recovery/80% recycling in the same time frame. Recovery is to be understood as the physical operation leading to the reclamation of a specific material stream or fraction from the general stream. Recycling, on the other hand, should be understood in the context of preparing that reclaimed stream for treatment and reuse (European Commission, 2015).

The e-waste recovery quotas are specified in a separate directive detailing minimum treatment requirements and technical treatment standards and specifications for specific equipment such as PV panels (European Commission, 2008). This two-pronged approach enables the implementation of 'high-value recycling' processes (see Box 8 for definition). The European Commission has also committed to further developing methodologies establishing individual collection and recycling targets for PV panels. They will take into consideration recovery of material that is rare or has high embedded energy as well as containing potentially harmful substances (European Commission, 2013).

11. EEE is defined as equipment designed for use with a voltage rating not exceeding 1,000 V for alternating current and 1,500 V for direct current, or equipment dependent on electric currents or electromagnetic fields in order to work properly, or equipment for the generation of such currents, or equipment for the transfer of such currents, or equipment for the measurement of such currents (EU, 2012).

12. 'Put on the market' is a complex legal construct defined in the Blue Guide of the European Commission on the implementation of EU product rules (Commission Notice C(2016) 1958, 5 April 2016). It can have different meanings depending on the sales channel used to market a product and effectively provides a temporal determination of the legal responsibility of the producer.

Table 11 Annual collection and recovery targets (mass %) under the WEEE Directive

	Annual collection targets	**Annual recycling/Recovery targets**
Original WEEE Directive (2002/96/EC)	4 kg/inhabitant	75% recovery, 65% recycling
Revised WEEE Directive (2012/19/EU) up to 2016	4 kg/inhabitant	Start with 75% recovery, 65% recycling, 5% increase after 3 years
Revised WEEE Directive (2012/19/EU) from 2016 to 2018	45% (by mass) of all equipment put on the market	80% recovered and 70% prepared for reuse and recycled
Revised WEEE Directive (2012/19/EU) from 2018 and beyond	65% (by mass) of all equipment put on the market or 85% of waste generated[13]	85% recovered and 80% prepared for reuse and recycled

13. *Products put on the market are reported by producers so these figures have a low uncertainty. However, a 65% target is unrealistic for items like PV panels, which have a very long life. It will not account for increasing amounts of historic waste (not recorded in the past) as well as varying life cycle curves per product category. An alternative measure is provided to account for the actual waste generated alone.*

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Box 8 EU end-of-life management through 'high-value recycling'

The environmental and socio-economic impacts of the different end-of-life waste-management options for PV panels have been widely assessed in previous literature (GlobalData, 2012; Münchmeyer, Faninger and Goodman, Sinha and Cossette, 2012; Held, 2009; Müller, Schlenker and Wambach, 2008; Sander, *et al.*, 2007). These assessments have concluded that 'high-value recycling,' is the option preferred for all technologies for the benefit of society in general. It not only ensures the recovery of a particular mass percentage of the total panel but also accounts for minor fractions. The high-value recycling approach is now the foundation for the WEEE Directive and ensures the following:

- Potentially harmful substances (e.g. lead, cadmium, selenium) will be removed and contained during treatment;
- Rare materials (e.g. silver, tellurium, indium) will be recovered and made available for future use;
- Materials with high embedded energy value (e.g. silicon, glass) will be recycled;
- Recycling processes will consider the quality of recovered material (e.g. glass).

The European Commission also asked the European Committee for Electrotechnical Standardization to develop specific, qualitative treatment standards for different fractions of the waste stream to complement the high-value recycling approach. As part of that mandate (European Commission, 2013), a supplementary standard and technical specification for PV panel collection and treatment is under development (European Committee for Electrotechnical Standardization CLC/TC 111X, 2015). The findings are due to be released in 2016 and may lead to another revision of the WEEE Directive.

Future WEEE Directive revisions might impose even further cost-effective, high-quality and high-yield recovery and recycling processes as these become available. They would minimise societal material losses that could occur through 'downcycling'. The term 'downcycling' refers to the deterioration of intrinsic material or energy value of a secondary raw material by using it for new purposes (e.g. using a high-grade semiconductor material such as broken silicon scrap as backfill for street construction).

In addition to quotas and treatment requirements, the revised WEEE Directive also references measures specific to PV panels to prevent illegal shipments (European Parliament and Council, 2006) and new obligations for trade (Directive 2012/19/EC, Art. 14). Modified provisions to trade include, for example, the need to provide information to end-users on environmental impact. They equally contain proper collection mechanisms and the acceptance of old products free-of-charge if a replacement is bought (European Parliament and Council, 2012).

The WEEE Directive sets minimum requirements which member states may adjust when they transpose the directive into their own legislation. They may, for instance, define more stringent requirements or target quotas and add requirements. At the time of this report's publication, all EU member states have incorporated the WEEE Directive into national legislation, sometimes with the addition of certain country-specific regulations.

This can pose challenges for producers because almost every member state has implemented slightly varying definitions of extended-producer-responsibility (see Chapter 5 for case studies on Germany and the UK). Since the directive has been transposed very recently (in some cases as recently as early 2016), no statistical data on PV collection and recycling is available at the time of the publication of this report in June 2016.

WEEE Directive financing schemes

Varying requirements for end-of-life PV panels under the WEEE Directive have included classifying the waste stream as 'waste from private households' in France and the option to classify the waste as 'waste from other users than private households' in the UK. These differing definitions have implications for collection and recycling financing as well as waste responsibilities. Another important issue that has evolved during transposition is the different estimates of treatment costs among member states.

Two financing approaches can be distinguished in the WEEE Directive:

- Individual pre-funding or collective joint-and-several liability schemes;
- Contractual arrangements between producer and customer (dependent on B2C or B2B transaction).

The implementation of the original WEEE Directive of 2003 has shown that pre-funding approaches are only practical for e-waste sold in very low quantities such as specialty e-waste (e.g. custom-made fridges). Thus, the pre-funding scheme for collecting and recycling high-volume e-waste such as PV panels has not proved cost effective. Producer pay-as-you-go (PAYG) approaches combined with last-man-standing insurance and joint-and-several liability producer schemes are therefore more commonplace today although the revised 2012 directive still allows the pre-funding scheme.[14]

PV CYCLE

The revised WEEE Directive distinguishes between private household or business-to-consumer (B2C) transactions and non-private household or B2B transactions when mandating an effective financing mechanism (see Box 9). The regulation is flexible on the responsible party (owner or producer) and financing methods. This depends on the characteristics of the PV system (e.g. system size) and the characterisation of PV panels themselves in the respective member state. For example, France stipulates that all PV panels are characterised as B2C product independent of system size or other product attributes.

To fulfil the ambitious WEEE Directive recycling targets starting 2016, PV panels will have to be rapidly incorporated into new or existing waste management systems. Several national schemes by EU member states have already been managing other parts of the electrical and electronic waste stream for years, organising collection, treatment, recycling and reporting to regulators. These can serve as an important reference point to manage increasing PV panel waste streams.

The next chapter describes in more detail the EU legal framework and different national applications in EU member states such as Germany and the UK.

14. *In a pay-as-you-go (PAYG) approach, the cost of collection and recycling is covered by market participants when waste occurs. By contrast, a pay-as-you-put (PAYP) approach involves setting aside an upfront payment for estimated collection and recycling costs when a product is placed on the market. Last-man-standing insurance is an insurance product that covers a producer compliance scheme based on a PAYG approach if all producers disappear from the market. In that situation, the insurance covers the costs for collection and recycling. In a joint-and-several liability scheme, producers of a certain product or product group agree to jointly accept the liabilities for waste collection and recycling for a specific product or product group. How the concept is put in practice is explained in the next chapter in the case of Germany.*

Box 9 Financing framework under the WEEE Directive

The WEEE Directive defines the framework for two financing mechanisms depending on the end-use (private household or not) of the product. Under this framework, each EU member state can further determine the financial responsibility of stakeholders and related transactions.

Private households (B2C transactions)
Requiring the producer to collect and recycle has proved to be more enforceable and efficient than forcing private household customers to recycle e-waste at their end-of-life. PAYG approaches combined with last-man-standing insurance/joint-and-several liability schemes (producer compliance schemes) are more efficient and viable for equipment sold in a B2C context.

For B2C transactions the producer is not allowed to enter into a contractual arrangement with the customer on financing. However, it is required to fulfil the mandatory requirements set out by the regulator.

Non-private households (B2B transactions)
In B2B transactions both customer and producer may be capable of collecting and recycling end-of-life e-waste. For example, for large volume or big equipment like large-scale PV plants, the project owner may be best positioned to fulfill the recycling obligation. It has the option to use project cash flows, hire the original producer or hire a professional third party to recycle. For B2B transactions a regulatory framework ensuring collection and recycling to common standards for all industry players and allowing contractual arrangements between producer and customer for financing end-of-life obligations is considered most effective.


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NATIONAL APPROACHES TO PV WASTE MANAGEMENT

This chapter analyses current approaches to PV waste management. It begins with an overview of how today's most comprehensive end-of-life PV regulation, the EU WEEE Directive (see Chapter 4), is applied in selected EU member states, including Germany and the UK. In the following sections, PV panel waste management approaches are outlined for Japan and the US. Finally, this chapter also includes case studies of China and India, two of the most important growing PV markets globally. The six case studies were chosen to span a range of maturity of both PV deployment markets, and regulatory and voluntary approaches.

5.1 GERMANY: MATURE MARKET WITH EU-DIRECTED, PV-SPECIFIC WASTE REGULATIONS

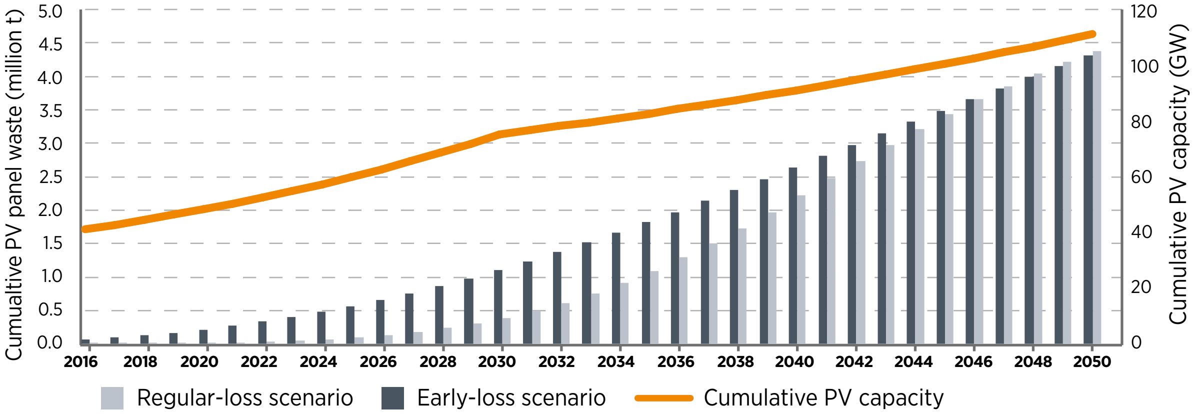
PV market and waste projection

The German PV market started growing in the 1990s. In that decade the first support schemes were introduced, clearly targeted at residential use, and there were scientific assessments of the feasibility of grid-connected, decentralised rooftop PV systems. One example was the 1,000 Rooftop Programme (Hoffmann, 2008). In the early 2000s this rooftop PV support programme was extended to 100,000 roofs and eventually led to the renewable energy support act, the first of its kind. This set a feed-in-tariff for electricity generated from renewable energy, including PV. The feed-in-tariff kick-started the German PV market and provided a significant global impetus for the PV industry to grow to the next scale.

In 2015, PV contributed 6% of total net electricity consumption in Germany with a total installed capacity of almost 40 GW distributed over 1.5 million PV power plants (IRENA, 2016b and Wirth, 2015). Germany was the world's largest PV market for two consecutive decades. Only in 2015 was it overtaken by China to become today the second-largest PV market.

In line with the Chapter 2 model, Germany's expected end-of-life PV panel waste volumes will cumulatively range between 3,500 t and 70,000 t by 2016. This is mainly due to its historic installed PV capacity. The figure varies according to scenario selected. In 2030 and by 2050 the regular-loss and early-loss scenario forecast between 400,000 t and 1 million t and 4.3-4.4 million t respectively (see Figure 13). Bearing in mind uncertainties inherent in these projections, as explained in Chapter 2, Germany will clearly be one of the first and largest markets for PV recycling technologies in coming years.

Figure 13 End-of-life PV panel waste volumes for Germany to 2050



Regulatory and non-regulatory frameworks

National regulation

The revised EU WEEE Directive (see previous section) was transposed into German Law in October 2015 through a revision of the Electrical and Electronic Equipment Act (Elektroaltgerätegesetz or ElektroG). Hence, the new requirements on the collection and recycling of PV panels have come into effect in Germany since that date.

Germany's e-waste management is regulated through the National Register for Waste Electrical Equipment (Stiftung Elektro-Altgeräte Register or Stiftung EAR). Stiftung EAR was founded during the implementation of the original WEEE Directive by producers as their clearing house (Gemeinsame Stelle) for the purposes of applying to the ElektroG (see Box 10). Entrusted with sovereign rights by the Federal Environment Agency (Umweltbundesamt), Stiftung EAR registers e-waste producers. It co-ordinates the provision of containers and pick-up at the öffentlich-rechtliche Entsorgungsträger (örE, public waste disposal authorities) in entire Germany (Stiftung EAR, 2015).

However, Stiftung EAR is not accountable for operational tasks such as collecting, sorting, dismantling, recycling or disposing of e-waste. These fall under the responsibility of producers accountable for e-waste recycling and disposal since March 2005 under the original Electrical and Electronic Equipment Act (ElektroG, 2005).

Box 10 Overview of Stiftung EAR clearing-house activities

Stiftung EAR is independent in terms of financing and personnel. Its work is funded by fees and expenses set by cost regulation from the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Bundesumweltministerium) (Stiftung EAR, 2015). The Stiftung EAR clearing house performs the following functions for all e-waste producers, including PV panel producers:

- Registers producers placing e-waste on the market in Germany;
- Collects data on e-waste amounts placed on the market;
- Co-ordinates the provision of containers and e-waste takeback at the public waste disposal authorities (örE);
- Reports the annual flow of materials to the Federal Environment Agency;
- Ensures that all registered producers may participate in the internal setting of rules;
- Identifies free riders and reports these to the Federal Environment Agency.

- **Implementation of WEEE Directive**

In line with the new transposed WEEE Directive in 2015, Germany has approved specific provisions for PV panel panel collection, recovery and recycling (Table 12). These set the amount of financial guarantee any producer must provide for each new panel sold.

The guarantee calculation depends on the form of financing selected by the producer. If the producer selects the joint-and-several liability scheme for B2C panels sold, the following simplified formula provides an understanding of the principle:

Cost responsibility =
basic amount for registration
(PV panel tonnage put on the market)
x presumed return rate (%)
x presumed disposal costs (EUR/t)

For B2B PV panels, the German regulator allows contractual arrangements between producer and owner to fulfil the legal requirements through recycling service agreements, for example.

Germany has also established a separate collection category for PV panels and thus provides separate collection and treatment of waste panels at municipal collection points. This means any PV panel owner who wishes to discard it can take it to a municipal collection point, where it will be accepted free of charge. This is the disposal pathway open to private customers owning residential PV systems. However, since removing a PV panel requires professional skills, most end-of-life PV panels are expected to be returned through B2B networks. This is because installers who remove rooftop panels will most likely also take care of the disposal. These PV panels will either be directly returned to B2B e-waste compliance schemes or to collection and recycling systems owned by producers.

Prior to the implementation of the revised ElektroG in Germany, there were a number of non-regulatory initiatives which organised the collection and recycling of end-of-life PV panels. They were mainly based on voluntary producer initiatives (e.g. PV CYCLE). These schemes will either cease or have to become compliant with the new regulation and register themselves as B2B e-waste compliance schemes.

- **National financing schemes under the WEEE Directive**

The most important aspect of the WEEE Directive is financing collection, recovery and recycling in coming years given the massive amounts of historic installed capacity in Germany destined to become waste. The German government foresees two distinct mechanisms based on the WEEE Directive depending on the type of transaction. They are outlined below.

Business-to-consumer (B2C) transactions

The new ElektroG mandates producers selling e-waste to private households (or users other than private households but with similar demand i.e. dual-use e-waste) to fulfil associated present and future

Table 12 Stiftung EAR factors for calculating guaranteed sum for PV panels

Category	Type of equipment	Presumed return rate	Presumed medium-life expectancy	Average maximum-life expectancy	Presumed disposal costs/ group
Consumer equipment and PV panels	PV panels for use in private households	30%	20 years	40 years	EUR 200/t

Based on Stiftung EAR (2015)

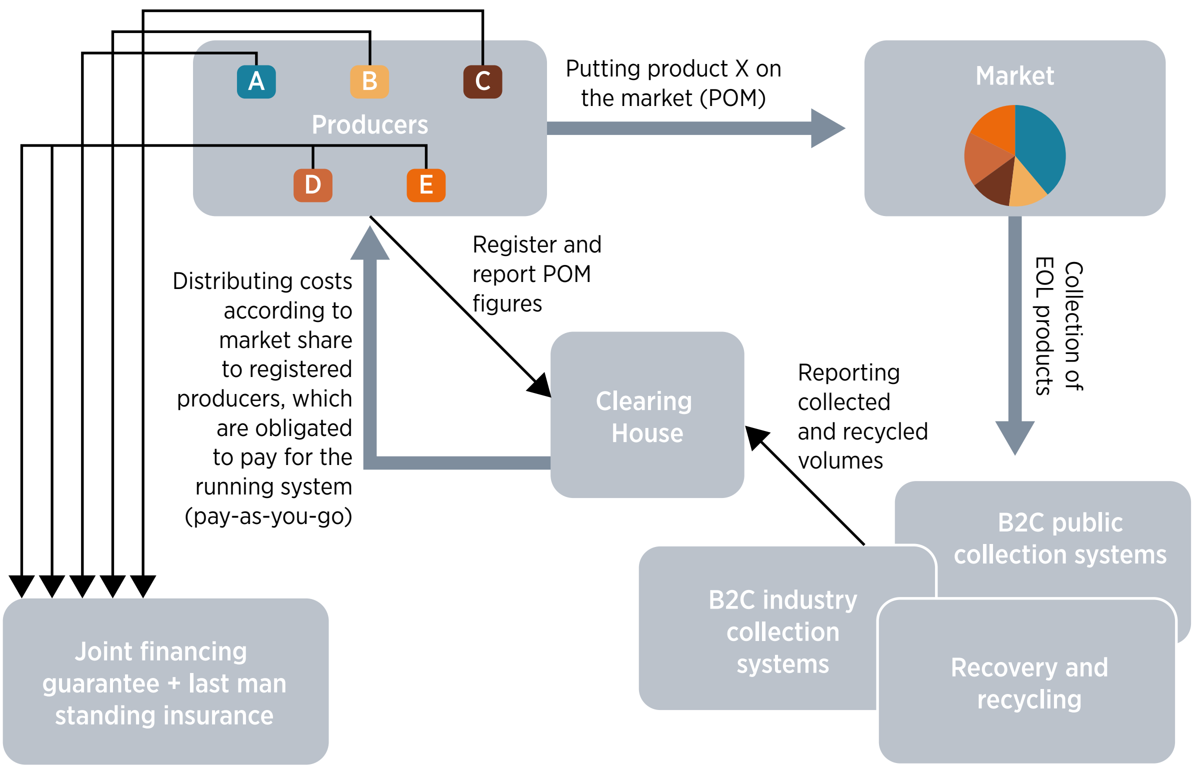
end-of-life obligations. This ensures producers are taking care of end-of-life management of PV panels sold to private households (e.g. residential rooftop systems) when placing products on the market. The approach is the result of previous experience of accredited producer compliance schemes that follow a joint-and-several liability format as illustrated in Figure 14.

The collective producer compliance system establishes two levels of operation and financing:

- Level 1 covers collection system operation and costs related to immediate collection and recycling of products (including historic products put on the market before being included in the scope of the law).
- Level 2 ensures that sufficient financing is available for future collection and recycling of products put on the market today i.e. after inclusion into the scope of the law. The costs forming the basis of Level 2 financing are uniform for the PV equipment category. They are calculated by the regulator, taking into consideration the average lifetime, the return quota at municipal collection points, and the treatment and logistic costs.

Level 1 costs are covered using a PAYG system for all market participants who put products of a certain category (e.g. PV panels) on the market through B2C transactions. In addition, before being allowed access to the market, producers must register with a clearing house. They have to declare they have made an agreement to cover Level 2 costs for B2C products placed on the market. At the same time, they have to accept responsibility for Level 1 costs based on their current market share (i.e. accepting the liability for other market participants). The clearing house then provides a producer e-waste registration number that must be printed on the product and invoices.

Figure 14 Collective producer responsibility system for end-of-life management of B2C PV panels



The producer now decides how to fulfil its Level 1 contribution. For example, it can run an individual collection and recycling system or join a co-operative system. Either way, costs for collecting and recycling all the B2C waste in a particular product category are distributed among all registered market participants according to volume collected. This ensures that historic waste (or orphan waste in the case of products made by producers now defunct) is collected and treated. If a producer demonstrates that it collected and recycled its share individually, those volumes will be deducted from the remaining fraction. If a producer disappears from the market, its market share will be taken up by the others along with the responsibility for financing collection and recycling.

Each producer must also ensure that sufficient Level 2 financing is available for B2C products placed on the market today. This occurs naturally if the joint Level 1 system continues to run. However, if all producers of a certain product category disappear, last-man-standing insurance has to provide financing. All Level 1 participants pay an annual premium for insurance that guarantees costs are covered if all market players disappear. Usually this premium is minimal because the likelihood of all market players disappearing is very low.

Business-to-Business (B2B) transactions

Germany's new ElektroG provides a different way of financing end-of-life PV obligations for producers that sell products on a B2B basis only owing to quantities, size, level of complexity etc. This is because collection and recycling could be more effectively organised if the final equipment or installation owner provides for it. It is up to the contractual partners to agree on end-of-life responsibilities as prescribed by the WEEE Directive either by contracting the producer to collect and recycle or seeking competitive market bids.

The B2B approach also includes the flexibility to agree on a funding/financing mechanism. For large-scale PV plants this will most likely result in models that generate funds for collection and recycling from near-commercial end-of-life project cash flows. Consequently, very cost-effective financing will be provided that enables previously agreed (pre-WEEE) end-of-life obligations to be honoured by contractual partners. Historic waste volumes will thus be covered.

Box 11 Outlook for Germany

Germany will most likely become the first end-of-life PV panel recycling market to reach profitable economies of scale. The current disposal costs identified by the regulator reflect the average treatment costs outlined in Table 12 above. However, with increasing amounts of waste, these costs should decrease once the industry has gone through a learning curve. This trend has already been observed in other parts of the e-waste stream. A number of R&D initiatives are currently driving the improvement of recycling technologies for the different PV technology families. These aim to further decrease recycling costs and increase the potential revenue streams from the secondary raw materials recovered through the recycling process.

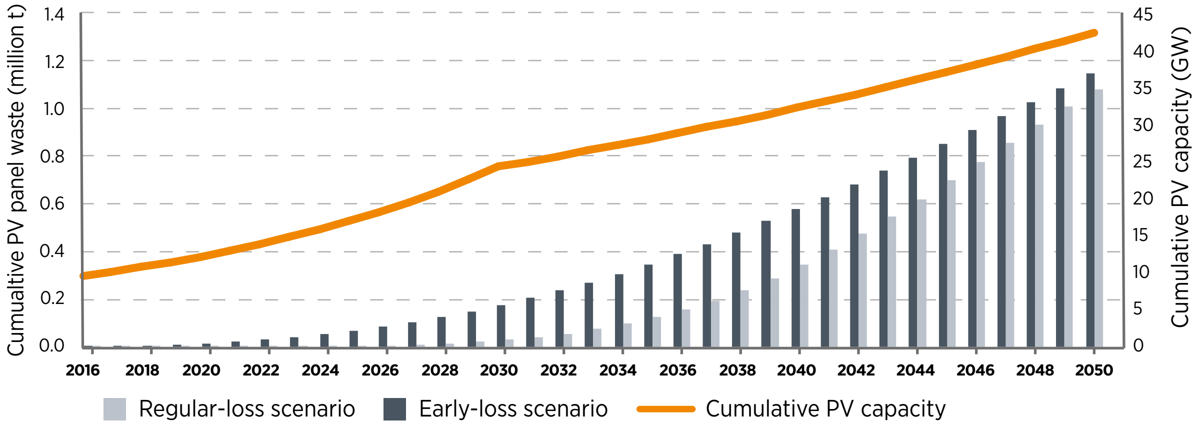
5.2 UK: YOUNG MARKET WITH EU-DIRECTED, PV-SPECIFIC WASTE REGULATIONS

PV market and waste projection

The UK is still a relatively young market for PV and thus end-of-life panels. However, it has recently experienced rapid PV deployment with an increase from just under 1 GW in 2011 to over 9 GW in 2015 and now more than 750,000 installations (IRENA, 2016b; UK Department of Energy and Climate Change, October 2015). Three-quarters of the existing PV capacity was installed after the WEEE Directive came into effect in the UK in early 2014 (UK WEEE Directive, 2013).

Figure 15 displays the UK's predicted end-of-life PV panel waste volumes modelled following the methods described in Chapter 2. The near-term cumulative volumes of PV panel waste are still limited (250-2,500 t). It is thus highly likely that most of the country's waste panels will be exported to centralised European treatment facilities or co-processed with other e-waste streams domestically to start with. However, in the medium and long term, PV panel waste is projected to increase exponentially. Regular-loss and early-loss scenarios estimate cumulative waste at 30,000-200,000 t by 2030. However, this figure could climb to 1-1.2 million t by 2050.

Figure 15 End-of-life PV panel waste volumes for the UK to 2050



Regulatory and non-regulatory frameworks

Since the UK's PV market is still young, the status quo for collection, treatment and recycling is essentially reflected in the implementation of the WEEE Directive transposed on 1 January, 2014. Prior to the WEEE Directive the UK was also covered by voluntary producer initiatives (e.g. PV CYCLE) and by takeback and recycling systems owned by producers. Due to the limited number of PV installations before 2014, the majority of end-of-life PV panels occurring then would have been covered by producer warranties and returned through the B2B channel.

The UK has set out some specific rules when it comes to defining a PV producer and hence the extended-producer-responsibility principle when transposing the WEEE Directive into national law. A PV producer under the UK WEEE legislation is defined as follows:

- UK manufacturer selling PV panels under its own brand;
- Importer of PV panels into the UK market;
- UK business selling PV panels manufactured or imported by someone else under its own brand.

As in other European markets, all PV producers in the UK must register via a producer compliance scheme (a takeback and recycling scheme managed by industry). They must submit relevant data on products destined for household (B2C) and non-household (B2B) markets.

However, when it comes to financing for B2C and B2B sales, the UK WEEE legislation contains requirements that differ significantly from the EU WEEE Directive.

- PV producers are required to finance the collection of household (B2C) PV panels on the basis of market share. For example, a producer placing 10% (by weight) of new panels on the UK market in any given year pays for the collection and treatment of 10% of old panels collected in the following year. The year when they were first placed on the market is ignored.
- PV producers must finance the collection and recycling of non-household (B2B) panels carrying the wheelie-bin symbol as well as those that do not if such panels are simultaneously being replaced by new ones.

In addition to the producer compliance scheme, the UK WEEE legislation has introduced a new requirement for installers to join a distributor takeback scheme. The UK now has several producer compliance schemes and distributor takeback schemes that offer their services for very similar fees (UK Environment Agency, 2015).

Box 12 UK WEEE legislation: Creation of a separate category for PV panels

After consultation between the PV sector and the UK Government, national legislation created a new separate category dedicated to financing the collection and recycling of PV panels. Had a new category not been created, PV producers would have paid heavily for the collection and recycling of consumer WEEE. This is because the financing obligations relate to the weight of products placed on the market and PV panels are by far the heaviest 'appliance' used by householders.

This special category status was granted "on the basis that the UK Government is satisfied that PV producers are able to deliver a sustainable strategy for the collection and treatment of end-of-life PV panels" (UK Department for Business, Innovation and Skills, 2014). The creation of a separate PV category will give the PV sector more control over financing PV panel collection and recycling.

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The UK's WEEE legislation requires first-level treatment of PV panels, which includes the registration of collected volumes, to take place within the UK. Further treatment will most likely happen abroad, since the economies of scale would not currently allow dedicated PV recycling facilities in the UK. In principle, the UK WEEE legislation requires waste to be treated in the UK.

However, in specific cases (such as PV panels) no high-value treatment facilities are available in the UK. Export to other EU member states is thus possible as long as the facilities there comply with the UK treatment facility requirements.

Box 13 Outlook for the UK

The UK PV panel recycling market will probably remain minor over the next couple of years. However, pricing dynamics and a strong political focus on building-integrated PV (BIPV) might motivate new technology developments for recycling BIPV components, for instance, as part of buildings waste streams.

5.3 JAPAN: ADVANCED MARKET WITHOUT PV-SPECIFIC WASTE REGULATIONS

PV market and waste projection

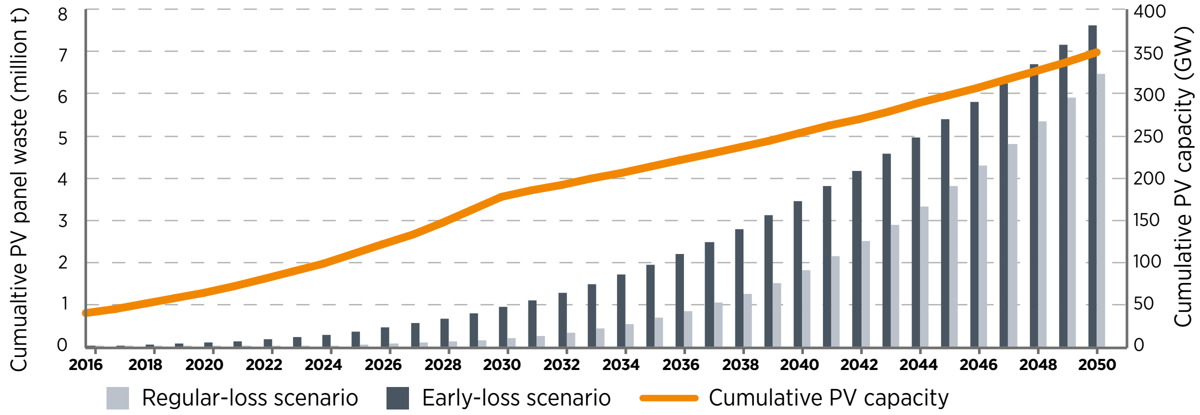
Japan has been a PV pioneer, contributing substantial R&D for decades and home to several of the world's leading manufacturers (e.g. Sharp, Kyocera and Panasonic). Although the country's own PV market was relatively small to start with, a feed-in-tariff introduced in July 2012 has stimulated rapid expansion. Cumulative installed PV capacity in Japan jumped from over 6.7 GW in 2012 to 34.3 GW in 2015 (IRENA, 2016b; IEA-PVPS, 2014b and IEA-PVPS, 2015).

Figure 16 and Box 14 show estimates for PV panel waste according to this report's model and Japanese governmental forecasts. Cumulative waste could amount to 7,000-35,000 t by 2016 rising to between

200,000 and 1 million to 2030. By 2050 it could reach 6.5-7.6 million t according to the scenarios employed in this report.

Ministry of Economy, Trading and Industry (METI) and Ministry of Environment (MOE) estimates are lower, predicting waste volumes at later date than figures in this report (see Box 14). This is mainly due to the methodology used herein, which includes early-stage failures covered through warranty replacements, and is not fully incorporated into end-of-life volume predictions by METI/MOE.

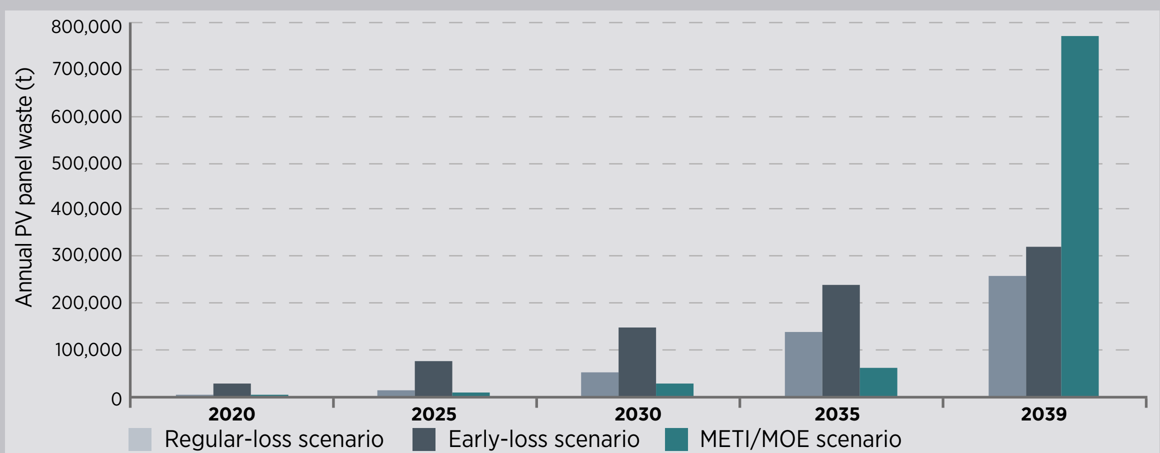
Figure 16 End-of-life PV panel waste volumes for Japan to 2050



Box 14 Japan's PV panel waste projections

According to Japan's Guidelines on Management of End-of-Life PV Panels released in April 2016 (METI and MOE, 2016), end-of-life PV panels will come to approximately 2,808 t per year in 2020. This will rise to an annual amount of 9,580 t in 2025 and 28,800 t after 2030, leading to 61,000 t in 2035 and finally 775,000 t in 2039. These estimates assume an expected panel lifetime of 25 years and initial failure and/or warranty activation in 0.3% of panels installed each year. Figure 17 compares the report's annual PV panel waste volumes for selected years with the METI/MOE scenario. In the national Japanese scenario, waste streams are lower than in the regular-loss and early-loss scenarios but jump far ahead of this report's scenarios after 2035.

Figure 17 Comparison of PV panel end-of-life scenarios for Japan



Regulatory and non-regulatory frameworks

Japan has no specific regulations for end-of-life PV panels, which therefore must be treated under the general regulatory framework for waste management: the Waste Management and Public Cleansing Act (METI and MOE, 2015). The act defines wastes, industrial waste generator and handler responsibilities, industrial waste management including landfill disposal etc.

In addition, the Construction Waste Recycling Law (METI and MOE, 2015) prescribes how to manage construction and decommissioning waste. The law requires recovery and recycling of concrete, wood and construction materials (containing concrete, iron and asphalt). Although PV panels are not specifically identified in the law, PV panels integrated with building material might require recycling, according to current interpretations. Panels in ground-mounted PV plants are not affected by this regulation. However, system components made of concrete or iron would also be subject to the law.

A proposed amendment to Japan's feed-in-tariff scheme for renewable electricity includes the consideration of end-of-life management with recycling but without obligations and penalties (METI, 2015).

Since 2013, METI and MOE have jointly assessed how to handle end-of-life renewable energy equipment such as PV, solar water heaters and wind turbines. A June 2015 report produced a roadmap for promoting a scheme for collection, recycling and proper treatment. It also covered the promotion of technology R&D, environmentally friendly designs, guidelines for dismantling, transportation, and treatment, and publicity to users (METI, 2015 and METI and MOE, 2015).

On the basis of this roadmap, the first edition of guidelines for promoting proper end-of-life treatment including recycling was published in April 2016 (METI and MOE, 2016). The guidelines cover basic information such as relevant law and regulations on decommissioning, transportation, reuse, recycling and industrial waste disposal. It is expected that these reports will lead to further consideration of policies on end-of-life management of PV panel waste.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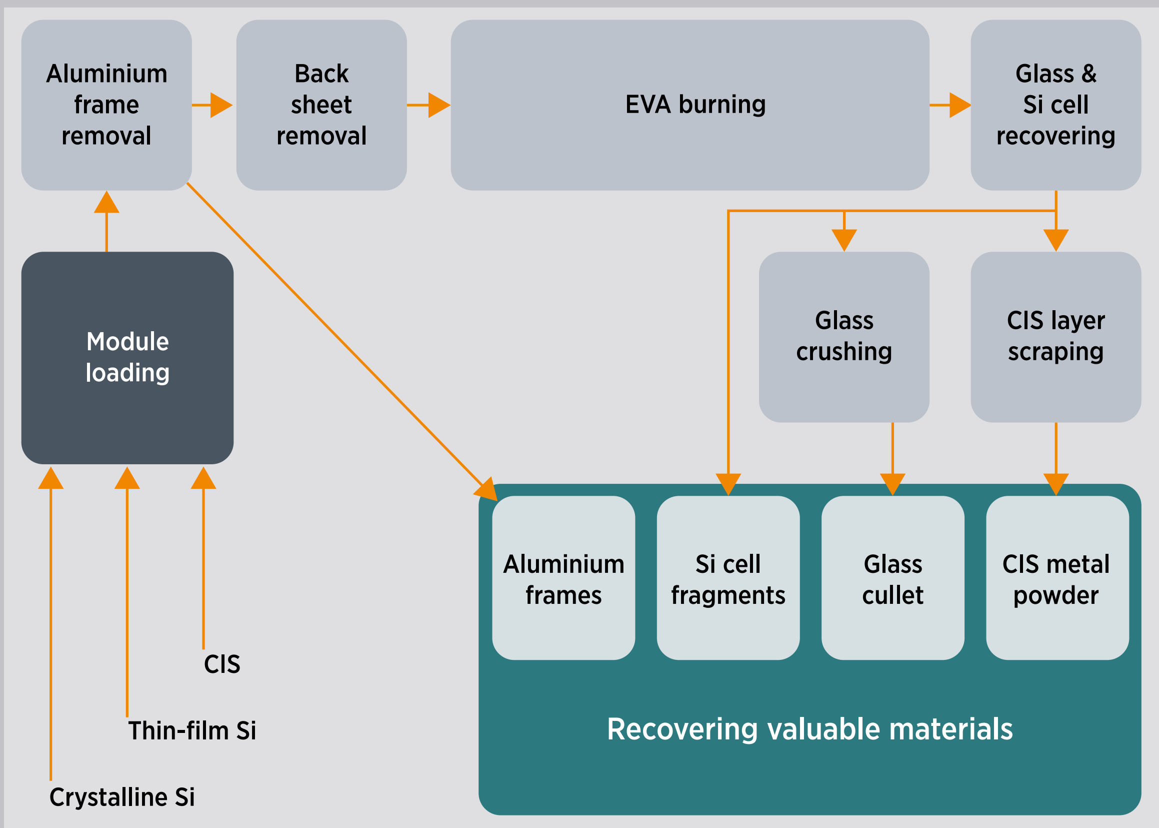
Box 15 R&D on PV panel recycling in Japan

In Japan, PV R&D has been conducted by the New Energy and Industrial Technology Development Organization (NEDO), and some PV panel recycling projects have taken place. Figure 18 shows an example of PV recycling technology developed under NEDO in 2014. The technology enables the automatic separation of different types of panels (c-Si, thin-film Si and copper indium selenide – CIS) and consists of four main processes: aluminium frame removal, backsheet removal, ethylene-vinyl-acetate resin burning and CIS layer scraping (for CIS panels only). The technology is currently in its experimental phase. Its early loss annual throughput is about 12 MW for c-Si panels and 7 MW for CIS panels, depending on panel type and size. Long-term field tests are expected in order to verify performance at potential industrial scale, including operating cost, throughput and stability (Noda *et al.*, 2014).

Figure 18 Foundation for Advancement of International Science (FAIS) PV panel recycling system



Based on Noda et al., (2014)

The objective of a different NEDO PV recycling R&D project (Komoto, 2014) is to contribute to a social system for PV recycling. This is achieved by establishing low-cost recycling technology and investigating optimal removal, collection and sorting. The R&D project has advanced to the demonstration stage since 2015. Further R&D for low-cost reuse technologies will be launched in 2016 and R&D should be concluded by 2018.

There are no specific schemes for treating end-of-life PV panels in Japan so they are expected to be dealt with in much the same way as other industrial wastes. PV panels will be removed from buildings or installation sites and transported to intermediate processors for waste treatment. There, components of PV panels will be separated as much as possible, and valuable materials will be recovered and recycled. For example, recoverable metals will be transported to companies which refine metals and recycled as secondary metals. Glass that can be separated and retain high purity will be recycled as glass cullet. Materials difficult to separate, recover and recycle will be sent to landfill subject to regulation and classification of hazardous content.

Box 16 Outlook for Japan

Despite a lack of current statistical data on end-of-life PV panels in Japan, the volume will probably be low in the near term given only recent market growth to significant levels. Although Japan has no specific regulations for end-of-life PV panels, several political trends and R&D activities are helping build the groundwork for recovery and recycling.

5.4 US: ESTABLISHED, GROWING MARKET WITHOUT PV-SPECIFIC WASTE REGULATIONS

PV panel market and waste projection

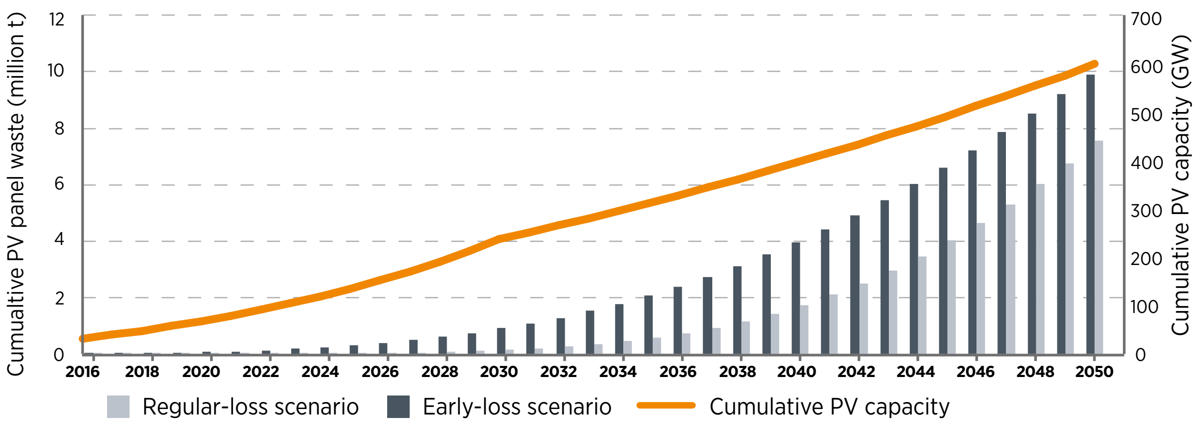
Since the mid-2000s, the US PV market has been growing rapidly, and cumulative installed capacity reached over 25 GW by the end of 2015 (IRENA, 2016b). With 7.2 GW new PV capacity installed in 2015 alone, the US presents today the fourth largest PV market in the world after China, Germany and Japan (IRENA 2016 and IEA-PVPS, 2015).

Large-scale PV deployment in the US has only occurred in the past ten years. Thus cumulative end-of-life PV waste volumes in the US are expected to remain low at the end of 2016 at 6,500-24,000 t. In 2030 cumulative waste is projected to rise to between 170,000 t and 1 million t and then possibly increase sevenfold to 7.5-10 million t in 2050 (see Figure 19).

Regulatory and non-regulatory framework

There is no PV-specific waste law in the US and no regulations mandating the collection and recycling of end-of-life PV panels. Hence, PV panels have to be disposed of in line with the Resource Conservation

Figure 19 End-of-life PV panel waste volumes for the US to 2050



and Recovery Act (Resource Conservation and Recovery Act, 1976) that is the legal framework for managing hazardous and non-hazardous solid waste.

As the Resource Conservation and Recovery Act does not include specific requirements for PV panels, they have to be treated under its general regulatory framework for waste management. For instance, there are two types of hazardous waste – characteristic hazardous waste and listed hazardous waste. The latter refers to actual listings of specific types of hazardous waste. Since end-of-life PV panels are not a listed hazardous waste, they must be evaluated using the characteristic hazardous waste method (US Environmental Protection Agency Method 1311 Toxicity Characteristic Leaching Procedure). This is done by assessing whether the extract from a representative sample of the waste contains contaminants exceeding regulatory levels. Within the US, different states can use additional leaching procedures such as California with the Total Threshold Limit Concentration and Soluble Threshold Limit Concentration for waste classification.

In California's 2014-2015[15] legislative session, Senate Bill 489 was proposed. It authorises the California Department of Toxic Substances Control to change the classification of end-of-life solar PV panels identified as hazardous waste to universal waste. This means they would meet Total Threshold Limit Concentration/Soluble Threshold Limit Concentration standards and be subject to Department of Toxic Substances Control regulations and proper management (California Legislature, 2015). The bill has been enacted into California law now. However, it will not take effect until the US Environmental Protection Agency authorises the addition of hazardous waste PV panels in California alone as an additional universal waste category under California's hazardous waste programme.

15. *Senate Bill 489, an act to add Article 17 (commencing with Section 25259) to Chapter 6.5 of Division 20 of the Health and Safety Code, relating to hazardous waste.*

Voluntary collection and recycling of end-of-life PV panels has been provided by several PV industry stakeholders. For example, the company First Solar operates a commercial-scale recycling facility with a daily capacity of 30 t in Ohio for its own CdTe products (Raju, 2013). The US Solar Energy Industries Association maintains a corporate social responsibility committee that reviews developments related to PV recycling.

Box 17 Outlook for the US

No federal regulations currently exist In the US for collecting and recycling end-of-life PV panels, and therefore the country's general waste regulations apply. California is in the process of developing a regulation for the management of end-of-life PV panels within its borders, though several steps remain before this regulation is implemented.

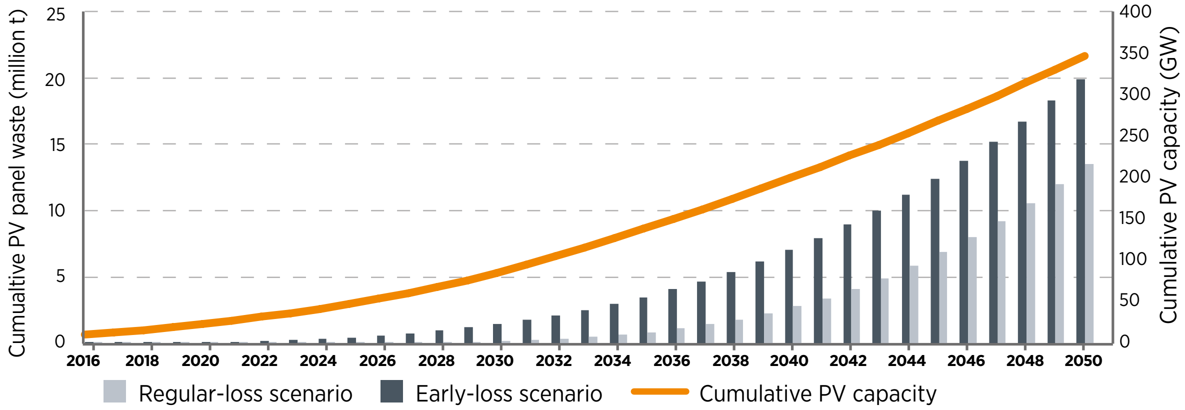
5.5 CHINA: LEADING MARKET WITHOUT PV-SPECIFIC WASTE REGULATIONS

PV market and waste projection

In 2015 China installed 15 GW of PV, for the second consecutive year reaching its 10 GW target for average annual growth and maintaining its position as the world's largest PV market. In December 2015 the National Energy Administration issued its 13th Solar Energy National Plan 2016-2020 (National Energy Administration, 2015). The main near-term targets proposed by 2020 are 150 GW PV of cumulative installation. This is to be composed of 70 GW of distributed PV and 80 GW of large-scale ground-mounted PV.

This report projects cumulative PV panel waste streams of 8,000-100,000 t in 2020. This is due to climb to between 200,000 t and 1.5 million t by 2030 and surge to 13.5-19.9 million t until 2050 (see Figure 20).

Figure 20 End-of-life PV panel waste volumes for China to 2050

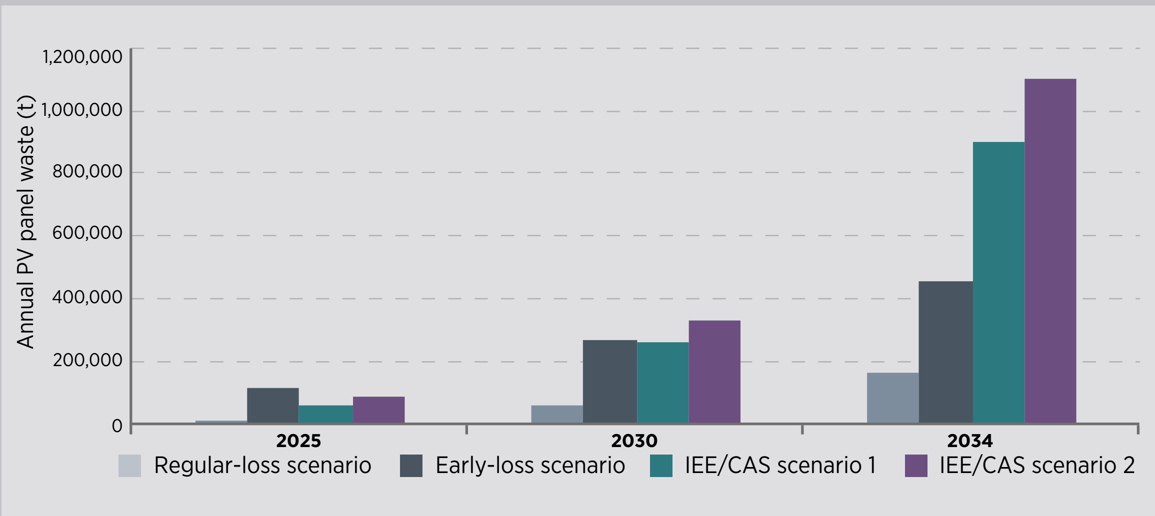


Because of China's rapidly developing PV industry, PV panel recycling is receiving more attention from the government and PV producers. China has therefore developed its own national PV panel waste projections outlined in Box 18.

Box 18 China's PV panel waste projections

China has developed its own PV panel waste projections through its Institute for Electrical Engineering of the National Academy of Sciences (IEE) (Zhang and Fang, 2014). The IEE produced two case scenarios (CAS), a business-as-usual scenario and a better-treatment scenario. Both consider different operation and maintenance behaviours over the lifetime of deployed panels. Overall, the IEE estimates are similar to the results of the regular-loss and early-loss scenarios of this report to 2034. The two IEE scenario annual predictions amount to 61,250 t up to 87,000 t for 2025, rising to 262,000-330,000 t for 2030. From 2034 the IEE scenarios show higher end-of-life volumes than this report's scenarios with 900,000 t per year and 1.1 million t per year for 2034 respectively (see Figure 21).

Figure 21 Comparison of PV panel end-of-life scenarios for China



Regulatory and non-regulatory frameworks

At present, PV panels in China do not have specific requirements for end-of-life treatment. In February 2009 the State Council promulgated the Waste Electrical and Electronic Product Recycling Management Regulation which came into effect in January 2011 (State Council of the People's Republic of China, 2011). The 2011 regulation requires e-waste to be collected in various ways and recycled in a centralised processing system. Producers can collect and recycle the products by themselves or entrust collection to the sellers, after-sales service agencies or e-waste recyclers and entrust recycling/disposal to qualified institutions. At present, however, PV panels are not included in the waste electrical and electronic products processing directory of the regulation.

Because of the current low volume of waste, China does not have a mature PV panel recycling industry. China has sponsored R&D on PV recycling technologies, focusing on two recycling methods for c-Si PV under China's National High-tech R&D Programme PV Recycling and Safety Disposal Research from 2012 to 2015. These methods are based either on physical or thermal recycling. In the physical method various processes — including crushing, cryogenic grinding and separation — yield aluminium, glass cullet, copper, ethylene-vinyl-acetate and backsheet particles as well as a silicon powder mixture. The recycling rate is at about 90% by mass but silicon cannot be recycled for use in the PV industry owing to low purity. In the thermal method the clean cell debris goes through a thermal process and is then used for chemical experiments for recycling silicon, silver and aluminium.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Box 19 Outlook for China

China currently has no specific regulations for end-of-life PV panels, and related technology research has just begun. However, the National High-tech R&D Programme PV Recycling and Safety Disposal Research provides policy and technology signposts for the future. On the policy side, these include the need for special laws and regulations for end-of-life PV panel recycling, targets for recycling rates and the creation of necessary financial frameworks. On the technology and R&D side, recommendations concentrate on developing and demonstrating high-efficiency, low-cost and low-energy consumption recycling technologies and processes for c-Si and thin-film PV panels. Specific attention should thereby be given to improving the onsite/mobile recycling and disposal platform for c-Si PV power plants.

5.6 INDIA: GROWING MARKET WITHOUT PV-SPECIFIC WASTE REGULATIONS

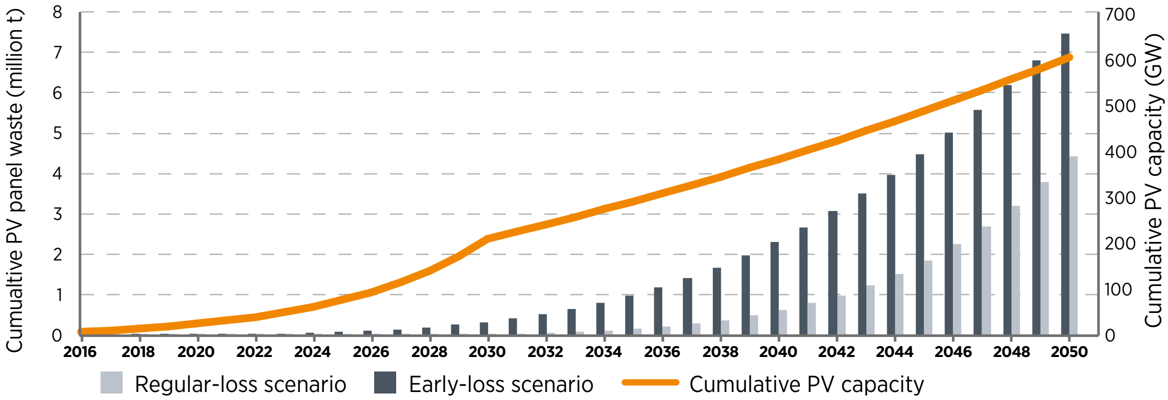
PV market and waste projection

Since 2012, India has installed over 1 GW of PV annually achieving a cumulative capacity of almost 5 GW in 2015 (IRENA, 2016b). This places India today amongst the top ten PV markets in the world (IEA-PVPS, 2014b). The Indian power sector faces two main challenges. Firstly, it needs to alleviate energy poverty (more than one-third of India's population lacks electricity access). Secondly, it needs to meet increased electricity demand arising from rapid economic growth (electricity demand is forecast to increase five- to sixfold by mid-century) (IEA, 2011). This represents a significant opportunity for renewable energy, including PV.

The Jawaharlal Nehru National Solar Mission (JNNSM) aims to install 100 GW of grid-connected PV systems by 2022 (Government of India, 2011). PV in India also represents an alternative to traditional grids, and the JNNSM targets to install 2 GW of off-grid systems.

Large-scale PV deployment has taken place only recently so major end-of-life PV waste volumes in India may not be expected until after 2030. Figure 22 shows India's expected end-of-life PV panel waste volumes in 2016-2050. Minimal waste is projected in 2016. However, waste could average 50,000-320,000 t by 2030, possibly culminating in 4.4-7.5 million t by 2050 (depending on scenario chosen).

Figure 22 End-of-life PV panel waste volumes for India to 2050



Regulatory and non-regulatory frameworks

India has no regulations mandating collection, recovery and recycling of end-of-life PV panels. This means waste PV panels generated today are covered by general waste regulations. Waste is managed by the Ministry of Environment, Forest and Climate Change under the 2016 Solid Waste Management Rules and the Hazardous and Other Wastes (Management and Transboundary Movement) Rules (Ministry of Environment, Forest and Climate Change, 2016a and 2016b). The recently amended Hazardous Waste Rules include use of Toxicity Characteristic Leaching Procedure. Transfer of hazardous waste requires authorisation from the State Pollution Control Board, and interstate transport is permitted under certain conditions (Ministry of Environment, Forest and Climate Change, 2016b).

Legislation covering requirements for general e-waste and restrictions on the use of hazardous substances in electronic products are included in the E-waste (Management and Handling) Rules of 2016 (Ministry of Environment, Forest and Climate Change, 2016c). However, these rules only apply to household electronics and not PV. Accordingly, an industrial-scale e-waste recycling infrastructure already exists in India but only covers household electronics and not PV.

Box 20 Outlook for India

In 2015 the original JNNSM deployment target of 20 GW of grid-connected PV systems by 2022 was updated to 100 GW by 2022. If supported by funding and grid infrastructure, progress towards the updated target would increase end-of-life PV panel waste volume projections for India by 2030 and especially by 2050. Although India currently has no specific PV-related waste regulation, increasing growth rates will most likely lead to waste regulations for end-of-life PV panels in the future.


06

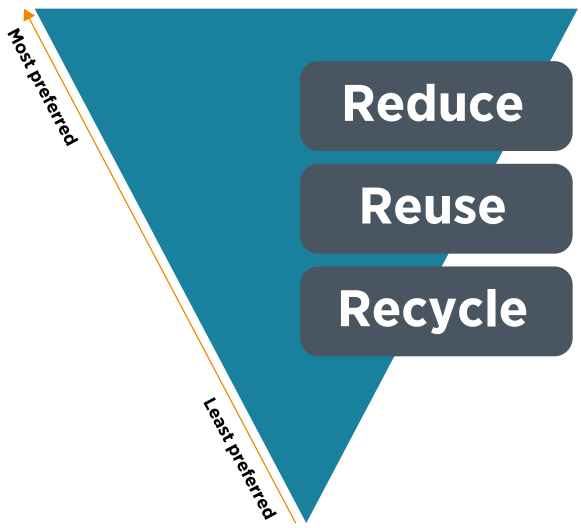
VALUE CREATION FROM END-OF-LIFE PV PANELS

Opportunities for value creation exist in each segment of the PV value chain, including the end-of-life stage. This chapter provides an overview of value creation opportunities relating to reductions in material use, options for repair and reuse and finally recycling and treatment considerations for PV panel waste. In the first section PV panel recycling is set in the context of well-known waste-reduction principles: reduce, reuse and recycle. The second section describes how socio-economic and environmental value is derived from end-of-life PV panels.

6.1 OPPORTUNITIES TO REDUCE, REUSE AND RECYCLE PV PANELS

The framework of a circular economy (cradle-to-cradle opportunities) and the classic waste reduction principles of the 3Rs (reduce, reuse, and recycle) can also be applied to PV panels (see also Chapter 4 on Waste Management Options). The preferred option among these is the reduction of material in PV panels and thus an increase in efficiency. Strong market growth, scarcity of raw materials and downwards pressure on PV panel prices are driving more efficient mass production, reduced material use, material substitutions and new, higher-efficiency technologies. This works towards cutting materials use per unit of generation.The reuse option follows the reduce option. This encompasses different repair and reuse modalities. Recycling is the least preferred option (apart from disposal) and only takes place after the first two options have been exhausted. It provides for the processing and treatment of PV panels and can unlock raw materials for new PV panel manufacturing or other products (see Figure 23).

Figure 23 Preferred options for PV waste management



PV panel material savings through R&D (reduce)

Chapter 2 included a projection of changes in PV panel composition between now and 2030. The following analysis will summarise potential "reduce" options for the material components used in different PV technologies.

Box 21 Definition of resource and material efficiency

Resource or material efficiency means using the world's limited resources in a sustainable manner while minimising impacts on the environment. Resource/material efficiency enables the creation of more value (e.g. products) with less input (e.g. resources or materials).

The mix of materials within PV panels has not changed significantly in the past. However, considerable material savings have been achieved due to increased resource and material efficiency (see Box 21 for definition). For instance, materials savings and even substitutions have been and are continuing to be researched for lead, cadmium and selenium so that the amount of hazardous materials can be reduced. For the other materials used for different PV panel technologies, research mainly focuses on minimising amount per panel to save costs. Since total consumption of rare and valuable materials will increase as the PV market grows, availability and prices will drive reduction and substitution efforts. Recent studies agree that PV material availability is not a major concern in the near term although critical materials might impose limitations in the long term. In addition, increasing prices will improve the economics of recycling activities and drive investment for more efficient mining processes. This includes extraction of metals used in the PV manufacturing process like silver, aluminium, copper and tin (Marini *et al.*, 2014; Marwede, 2013; Zimmermann, 2013; Taoa, Jiang and Taoa 2011 and Erdmann, 2011).

PV R&D has specifically set priority topics for material use reduction or substitution for different components commonly used in current PV panels[16] including for:

- c-Si panels: glass, polymer, silicon, aluminium, silver and lead and others;
- CIGS panels: glass, polymer, aluminium, cadmium, gallium, indium, selenium and others;
- CdTe panels: glass, polymer, cadmium telluride, nickel and others.

Furthermore, considerable R&D is focused on new materials and material replacements. The following is an illustrative set:

- **Indium.** New transparent conducting oxide layers incorporating more abundant and hence cheaper compounds like fluorine doped tin-oxide may replace indium-tin-oxide as front electrodes (Calnan, 2014). This reduces the use of indium in indium-tin-oxide available in some thin-film PV technologies as transparent conducting oxide.

- **Glass.** Further optimisation of glass composition, thickness, anti-reflective coating and surface structures will increase the transmission of the front glass panes by another 2% by 2024. The use of glass two millimetres thick or even less in a single-pane laminate will require additional mechanical stabilisation effort which might be achieved by double-glass panels with a thin encapsulation layer. These are proven constructions deployed for decades in thin-film PV panels and could lead to significant material reductions by substituting the need for a backsheet (Raithel, 2014).

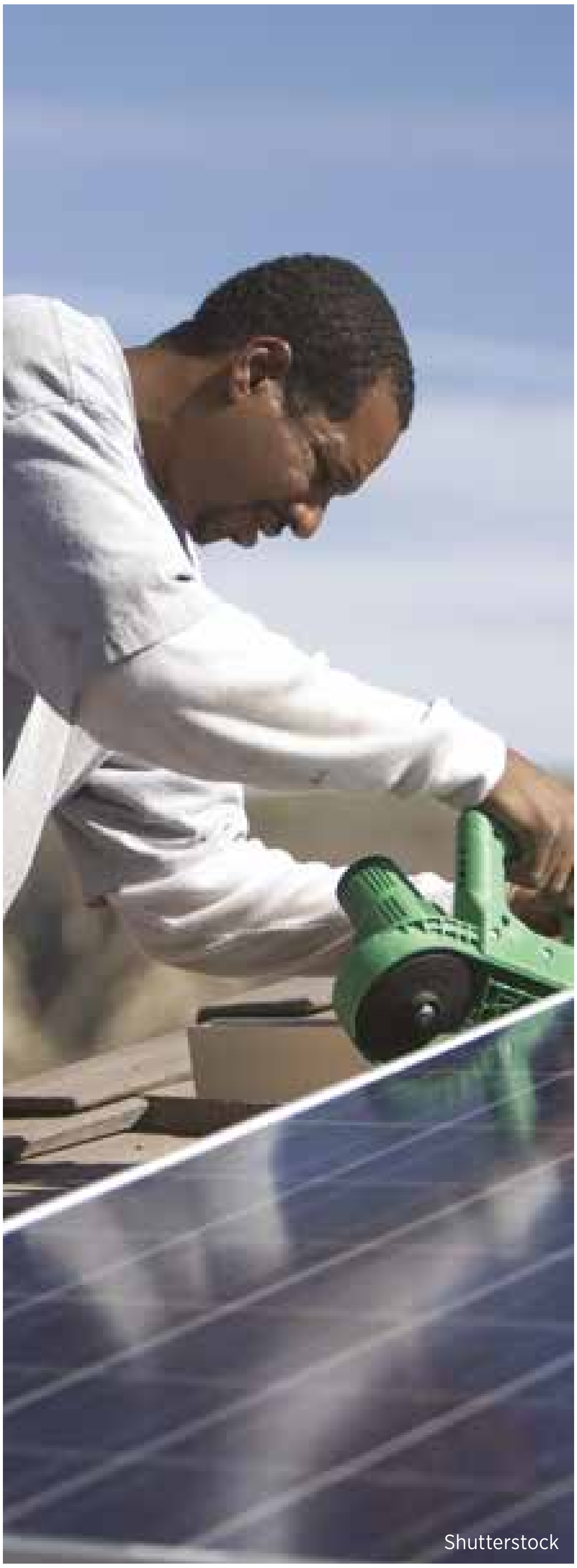
- **Polymers.** Encapsulants and backsheet foils are not recycled today because the duroplastic materials that dominate the market cannot be dissolved or melted for recycling without decomposition. Research is looking at reducing or replacing the amount of polymers, especially for backsheets that use a polyethylene terephthalate foil. They contain up to a few hundred parts per million of antimony used as polymerisation catalyst (Ramaswami, 2014). For example, the research project led by the Energy Research Centre of the Netherlands and PV CYCLE (CU-PV)[17] will develop and demonstrate alternatives to current practices. One example is the use of thermoplastics, which are easier to separate, as encapsulant. Another is the elimination of encapsulant use altogether (CU PV, 2016 and Oreski, 2014).

- **Silicon.** Thinner cells can reduce the amount of silicon used in c-Si cells. For instance, by moving to a back-contact cell design, the use of silicon could be cut by half, and energy consumption could be reduced by about 30% (Raithel, 2014).

- **Silver.** About 95% of c-Si solar cells are now produced with screen-printed silver contact lines on the front side covering roughly 6%–8% of the cell area. A significant reduction of silver on cells is expected by 2018 according to International Technology Roadmap for Photovoltaic (ITRPV) study (Raithel, 2014) owing to recent progress in inkjet and screen-printing technologies. This allows the use of other metals like copper in combination with nickel and aluminium. Use of rear-contact or bifacial cells can help further reduce silver consumption per watt (W) by enhancing cell efficiency (Raithel, 2014 and Perez-Santalla, 2013). For example, the research project led by CU-PV will develop new metallisation methods suitable for thinner wafers. These are based on inkjetting seed layers plated afterwards with nickel and copper and result in at least a 99% reduction in silver. The silver components used in PV panels are further explained in Box 22.

16. The list in this chapter focuses on key materials which are the subject of active materials reduction research for panels. This list may differ from the materials rank ordered by weight per panel as reported in Chapter 3.

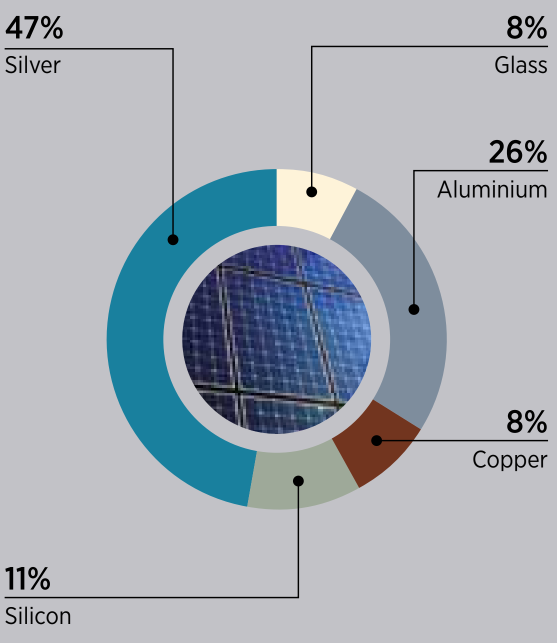
17. The CU-PV research project aims to address PV sustainability concerns by improving the recyclability of PV panels through advanced designs and collaboration over the value chain on recycling solutions.


Shutterstock

Box 22 Silver components

From a value standpoint, silver is by far the most expensive component per unit of mass of a c-Si panel, followed by copper, silicon, aluminium, glass and polymer (see Figure 24). The PV industry consumes about 3.5%-15% of global silver production (Berry, 2014 and Marini *et al.*, 2014). The higher numbers in this range include production losses while the lower numbers result from analysis of the silver content of solar cells. On average, a typical c-Si panel contains about 6-10 grammes of silver.

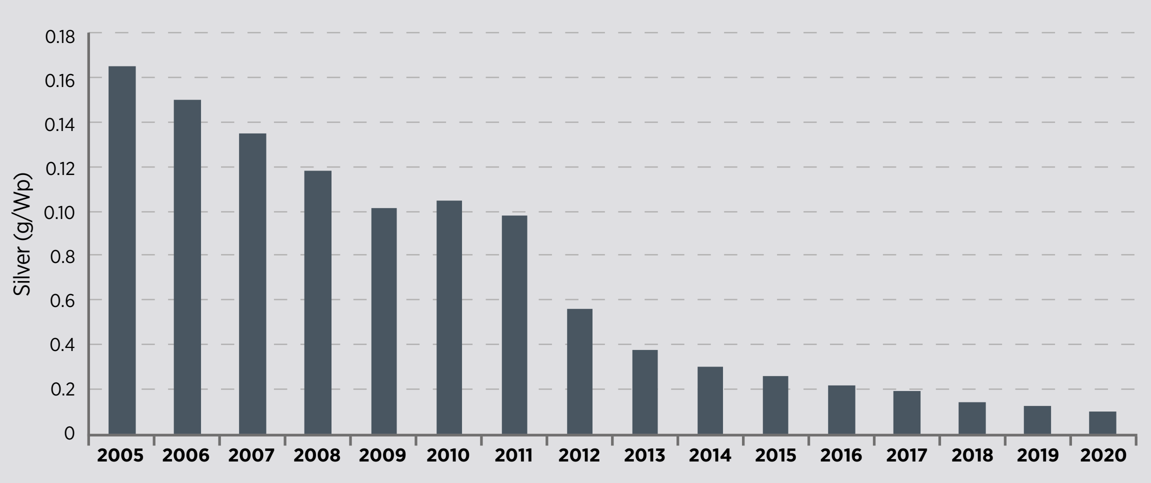
Figure 24 Relative material value (%) of a c-Si PV panel



Based on Raithel (2014)

Figure 25 shows recent silver consumption per watt and future projections. New printing techniques and pastes brought in silver savings of more than 30% in 2009-2012 (Silver Institute, 2014; Schubert, Beaucarne and Hoornstra 2013 and Perez-Santalla, 2013). Owing to expected growth rates in the global PV industry, the Silver Institute forecasts a mid- to long-term increase in silver consumption although the use per unit of power will shrink further. Silver consumption per watt is projected to decline by two-thirds from 2013 to 2017 while total silver consumption is expected to be the same in 2017 as in 2013 (Silver Institute, 2014). Assuming the silver contacts are ten microns thick and cover roughly 10% of a cell's surface, total c-Si cell manufacturing capacity would be limited by silver availability to five terawatt-peak (assuming 15% efficiency) (Tao, Jiang and Tao 2011). According to Raithel (2014), improved efficiencies, reduced consumption and better recovery should increase this limit in coming years.

Figure 25 Historic and expected specific silver consumption per watt-peak



Estimates based on Perez-Santalla (2013)

Various new technologies for cells, backsheets, coatings and encapsulation materials have been implemented, resulting in over 50,000 panel types (Photon, 2015 and 2016). Tracking all materials for the purposes of waste treatment and recycling is challenging and will continue to be so. Establishing global information flow systems with panel and material databases could facilitate the objective of long-term end-of-life management systems that maximise material recovery.

The next section analyses the different end-of-life options for PV panels. The environmentally preferable approach is to repair a potential end-of-life panel and make it fit for reuse.

Repair of PV panels (reuse)

Most PV systems were installed in the last six years (from 15 GW in 2008 to 222 GW in 2015), which means that these have aged to an early loss of 20% of the expected average lifetime (30 years) today. If defects are discovered during the early phase of a PV panel's life, customers may try to claim warranties or guarantees for repair or replacement provided the contract partner still exists. Insurance companies may be involved to compensate for some or all of the repair/replacement costs within the contract agreements. In such cases the ownership of the panels often changes to the insurance company. Most defective panels are thus typically returned to the contract partner, a producer service partner or the producer itself for inspection and repair.

In order to recover some value from a returned panel through resale, quality tests have to be made checking mainly electrical safety and power output. A flash test characterisation and a wet leakage test is one example. When repairs are both required and feasible, they typically involve applying a new frame, new junction box, diode replacement, new plugs and sockets and more. Solar cells may even be replaced, and panels relaminated. This is similar to the 'B-spec' and 'C-spec' qualities[18] in panel products that might be sold into special projects or relabelled to another brand name in some cases prior to marketing. In consequence, the product receives a new label with new guarantees (in compliance with national laws).

The repaired PV panels can be resold as replacements. Alternatively they can be **resold as used panels** at a reduced market price of approximately 70% of the original sales price compared to new panels, according to research conducted for this report. Partly repaired panels or components might be sold in a second-hand market. A modest **used panel market** has already been emerged supported by virtual internet platforms such as www.secondsol.de and www.pvXchange.com. With more and more PV installed, the number of these second-generation panels or components may well increase, generating a market for their use. Chapter 6.2 provides further information on emerging industry stakeholders in this market.

According to the Weibull statistics applied to the PV forecast in this report, a proportion of installed panels may remain intact even after an average lifetime of 30 years. If a PV system is dismantled after its nominal lifetime, these panels may be reused after a quality check and refurbishment. This creates a good opportunity for a significant secondary market of used panels and new repair service jobs in the future.

Panels that cannot be repaired or reused will be taken apart (see next section) and then forwarded to local waste treatment companies for further processing according to local regulations.

18. *Panels are grouped according to the results of the final quality inspection. An A-panel is of excellent quality, a B-panel may suffer from some minor quality issues like a scratch, stains and other discoloration or slightly wrong cell position. The next letters (C, D...) indicate more defects. Such panels usually are sold at lower prices.*

Decommissioning and treatment of PV panels (recycle)

Disassembly and dismantling

The types and sizes of PV systems installed have important implications for future waste management. For example, the proliferation of highly dispersed, small rooftop PV systems can add significant costs to dismantling, collection and transport of expired PV panels. By contrast, waste management for large utility-scale PV applications is logistically easier.

It is useful to distinguish two different scenarios for the collection of PV panels depending on size and geographic location:

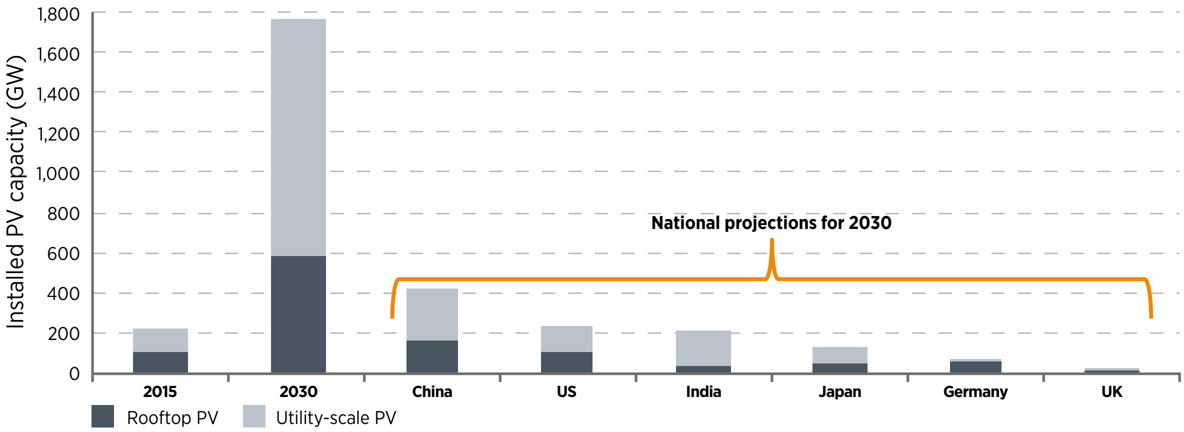
- Utility scale (> 100 kilowatts – kW);
- Home single-panel system (< 500 W), small rooftop (< 5 kW) and large rooftop system (> 5 kW).

Utility-scale systems (> 100 kW) are usually ground-mounted, regularly serviced and monitored. The panels may be placed on racks of aluminium or steel with concrete bases. The electrical system is based on string or central inverters with a grid connection. In some cases even an energy storage system may be present, which can be based on lithium-ion batteries, lead-acid batteries or other technologies.

For these large plants, competition among decommissioning actors results in high cost efficiency. Dismantling, packing, transport and recycling can be easily contracted for parts of or the whole system. Dismantling and pick-up services for transport to the recycling facilities will usually be defined during contractor bidding processes and supervised and performed by skilled workers. The tendering processes may include the entire dismantling of the plant or parts of it depending on the intended use of the area afterwards. It can be assumed that relatively high quality standards will be applied in such a case. The components of the PV plant will be stored separately: panels, cables, electronics (inverters, charge controllers, transformers, monitoring electronics etc.), metals (aluminium, steel), typical buildings and construction demolition waste etc. The quantities of the different wastes are relatively high and can easily be collected separately at reasonable cost for transport to specialised recyclers or landfill sites (Brellinger, 2014 and Fthenakis, 2000). Depending on the local regulations, some components — typically some batteries or power transformers — may be considered hazardous or toxic waste.

Costs of dismantling **smaller installations (5-100 kW)** depend on the type of PV system (ground-based, BIPV, rooftop, etc.) and the location. Dismantling small PV installations may require skilled workers like roofers and electricians. Single panels, small **home single-panel systems (< 500 W)** or other **small systems (< 5 kW)** might be returned by bring-in or pick-up services. In these cases, logistics costs

Figure 26 Projected rooftop and utility-scale PV deployment in 2030 compared to 2015



Based on IRENA (2016a)

can dominate the overall costs of the takeback and recycling systems. The different wastes will be sent to recyclers or landfill sites depending on local regulations and the presence of specialised waste-treatment companies.

IRENA's *REmap* study (IRENA, 2016a) predicts that rooftop deployment with system sizes of a few kilowatts up to the megawatt range will be substantial through to 2030 with 580 GW installed. Nevertheless, larger utility-scale (mostly ground-mounted) applications will make up larger share of total installed capacity at 1,180 GW (see Figure 26).

Logistics costs can become decisive in takeback systems for PV panels in remote areas like islands or rural areas. On the basis of the dismantled PV generator costs at Pellworm Island in Germany's North Sea, the costs for ship and truck transport can be at least three to five times higher than with mainland installations (United Nations Conference on Trade and Development, 2014). The presence of monopolistic structures (e.g. in the logistics system) can be an additional cost driver given the general observation that competition can reduce prices.

Damage to PV panels should be avoided during dismantling, transport and storage to support sound waste treatment with best available technologies and best possible results. Cables, junction boxes and frames should not be removed during dismantling. These may require special attention for their secondary material value and possibly in line with local legal requirements (Wambach *et al.*, 2009).

- **Recycling**

Since currently only moderate PV waste quantities exist on the global waste market, there are not sufficient quantities or economic incentives to create dedicated PV panel recycling plants. End-of-life PV panels are thus typically processed in existing general recycling plants. Here, the mechanical separation of the major components and materials of PV panels is the focus. This still achieves high material recovery by panel mass even although some higher value materials (that are small in mass) may not fully be recovered. This current strategy offers legal compliance without the need for new PV-specific recycling investments. In the long term, however, constructing **dedicated PV panel recycling plants** could increase treatment capacities and maximise revenues owing to better output quality. In addition, it could increase recovery of valuable constituents.

Recycling technologies for PV panels have already been researched for the past 15 years. This knowledge has provided a foundation for developing specialised recycling plants once the waste streams are sufficiently large for profitable operation. For example, extensive research was conducted by solar PV companies including AEG, BP Solar, First Solar, Pilkington, Sharp Solar, Siemens Solar, Solar International and many others (Sander *et al.*, 2007). Research institutes have also examined different recycling options for PV. Examples include the Brookhaven National Laboratories in the US, the National Institute of Advanced Industrial Science and Technology in Japan, the Interuniversity MicroElectronics Center in Belgium and the Energy Research Centre in the Netherlands (CU PV, 2016). All future recycling processes will need to keep abreast of ongoing cell and panel innovations to obtain the best possible results at acceptable costs. Such processes will have to recover major components like glass, aluminium, copper and other potentially scarce or valuable materials (e.g. silver, indium) at sufficient quality for sale on the world market. They might equally need to handle modest quantities of hazardous and toxic materials (e.g. cadmium) (see Chapter 3 for PV panel waste composition).

One of the main technical challenges in PV recycling is the delamination or the removal of the encapsulant material (e.g. ethylene-vinyl-acetate). Various methods have been explored for effective delamination, including mechanical crushing (Giachetta *et al.*, 2013 and Berger *et al.*, 2010), thermal processing (Wang *et al.*, 2012), organic solvents (Kang *et al.*, 2012 and Doi, 2001), pyrolysis and vacuum blasting

(Berger *et al.*, 2010 and Kushiya, 2003), micro-emulsions (Marwede and Reller, 2012) and ultrasonic radiation (Kim and Lee, 2012).

The following points are important for designing any future PV panel waste recycling systems independent of the PV technology used: These considerations would produce the best possible results, including high recovery rates and high quality even for materials present in low quantities (Sander *et al.*, 2007).

- Avoid further damage to the PV panel during dismantling, collection and transport phases;
- Depending on economic feasibility, reclaim as much valuable (e.g. silver, copper, silicon, glass, aluminium), scarce (e.g. indium, tellurium) and most hazardous materials (e.g. cadmium, lead, selenium) as possible;
- Use durable labelling to help identify the product;
- Link material compositions relevant to recycling and recovery processes to the label;
- Create recycling-friendly panel designs.

In the rest of this section, some of the more commonly used methods are described for the two main PV technologies: crystalline silicon and thin-film PV panels.

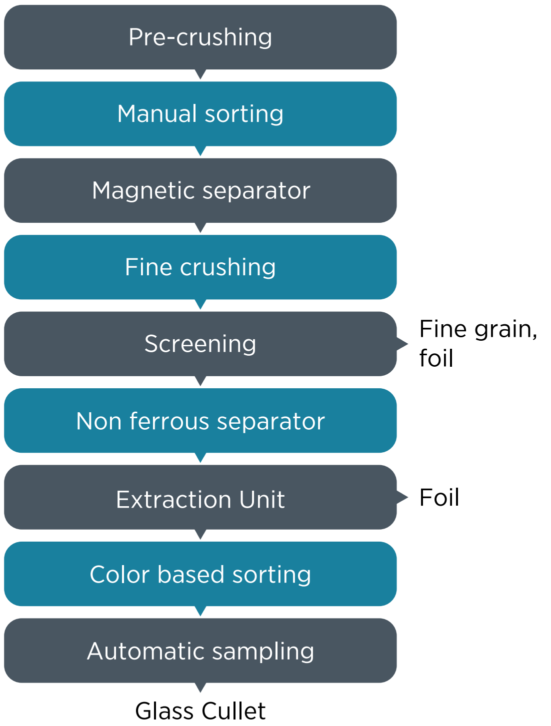
Recycling crystalline silicon PV panels

The major components of c-Si panels, including glass, aluminium, and copper, can be recovered at **cumulative yields greater than 85%** by panel mass through a purely mechanical separation. However, without a combination of thermal, chemical or metallurgical steps, impurity levels of the recovered materials could be high enough to reduce resale prices (Pennington *et al.*, 2016 and Sander *et al.*, 2007).

Separation of the major components such as laminated glass, metal frames, wiring and polymers is the first step in current and first-generation recycling processes. Recycling strategies for each of these major components is discussed below.

Recycling the laminated glass component of c-Si panels is a relatively low-cost process which flat-glass recycling companies can implement with little additional investment (see Figure 27). The process is frequently run in batches to enable adjustment of parameters and account for the modest quantities available for processing today. Typical equipment for removing impurities like polymer (glue) residues or screws from the glass cullet includes magnets, crushers, sieves, eddy-current devices, optical sorters, inductive sorters and exhaust systems. The resulting crushed-glass fraction, which may still be heavily contaminated with silicon, polymers and metals, can be blended with other recycled glass as thermal insulating material in the glass-foam or glass-fibre industries. Research conducted for this report shows a blend composition including 15%–20% of PV panel glass is thereby achievable. However, with increasing waste PV streams, this market could become saturated, and investments in new recycling technologies will be required.

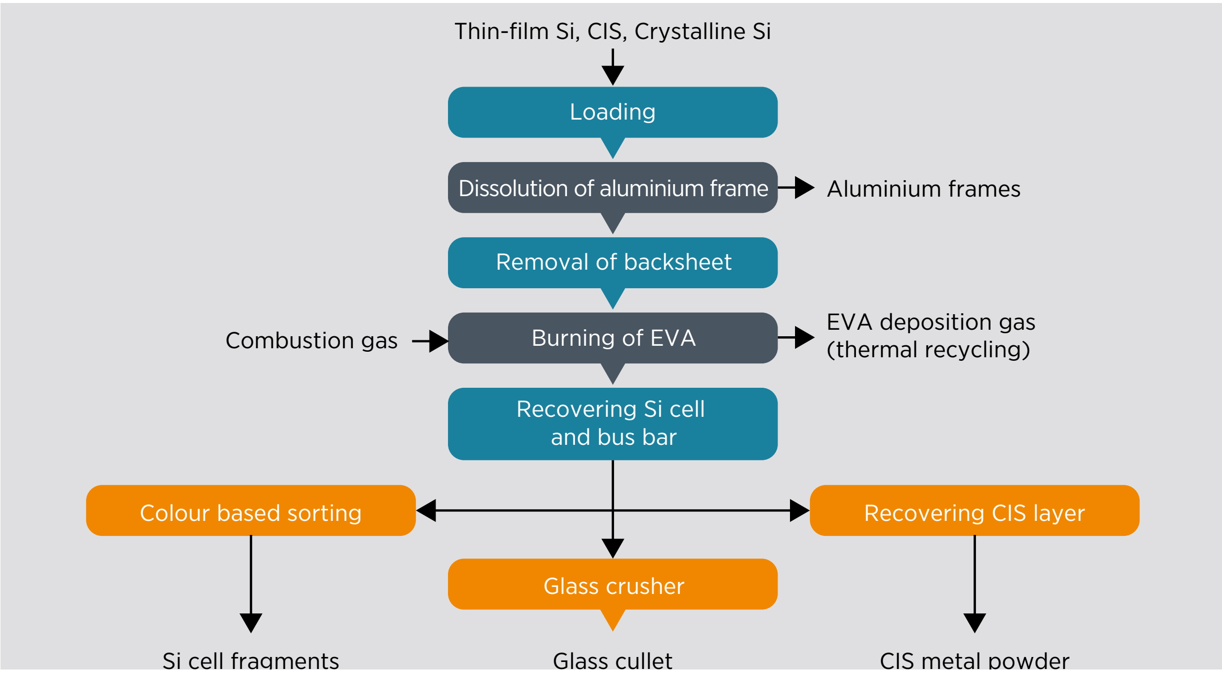
Figure 27 Process for laminated glass recycling



The aluminium or steel of the frames, and the copper of the cables can become part of the already well established metal recycling loops and therefore have easy potential for recycling. The polymer fractions can partly be processed in waste-to-energy plants provided they meet the input specifications of the plants.

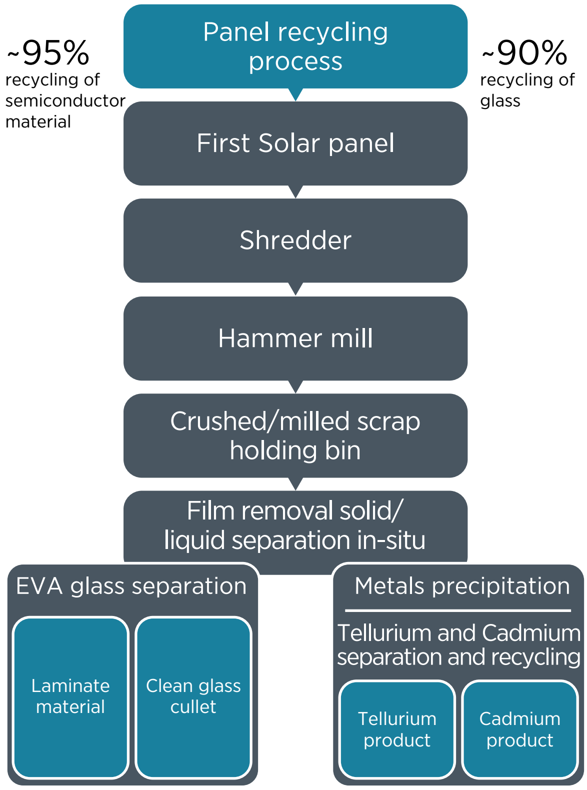
Recovering small amounts of valuable (e.g. silver, copper), scarce (e.g. indium, tellurium), or most hazardous materials (e.g. cadmium, lead, selenium) as components might require additional and more advanced processes. These are found predominantly in the glass and encapsulant (polymer) fractions. For example, the technical feasibility of recovering and purifying silicon from end-of-life c-Si PV panels has been demonstrated by Wambach *et al.*, (2009) which separated the panels in a pyrolysis step. It removed the solar cell metallisation and dopant layers in several selective etching steps and cast a new silicon ingot from the silicon obtained. A very similar process was developed by the Japanese NEDO programme by the FAIS – see Figure 28 (Komoto, 2014). The pilot plant also relies on pyrolysis of the polymers in a conveyor kiln. One main difference is the removal of frames and backsheet foil prior to the thermal step that precedes semiconductor material recovery (Si or CIS) and the glass cullet (see also Chapter 5.3 on Japan).

Figure 28 Recycling scheme proposed by NEDO/FAIS



Based on Komoto (2014)

Figure 29 Thin-film recycling process



Based on First Solar (2015a); cadmium and tellurium separation and refining are performed by a third party

Recycling thin-film PV panels (CIGS and CdTe)

The large-scale recycling of thin-film PV panels is still in its early stages and will improve as waste volumes and corresponding waste treatment knowledge increases. Thin-film panels are currently processed and recycled using a combination of mechanical and chemical treatments (see Figure 29).

A prominent example of this process includes the following steps (Sinha and Cossette, 2012) which can achieve about 90% recovery of the glass and about 95% of the semiconductor material by mass:

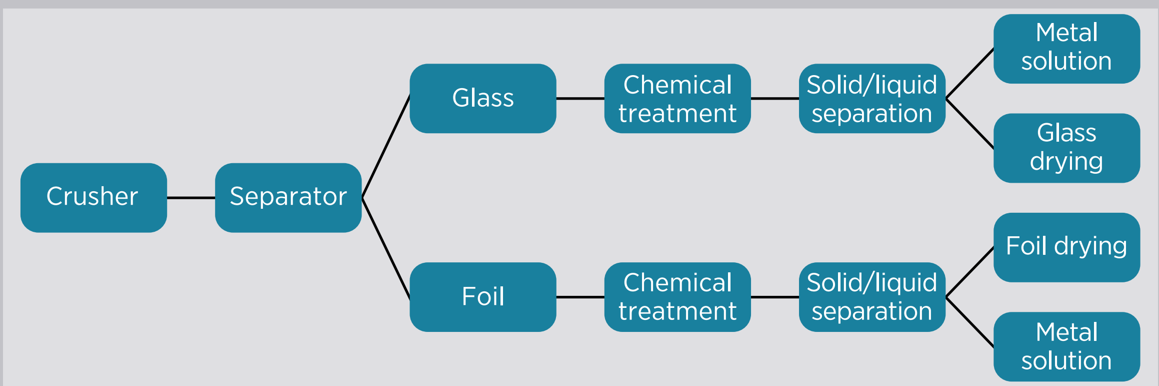
1. Panels are shredded and crushed in a hammer mill to particles of about 5 millimeters to break the lamination bond. The dust is then collected in an aspiration system equipped with a high-efficiency particulate air filter.

2. Semiconductor layer etching is carried out with a mixture of sulphuric acid and hydrogen peroxide. The glass and larger pieces of ethylene-vinyl-acetate are separated in a classifier and on a vibrating screen. Finally, the glass is rinsed with water and dried on a belt filter unit.

Box 23 Innovative treatment processes for thin-film PV panels

Loser Chemie (Palitzsch and Loser, 2014) has developed and patented new processes to enrich the compound semiconductor metals or silver of solar cells via chemical treatment after panels are pre-crushed (see Figure 30). The aluminium metallisation can subsequently be used for producing wastewater treatment chemicals (aluminium oxides).

Figure 30 Loser Chemie recycling process



3. The filtration liquids with the metals can be extracted via ion exchangers or precipitated. The cadmium and tellurium can be further purified by third parties for reuse in the solar industry.

Several new treatment processes for thin-film PV panels are currently undergoing research. The innovative Loser Chemie process described in Box 23 is one example.

6.2 MATERIAL SUPPLY AND SOCIO-ECONOMIC BENEFITS

With estimated PV panel waste volumes growing steadily in the coming years, the last section of this report assesses value creation of end-of-life PV by looking at potential socio-economic and environmental benefits. If approached and co-ordinated in time, significant opportunities can arise from managing the end-of-life of PV panels.[19]

Unlocking raw materials and their value

Important value can be created by extracting secondary raw material from end-of-life PV panels and making them available on the market again. Having an average lifetime of 30 years, PV panels will build up a large stock of raw materials embodied in products that will not become available for recovery for a considerable period of time. For example, a large flow of silver from panel recycling is not expected until 2025 (Perez-Santalla, 2013).

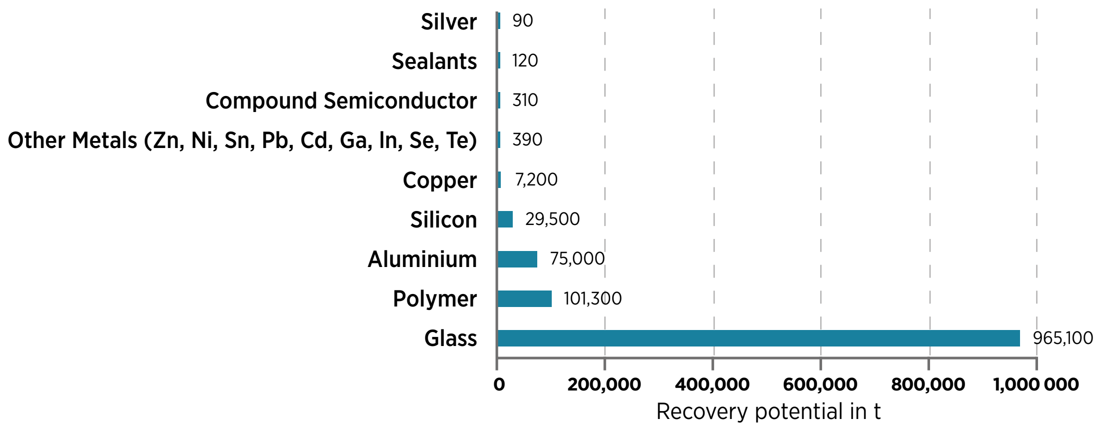
Value creation from unlocking raw materials is estimated below. The following assumptions are used:

- Raw materials can be treated and recycled at a rate of 65%-70% by mass. These recovery rates are already achievable today and are in line with the only existing regulation for PV panel recycling to date, the EU WEEE Directive (see Chapter 4). They are also a blended rate and assume a collection rate of 85% of total end-of-life PV waste stream as well as high value treatment and recycling technologies available to recover the majority of material fractions. This excludes losses from mechanical processing (e.g. shredder and mill dusts) and thermal recovery of non-recyclable polymer fractions (e.g. duro-plastics).
- The estimates are based on expected PV cell technology ratios and related waste composition multiplied by the cumulative waste volume of 1.7 million t for 2030 under the regular-loss scenario.
- Monetary value estimates reported are based on April 2016 market prices (Europäischer Wirtschaftsdienst, 2016) and may vary in future due to 1) possible price fluctuations on the raw material market and 2) changes in the raw material composition of PV panels.

The results of potential cumulative raw materials recovered by 2030 are displayed in Figure 31.

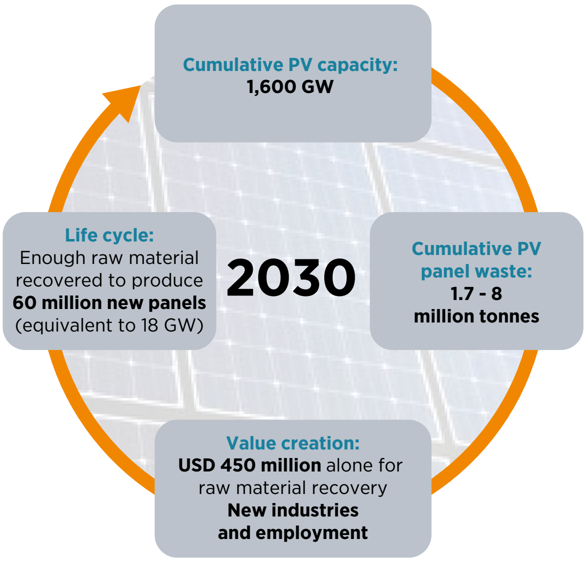
19. *The value creation in different segments of the solar value chain has been studied in IRENA's publications "The Socio-economic Benefits of Solar and Wind" (2014) and "Renewable Energy Benefits: Leveraging Local Industries" (2016 forthcoming).*

Figure 31 End-of-life recovery potential under regular-loss scenario to 2030 (t)



The total potential material value recovered through PV panel treatment and recycling amounts to USD 450 million by 2030. This is equivalent to the current raw material value needed to produce 60 million new panels or 18 GW. By comparison, 180 million new panels were produced in 2015.

Figure 32 Potential value creation through PV end-of-life management to 2030



Over 80% of the weight of panels made through any PV technology is **glass**; thus the greatest mass of recycling material comes from glass, estimated at approximately 960,000 tonnes by 2030. Hence, development of efficient recycling technologies for PV panel glass is essential. With an average secondary material market price for glass at USD 30-50/t depending on recovery quality (Eurostat Statistics, 2014), the potential for recovery value exceeds USD 28 million.

Significant amounts of **aluminium** (approximately 75,000 tonnes) and **copper** (approximately 7,000 tonnes) are projected to be re-released on the secondary material market through PV panel treatment. Both can easily be recycled using mature infrastructure available today. Their current combined value is up to USD 140 million (Europäischer Wirtschaftsdienst, 2016). If compared with world production in 2015 (see Table 13), these unlocked materials offer an important additional raw material supply by 2030.

Material usage for **silicon** cells has been reduced significantly during the last ten years, from around 16 grammes/Wp to less than 4 grammes/Wp due to increased efficiencies and thinner wafers. Silicon crystalline technologies continue to dominate the PV market. This means up to 30,000 tonnes of silicon, a valuable material, can potentially be recovered in 2030, assuming low yield losses. This is equivalent to the amount of silicon needed to produce over 45 million new panels or around USD 380 million (using current polysilicon prices at USD 20/kg and a value recovery rate of 70%).

Silver recovered from PV panels also has significant potential value. Based on an estimate of 90 tonnes recovered in 2030 and at a current market price (April 2016) (Europäischer Wirtschaftsdienst, 2016), the value of recovered silver is estimated at USD 50 million. This is enough to produce 50 million new panels.

The potential recoverable mass of **other materials** is 390 tonnes. These include zinc, nickel, gallium, indium, selenium tellurium and others. By comparison, the world production of these raw materials amounted to 3 billion tonnes in 2015 (see Table 13). This is equivalent to approximately USD 180 million. Up to 60 million new PV panels can be manufactured with this amount of material assuming increasingly efficient use of rare materials in manufacturing processes as well as improved recovery of purity in recycling treatments.

The potential recoverable amount of **semiconductors** is 310 tonnes, a relatively low number compared to the other materials discussed above. However, this could be used for the production of 40 million new PV panels.

Sealants and **polymers** are hard to recover today. New treatment and recycling processes are needed in order to create value for over 100,000 tonnes of these materials and substances potentially recoverable by 2030.

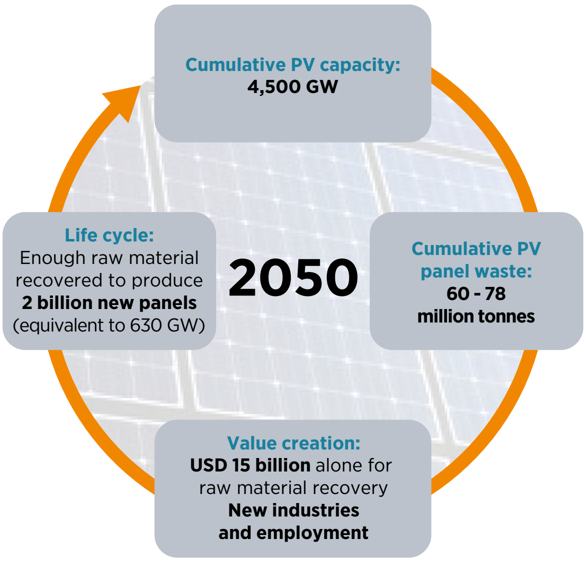
Table 13 World production of mineral commodities used in PV panels, 2015

	World production 2015 (thousand t)
Aluminium	58,300
Cadmium	24,200
Copper	18,700
Gallium	435
Indium	755
Lead	4,710
Lithium	32,500
Molybdenum	267,000
Nickel	2,530,000
Selenium	> 2,340
Silicon[20]	8,100
Silver	27,300
Tellurium	> 120
Tin	294,000
Sum	**3,268,460**

Based on US Geological Survey, 2016

20. Production quantities are combined totals of estimated silicon content for ferrosilicon and silicon metal.

Figure 33 Potential value creation through PV end-of-life management to 2050



As shown above, significant value could be created by recovering secondary raw materials by 2030. Applying the same regular-loss scenario until 2050, the value potential for unlocked raw materials is expected to surge to over USD 15 billion. This equates to the raw material needed to produce two billion new panels – 630 GW.

Recovered raw material tonnage can be traded and shipped just like primary raw materials from traditional extractive resources. The volumes injected back into the economy can serve for the production of new PV panels or other products, thus increasing the security of future PV supply or other products dependent on raw materials used in PV panels. As a result, rapidly growing panel waste volumes over time will stimulate a market for secondary raw materials originating from end-of-life PV.

Additional R&D and optimisation of recycling processes will be required to realise the full potential of material recovery, especially considering previous and current panel designs not yet incorporated into designs for recycling.

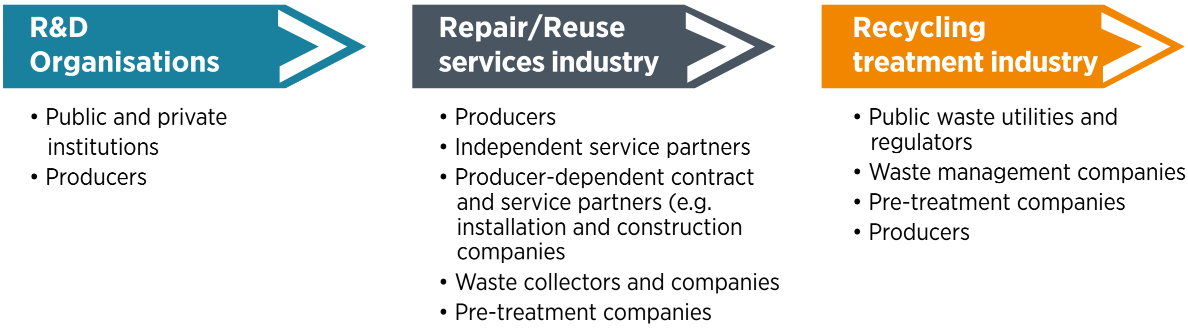
Creating new industries and jobs in PV

The overall waste management industry includes different stakeholders such as producers, importers, dealers, system operators, utilities, municipalities, governments, waste treatment companies and end-users. Co-operation is needed among these players to guarantee the acceptance of future PV panel waste management systems.

End-of-life PV panel management for holds the potential to develop new pathways for industry growth and offers employment opportunities to different stakeholders. These jobs are distributed among the public sector (governments, public research, etc.) and private sector (producers, waste management companies, etc.) (see Figure 32).

The emerging PV recycling industry will necessitate trained staff with specific skills and knowledge of recycling processes. Specific education and training programmes will need to become part of the renewable energy education sector. This will supply the technical skillset required to make the renewable energy industry part of the 3R and circular economy model.

Figure 34 Industry value creation from end-of-life PV management



Firstly, **R&D organisations** will have an important role to play to achieve the further reduction of materials, increase efficiencies and further investigate the best available recycling and treatment processes for PV panels. As seen in Chapter 5, **public institutes** in several countries (e.g. Germany, Japan and China) have already started to research recycling methodologies with support from the **local government**.

With PV panel cost reduction as a primary driver, **producers** have since the industry's infancy built high-tech research capabilities to increase material and panel efficiencies. However, traditionally producers have concentrated more on production rather than end-of-life (repair/treatment and recycling). This is also explained by the renewable energy industry's relatively recent significant growth. The increasing PV waste volumes will change this perspective and should redirect R&D to the entire life cycle of a panel.

The private sector is also expected to be at the forefront of a new **repair and reuse service industry** for PV panels. Most likely, additional employment opportunities will arise for the **producers** themselves and **independent or contract and service partners** dependent on producers (e.g. installation and construction companies). However, **waste collectors and companies** and **pre-treatment companies** are also expected to expand their portfolio as investment opportunities in this sector rise.

Most importantly, the end-of-life management of PV panels in itself will trigger an important **recycling and treatment industry**. All waste management is regulated by governments so it entails different responsibilities for concerned stakeholders, depending on the legislation. Everywhere except in the EU, PV panels are part of regular waste streams. At the same time, actors mostly include **general waste utilities and regulators or waste management and pre-treatment companies**. No formal and established PV panel recycling market exists today. Yet waste treatment companies are studying the new business case for PV panel treatment given the increase in e-waste regulations and PV markets (see Chapter 5 country case studies).

With binding extended-producer-responsibility through the EU WEEE Directive, for instance, **producers** have become additional players essential to driving end-of-life management practices for PV. According to Nasr and Thurston (2006) "… (when a product manufacturer has a leading role in the entire product life cycle… (it) promotes… efficient material use and reuse." Contracting waste management partners with specialised knowledge in PV end-of-life has therefore become essential for big producers to maintain market competitiveness. A small number of producers have or are also in the process of investigating the option of developing their own recycling production facilities (e.g. First Solar).

This study has analysed how different frameworks for end-of-life PV provide the potential to grow local PV recycling industries, especially in jurisdictions with specific PV waste legislation, such as the EU. Yet the recycling industry is also one of the few true global industries today and therefore needs to be treated accordingly. For PV panel waste, many opportunities can therefore emerge in developing or transitioning economies with informal sectors dominating collection and recycling services. Producers are active in many of these countries so a mandatory PV waste system could retain additional employment, especially in the repair/reuse and recycling/treatment industries. At the same time, it would improve national waste management practices.

Box 24 Socio-economic benefits of the WEEE Directive in the EU

According to Monier and Hestin (2011), the main socio-economic benefits of the WEEE Directive arise from the inclusion of PV panels in the regulatory framework.

Firstly, they estimate that the environmental impact of end-of-life PV panels can be reduced by a factor of six in comparison to a baseline scenario which assumes no pre-treatment and recycling of PV panels. By implementing high-value recycling processes, the recovery of a certain mass percentage of the total panel is guaranteed but also minor fractions are accounted for. For e-waste, it means the costs of collection and treatment are more than offset by potential revenues of materials recovered from the PV panels and create additional value. Monier and Hestin estimate that jobs will increase alongside the quantity of end-of-life PV panels collected and properly treated in high-value recycling operations.

The evaluation concludes that the resulting net benefits of including PV panels in the WEEE Directive could amount to up to EUR 16.5 billion in 2050.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CONCLUSIONS: THE WAY FORWARD

Effective deployment policies have supported the growth of renewables globally, including PV. In early 2015, more than 145 countries had introduced regulatory support mechanisms (e.g. feed-in tariff, net-metering or auctions), fiscal incentives and public financing (e.g. capital subsidy, investment or production tax credit). Overall, the number of incentives related to renewable energy has increased nearly tenfold over the past decade, leading to a global cumulative installed capacity of 222 GW at the end of 2015 (IRENA, 2016). PV now makes up a distinct share of the energy mix in several countries. Substantial growth is anticipated in coming decades, leading to a projected installed capacity of approximately 4,500 GW in 2050.

PV panels have a long life (average life expectancy is 30 years) and in most countries have only since the middle of the 2000s been installed at a large scale. This study predicts that significant amounts of PV panel waste will be generated by 2030 as these long-lived PV systems age.

PV end-of-life recycling systems and regulatory schemes to deal with PV end-of-life management have only recently emerged. Certain countries and regions are ahead of that curve, such as the EU. Long lead times have already preceded the implementation of environmentally and economically robust technological and regulatory policies for e-waste. Given this experience, the time to start devising these systems for PV panel waste in many countries is now.

A range of potential policy options exist for PV waste management which can be adapted to the unique conditions of each country or region. Previous experience, particularly in relatively mature EU markets, has identified numerous lessons learned and best practices from which newer market entrants can draw. For example, various models for financing PV collection and recycling have evolved and been tested. However, voluntary-producer and public-private-partnership programmes have not achieved the desired results, making way for uniform regulatory regimes with clearer roles and responsibilities.

End-of-life management policies need to be part of a broad range of cross-cutting enabling instruments that support the transition to sustainable PV life cycle policies. Tailored to specific national conditions and relative PV sector maturity, the enabling framework should focus on adopting a system-level approach. It should build institutional, technological and human capacity, strengthening a domestic or regional PV recycling industry and creating a financial framework in support of end-of-life management.

CENTRAL ROLE OF AN ENABLING FRAMEWORK

Institutional development is essential to supporting sustainable end-of-life practices for PV. Sustainable management of end-of-life PV panels will be strongly influenced by the abilities of public sector institutions and the private sector to take informed and effective decisions on management and treatment opportunities. Thus far, end-of-life regulation exists only in the EU, which is pioneering rules that categorise PV panels as a type of e-waste. However, other countries are investigating institutional capacities to implement end-of-life policies (e.g. China, Japan). To improve decision-making and ensure better planning, a monitoring and reporting system covering PV waste streams needs to be included into national and regional regulations. This can in turn provide the statistical data needed to enhance waste stream predictions, better understand the causes of panel failure and further refine regulatory frameworks.

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. Considerable efforts to develop technologies and policies to support PV deployment have taken root over the last few years. To meet the challenge of managing greater PV waste volumes in a sustainable way, support will also need to include end-of-life technologies and policies. Such support can ensure deeper integration across the different PV life cycle stages and other policies targeting a comprehensive life cycle approach of products (e.g. 3R concept, circular economy approach). End-of-life management can affect a variety of stakeholders, including producers and owners, such as households and larger consumers. Growing PV panel waste is transforming the ownership structures in the sector. For instance, PV panel producers wishing to sell in the EU are now liable for the end-of-life phase of a panel and financing waste management (see Chapter 4 on extended-producer-responsibility framework in the EU). A system-level approach to policy making for PV end-of-life can balance the ambitions and responsibilities of PV suppliers with those of PV consumers, new entrants (e.g. waste companies) and other stakeholders.

R&D, education and training, are all needed to support PV end-of-life management to design and implement socio-technological systems. Support for R&D in PV end-of-life activities can improve technological performance and produce greater value from the recycling output. Further technology innovations can create high-value recycling processes for rare, valuable and potentially hazardous materials which surpass legal requirements and provide additional environmental and socio-economic benefits and that do not exist today. Industrial cluster cultivation between the energy and waste sectors as well as cross-cutting R&D programmes can contribute to increased quality for recycling technologies and processes. Just as importantly, technological R&D must be coupled with prospective techno-economic and environmental analyses to maximise societal returns, minimise detrimental outcomes and avoid unintended consequences. This requires systematic access to human talent across different disciplinary fields, including engineering, science, environmental management, finance, business and commerce. In addition, vocational training programmes will be necessary. They can, for instance, retrain PV installers on potential repair and reuse opportunities for PV panels showing early failures.

With the right policies and enabling frameworks in place, the spawning of new industries that recycle and repurpose old solar PV panels will drive considerable economic value creation. This will be an essential element in the world's transition to a sustainable energy future.

Strengthening domestic capabilities and boosting the development of local PV recycling industries can help to maximise the value creation of PV end-of-life. As a result of increasing PV waste streams, new markets will emerge. They will create new trade flows while providing local opportunities for the energy and waste sectors in different segments of the decommissioning stage (e.g. repair or recycling of PV panels). The ability to localise depends on the characteristics and competitiveness of local complementary industries – mainly the waste sector. It relies on the quantity, quality and reliability of supply of projected local waste streams and projected demand for secondary panels and secondary raw material extraction. The nascent PV waste and recycling industry can be further supported through measures that create demand for local recycled goods and services (e.g. purchase tax rebates for secondary raw material recovered through PV recycling processes).

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. Previous experience has produced technological and operational knowledge on financing end-of-life PV panel management that can inform the organisation of increasingly large waste streams. Experience in mature markets like Germany has shown that forcing household consumers to recycle WEEE is impractical. Voluntary approaches ultimately fail owing to the financial risks of free riders misusing the system and to a lack of enforceability over the long lifetime of the products. Extended-producer-responsibility schemes have thus proved the most successful in practice, including pay-as-you-go combined with last-man-standing insurance, and joint-and-several liability approaches in which producers become responsible for PV panel collection and recycling. The costs of proper treatment and recycling can be included in the production sales price through a modest fee per kilowatt-hour produced, for example.

Outlook

As countries strengthen their policy and regulatory frameworks to transform their energy systems, they have the unique opportunity to address sustainable end-of-life management goals at the same time. Establishing PV end-of-life management policies can generate value and secure long-term socio-economic benefits such as material recovery through recycling, creating new industries and jobs.

Going forward, holistic, adaptable frameworks capturing and measuring the multiple impacts of PV end-of-life management (e.g. EU WEEE Directive) can tip the balance in favour of sustainable life cycle practices and policies worldwide.

Governments and stakeholders in the PV sector need more complete analysis of projected PV waste management streams and compositions to make decisions. The IRENA and IEA-PVPS study *End-of-life Management: Solar Photovoltaic Panels* provides a first glimpse of the opportunities offered by the sustainable management of PV end-of-life. The report intends to establish a foundation to move countries more quickly up the learning curve in policies and technologies for PV end-of-life management. It leads the way for further exploration of this field.

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IEA INTERNATIONAL ENERGY AGENCY
PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

www.iea-pvps.org

IRENA
International Renewable Energy Agency

www.irena.org

Value of Recycling PV Modules, Market Size and Need for Design for Recycling

Garvin Heath, PhD

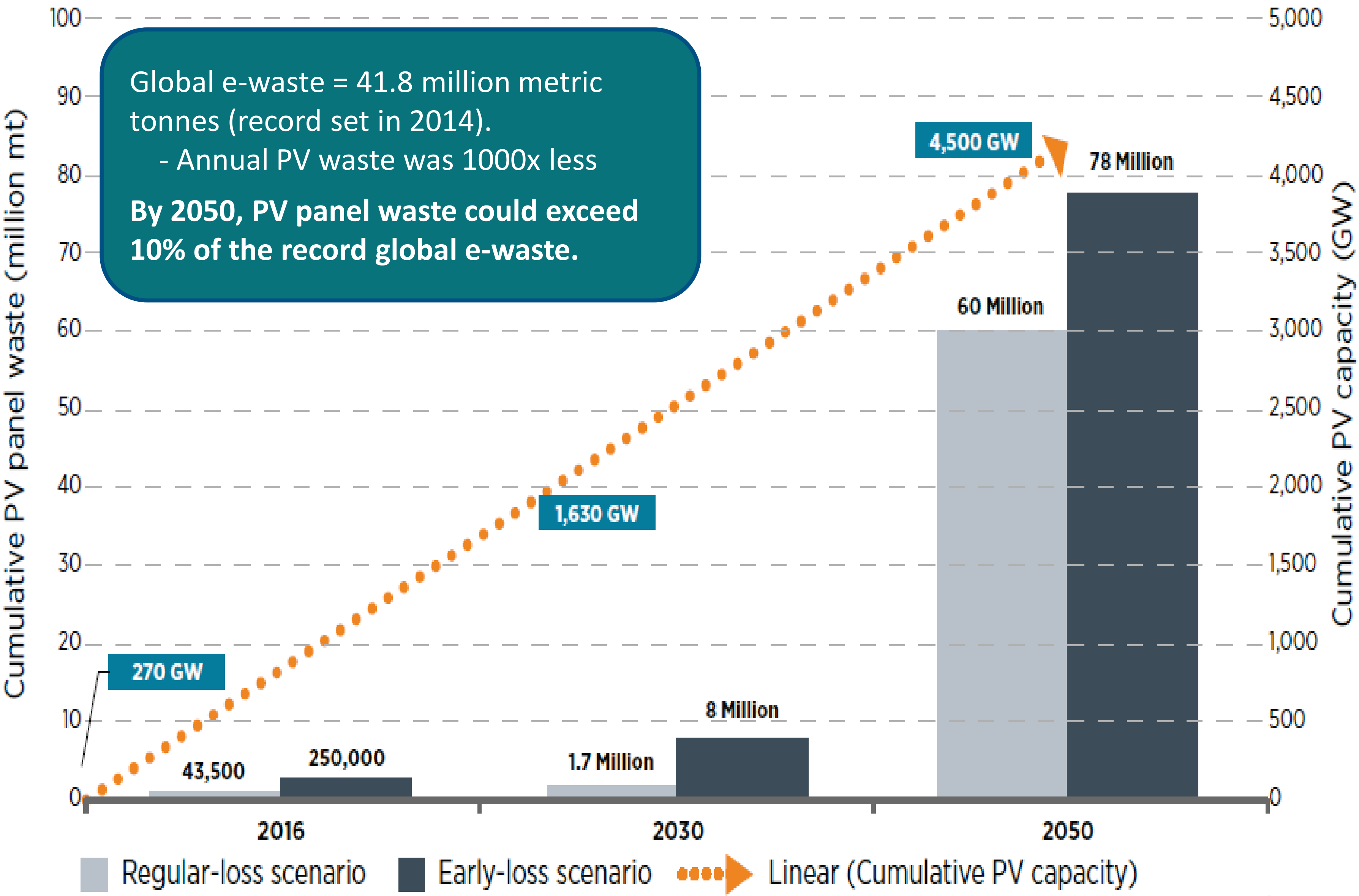
May 22, 2017

Team:
Michael Woodhouse, PhD
Jill Engel-Cox, PhD

DuraMat workshop
Stanford, CA

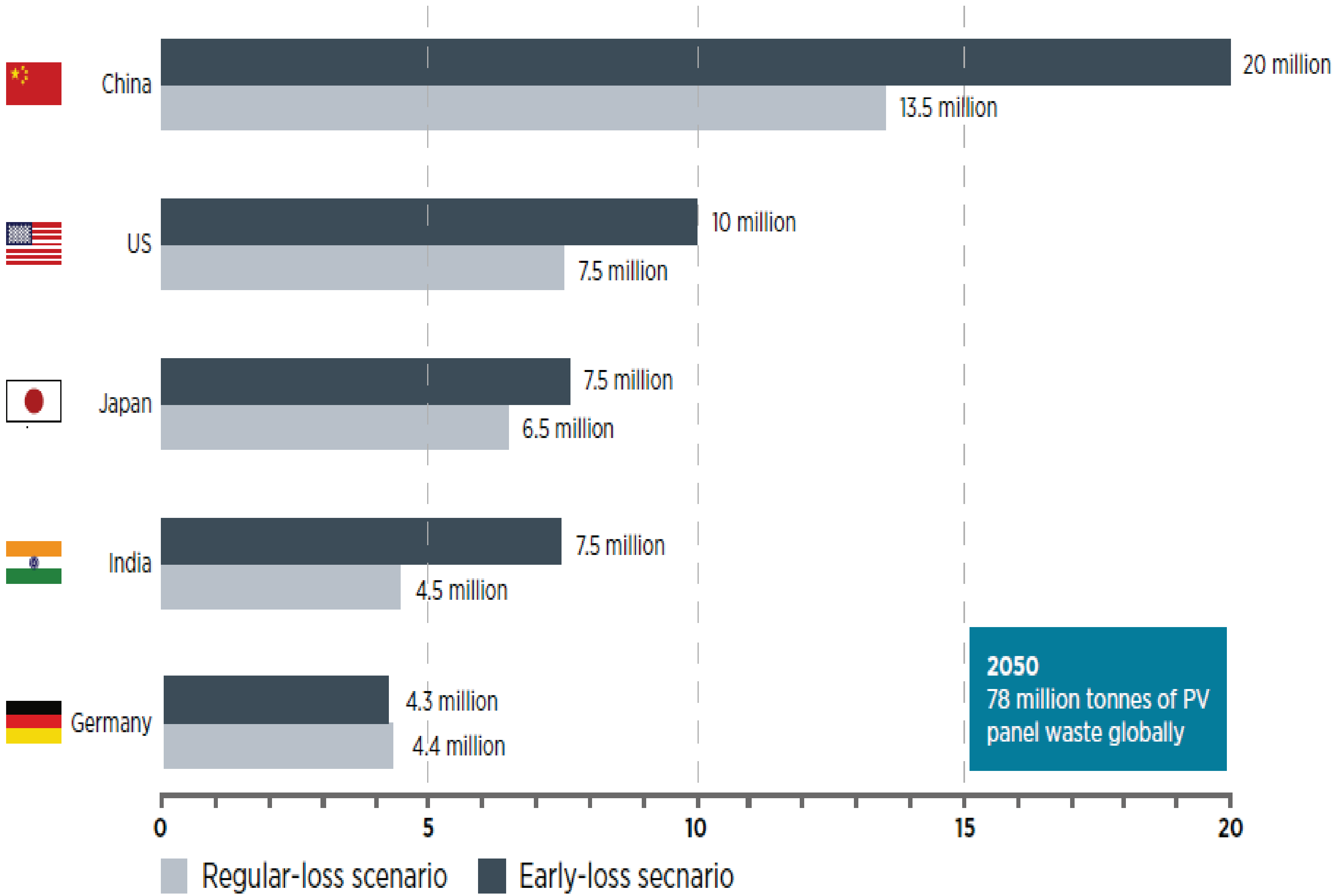
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Low Volumes Now, PV Waste Will be Significant Challenge in Future



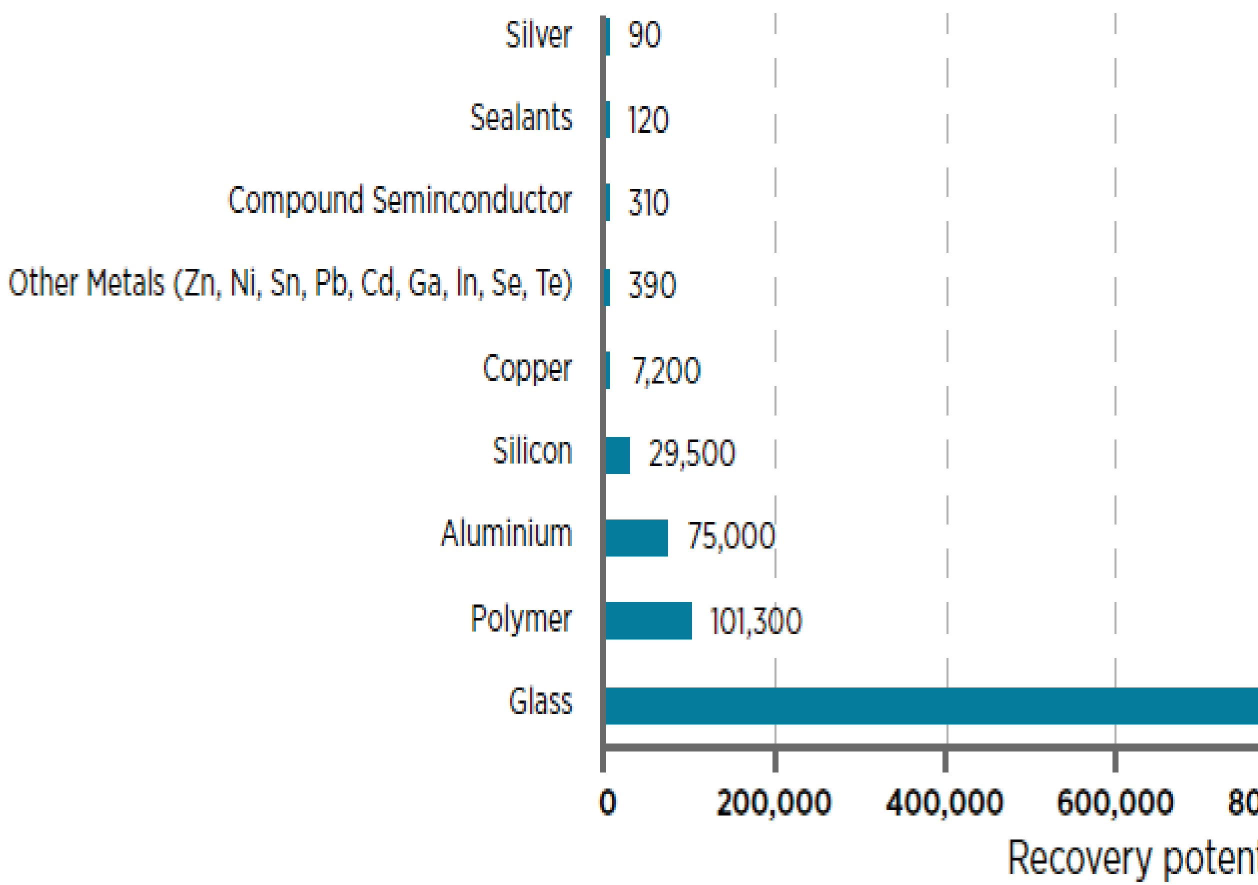
Source: IEA/IRENA, 2016

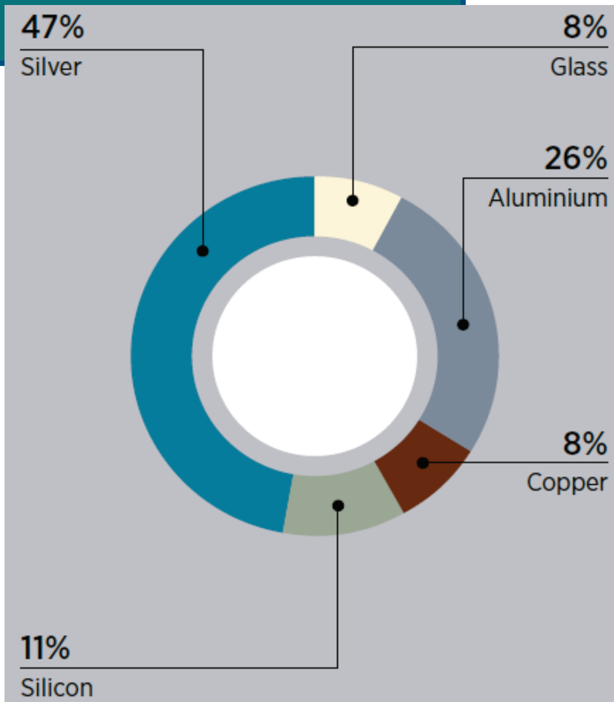
USA Expected As Second Largest PV Waste Volume – Challenge and Opportunity



Why Recycle Modules?

Cumulative technical potential for end-of-life material recovery (under the regular-loss scenario and considering anticipated changes to module design, like dematerialization)



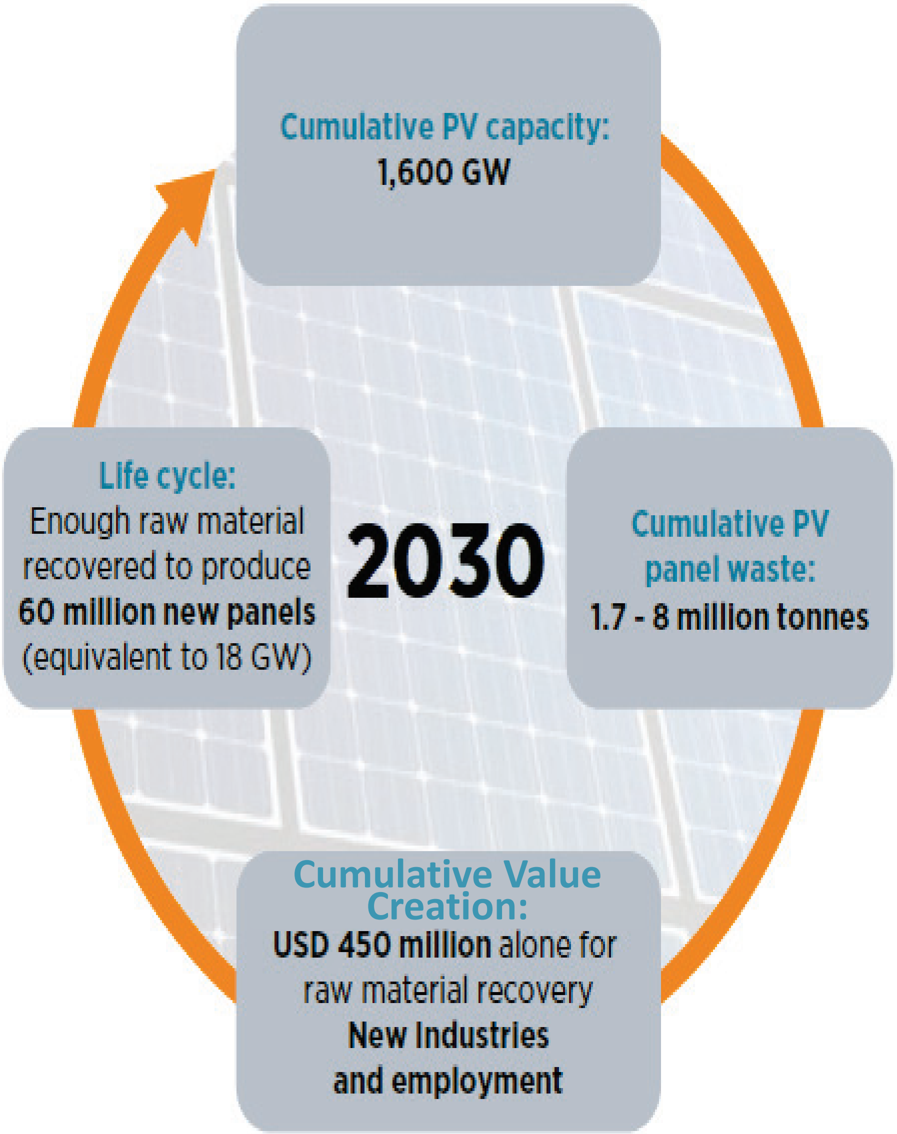


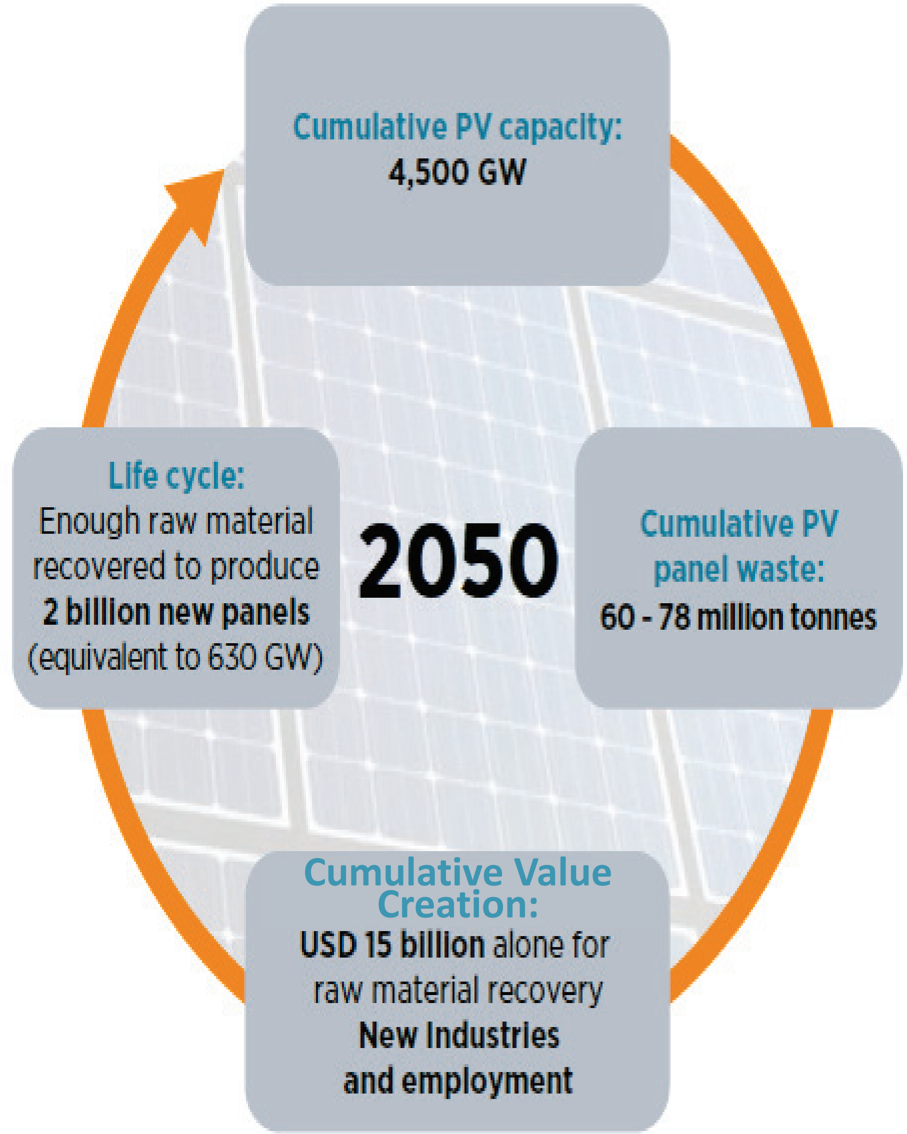
Relative material value of a c-Si Panel

Based on Raithel (2014)

Source: IEA/IRENA, 2016

Potential Value Creation – A Whole New Waste Management Industry?





Challenges

Waste Management and Recycling

The challenge is to prepare the technologies, systems and policies to manage decommissioning and disposal of end-of-life modules that can

- Minimize costs and
- Minimize environmental impacts while
- Maximizing materials recovery.

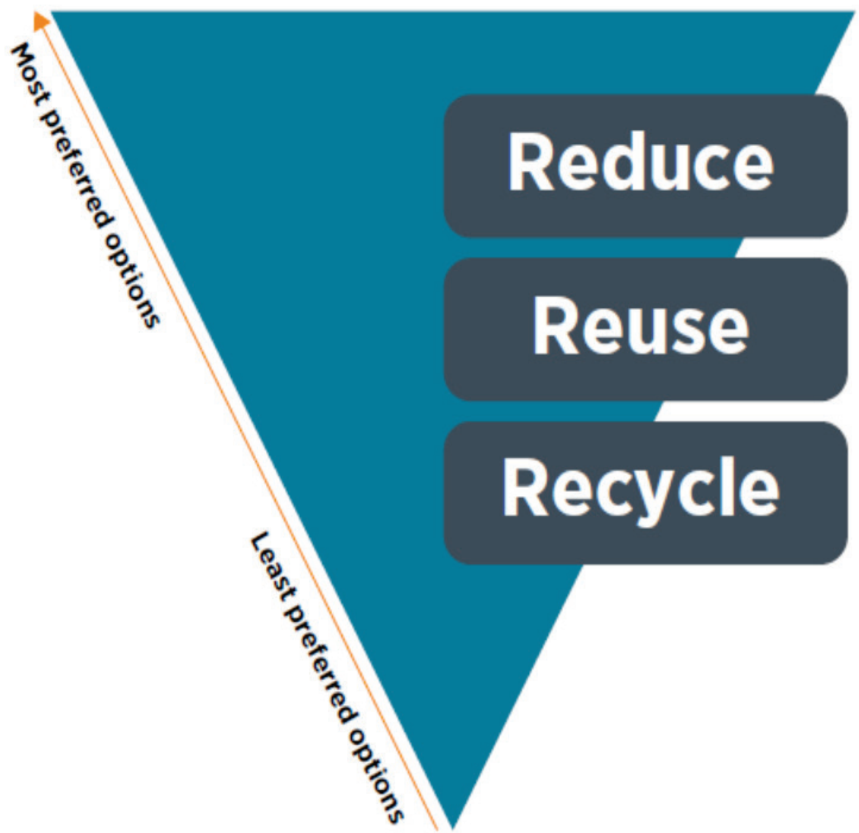
Design for Recycling

Conversely, one way to facilitate economical recycling and maximize material recovery is to design new modules that

- Increase speed and ease of dismantling,
- Improve rate and purity of recovered materials, and
- Reduce waste.

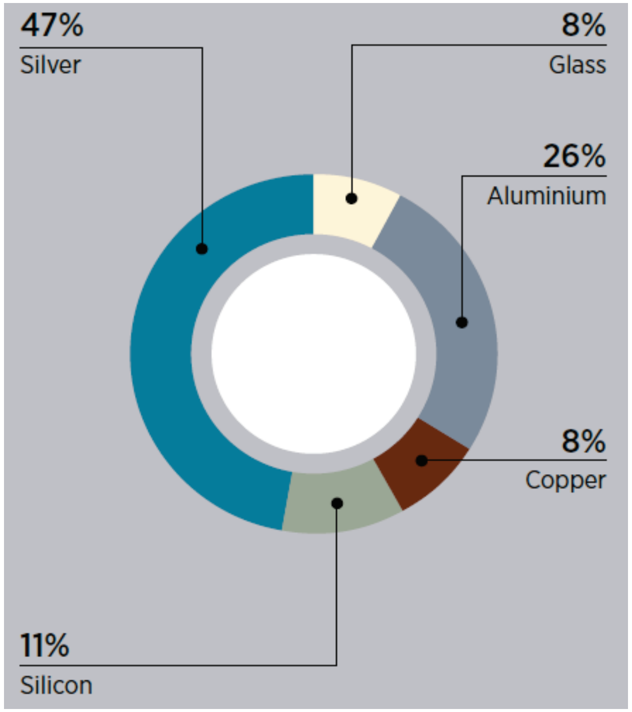
What Do We Do with PV Waste? The 3 Rs of Waste Management

- PV R&D has set priority topics for material use reduction or substitution for different components commonly used in today's PV panels
- Reusing modules (potentially preceeded by repairing) is conceivable, but practically and economically challenging
- 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***



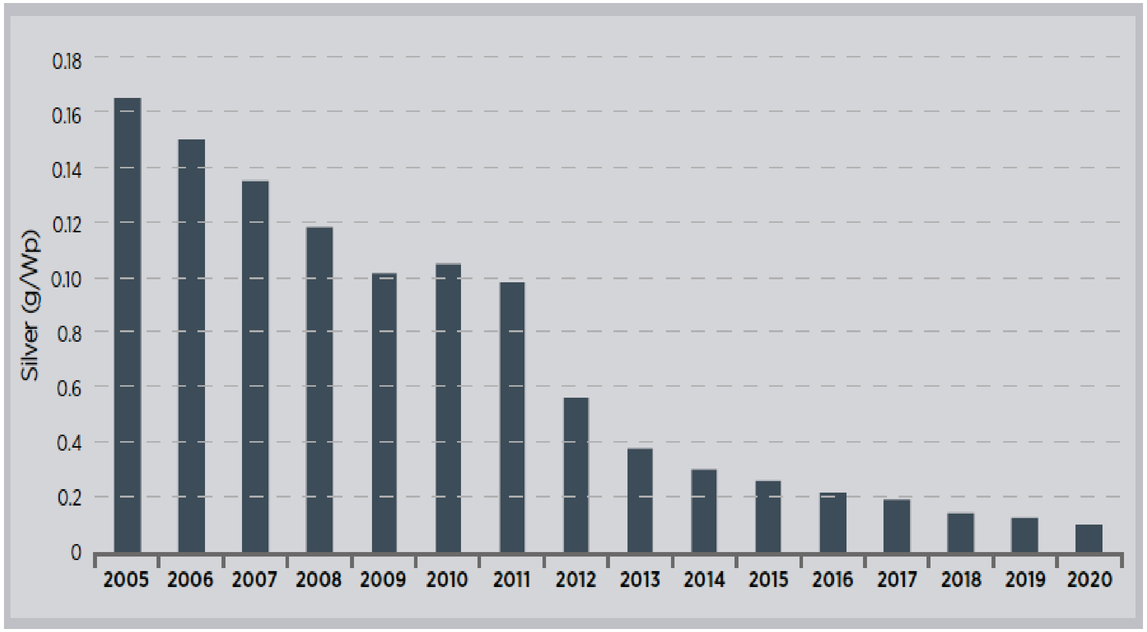
Reduce – Dematerialization

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 the use of silver is a clear technology target.



Relative material value of a c-Si Panel

Based on Raithel (2014)

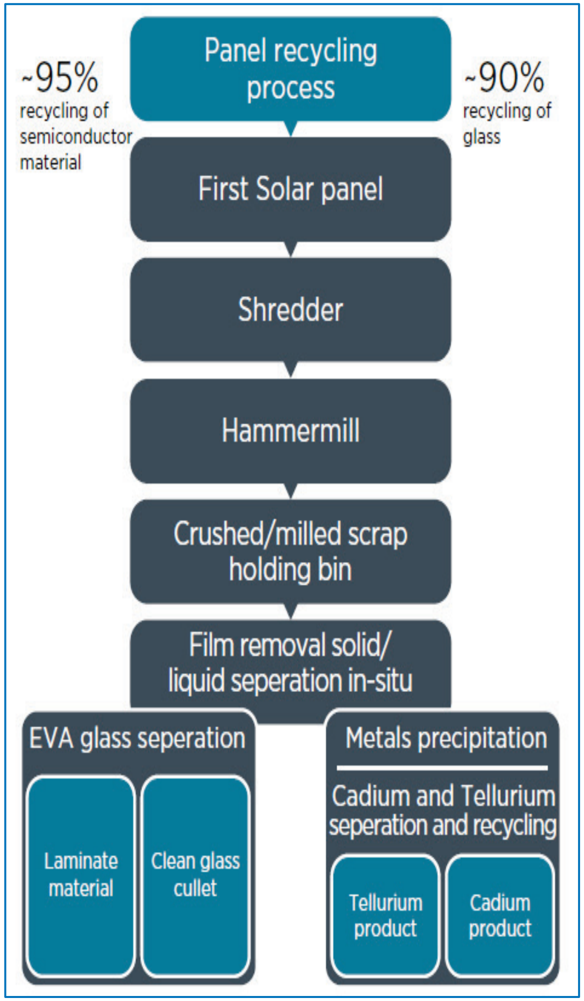


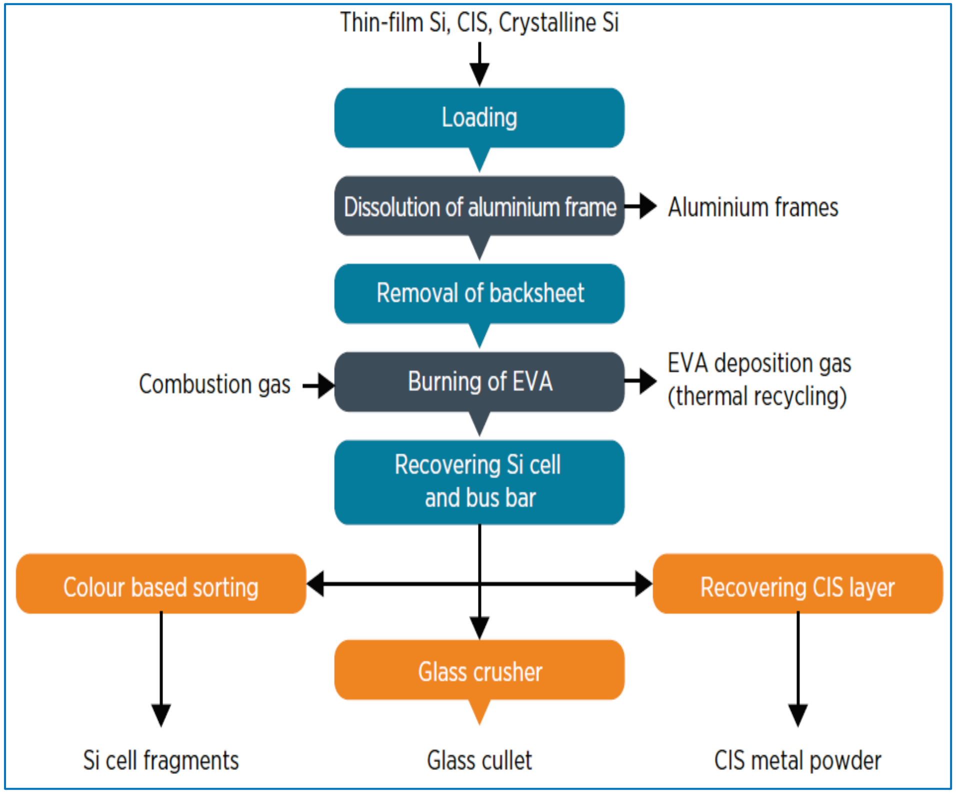
Historic and expected silver consumption per Wp

Based on: Perez-Santalla, M. (2013), Silver Use: Changes & Outlook,

Recycle – CdTe and C-Si Examples

Lacking volume for dedicated PV recycling plants, mechanical separation of major components of PV panels is current, first-generation PV recyclers' focus.





Recycling scheme proposed by NEDO/FAIS in Japan

CdTe recycling process (First Solar)

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

Optimal PV recycling industry will integrate energy and waste sectors

Path Forward – Recycling

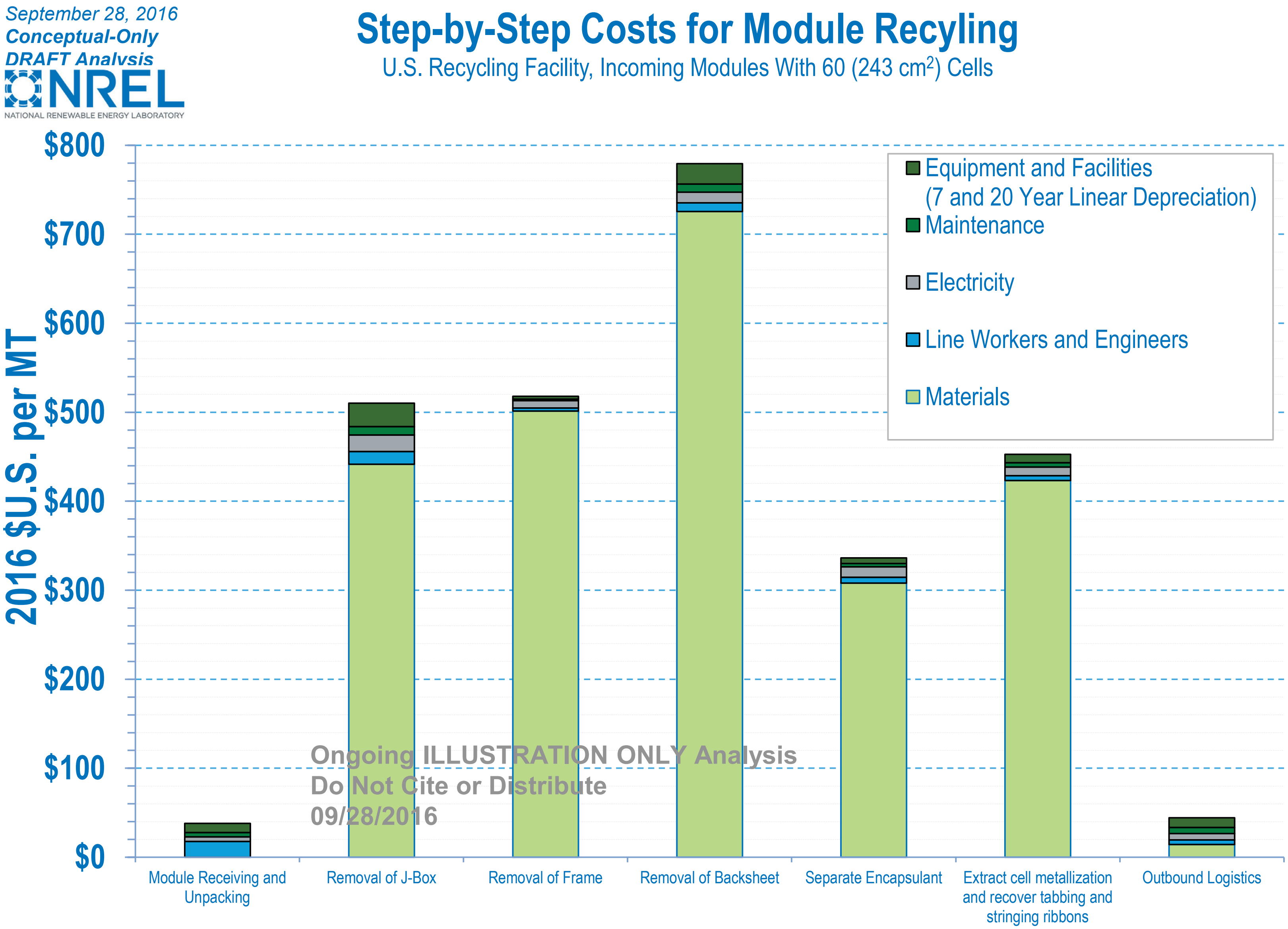
- Actions being taken (examples)
  - **IEA-PVPS**: report reviewing global trends in PV recycling technologies based on public sector and private sector (patents) documents (forthcoming)
  - **US Manufacturers**: SEIA voluntary commitment to PV recycling, though recycling network still under development

- Actions needed within broader industry
  - **Technological R&D coupled with prospective techno-economic and environmental analyses** to maximize societal returns, minimize detrimental outcomes and avoid unintended consequences.
  - **Decision support tools** for utility-scale PV owners regarding end-of-life management options, including costs of dismantling, decommissioning, testing and end-of-life treatment
  - **Better empirical understanding of module failure modes** and current disposition of end-of-life PV panels, as well as updated **estimate of market size**
    - Monitoring and reporting system
  - **Analysis of regulatory design options** – collection systems through treatment and disposal
  - **Deeper understanding of structure and experience in the e-waste** management sector to uncover potential lessons for PV

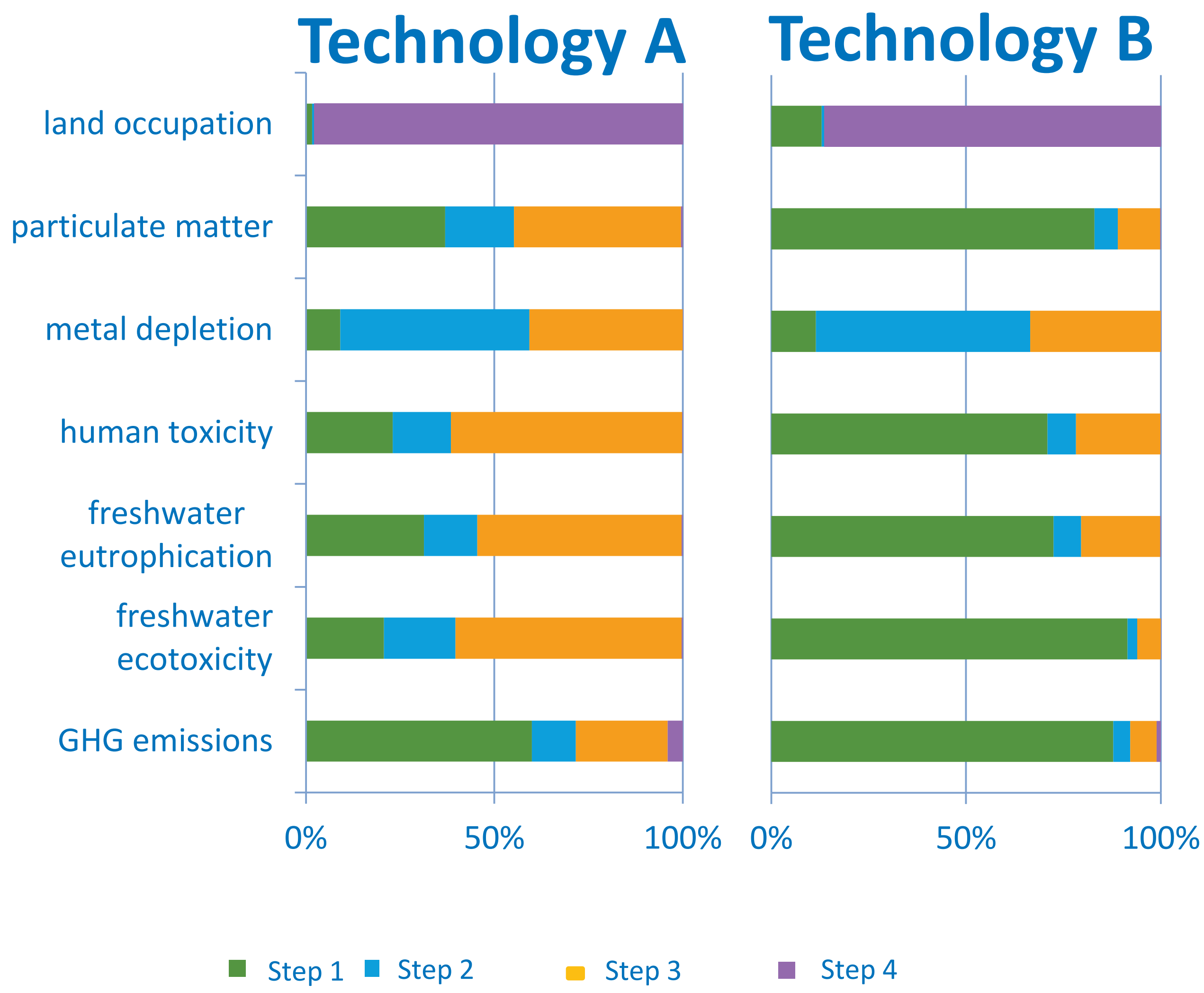
NREL Laboratory-Directed Research and Development Seed Project

- **Developed model framework to perform integrated bottom-up cost modeling and environmental assessment (TEA-LCA) of PV module recycling technologies**
  - LDRD funds did not populate the model
- Why?
  - Once populated, our TEA-LCA framework can **identify key cost drivers and major environmental hot spots** of recycling process designs
    - Data from multiple recycling process designs/recycling companies yields opportunities for industry benchmarking and goal-setting for continuous improvement
  - **Results can inform the development of technology research and development (R&D) roadmaps**

Illustrative Results of Cost Modeling – Which processes contribute most to cost?



Illustrative Environmental Results – Do any process steps contribute disproportionately to certain metrics?



Path Forward – Module Design for Recycling

- Actions being taken (examples)
  - **First Solar**: new models must be approved through recycling team to ensure ability to recycle using their in-house process
  - **IEA-PVPS:** Identification of the principles of the field of design for recycling that are applicable to PV (2018)

- Actions needed within broader industry
  - **Identification of key design features impeding recycling,** starting with generic and moving to model-specific
  - **Alternatives assessment of options to improve recyclability** which should consider feasibility, performance, cost and environmental benefit
  - **Test procedure for recyclability** so that recyclability can be objectively determined in a repeatable fashion.

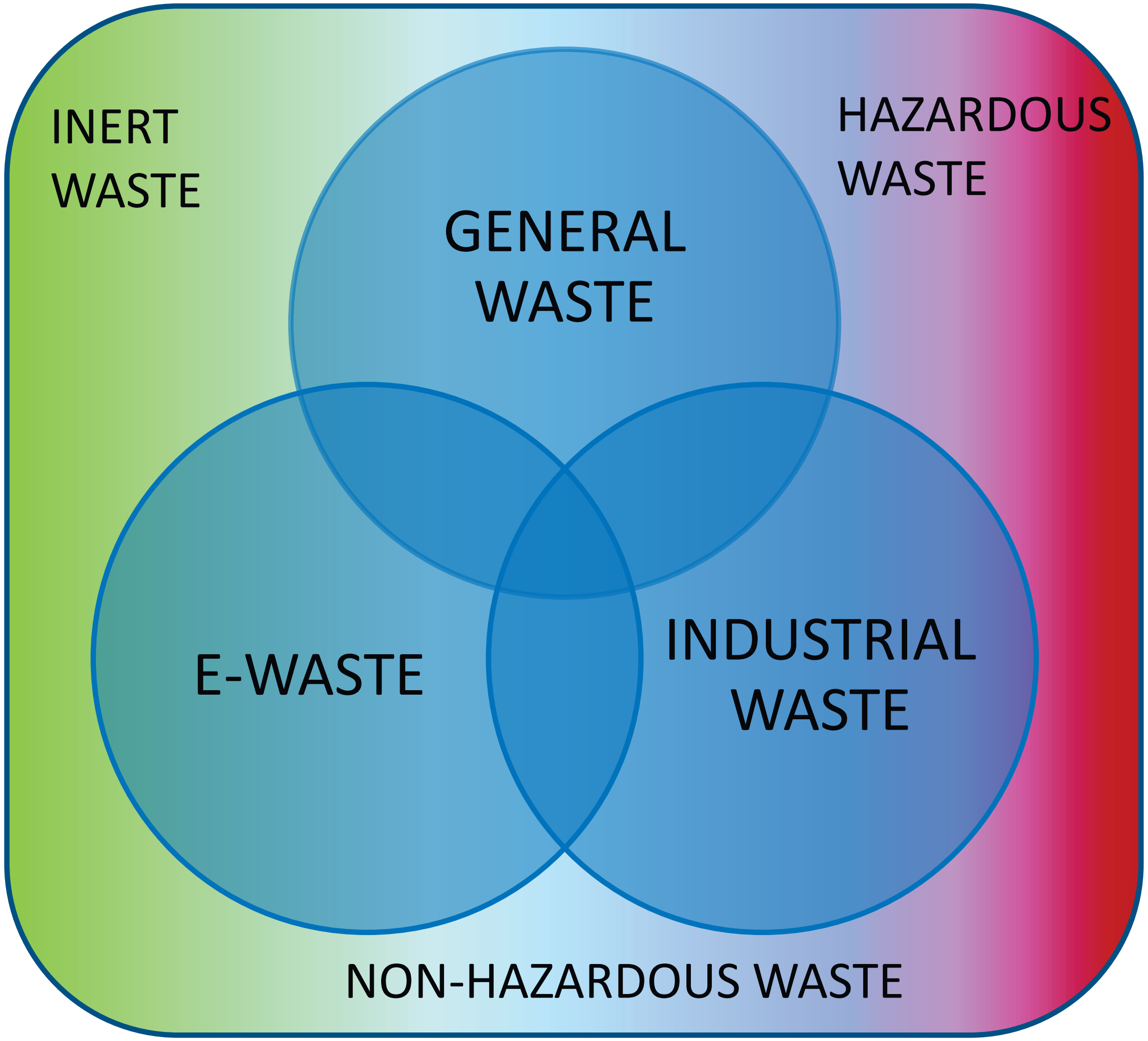
Thank you!

Garvin.Heath@nrel.gov

www.nrel.gov

NATIONAL RENEWABLE ENERGY LABORATORY

Waste Classification



- 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.

QUALIFYING FACILITY POWER PURCHASE

APPLICABILITY: Applicable to any Seller with nameplate capacity of 3 MW or less who enters into a Power Purchase Agreement (Agreement) with the Utility for the sale of electric power to the Utility from a Qualifying Facility (QF) as defined under the Rules of the Commission.

The Utility shall purchase electrical energy for a term of not less than one month and not more than 15 years.

The QF-1 Tariff rates do not reflect Network Upgrade costs. Seller must apply for interconnection and enter into the applicable generation interconnection agreement with the Utility addressing those items in addition to entering into an Agreement under the terms of this Tariff.

RATE OPTIONS: Seller may select from the following two rate options and sub-options:

For all Rate Options, refer to Special Terms and Conditions Item 3 Disposition of RECs, Item 4 Wind Integration, and Item 5 Contingency Reserves.

The selected rate will be adjusted by the value of Contingency Reserves per the current Contingency Reserves Tariff CR-1. Subsequent to this adjustment, QFs must either self-provide or purchase Contingency Reserves as described in Item 5 under Special Terms and Conditions.

QFs selecting Option 1 Rates will be paid the Avoided Energy and Capacity Rate which corresponds to their resource type and Agreement length as reflected in Table 1 below.

(continued)

Schedule No. QF-1

QUALIFYING FACILITY POWER PURCHASE

Option 1(a): Avoided Energy and Capacity Rates:

Option 1 Rates for Energy and Capacity

Contract Length (years)	Solar Off-peak Rate ($/kWh)	Solar On-peak Rate ($/kWh)	Wind Off-peak Rate ($/kWh)	Wind On-peak Rate ($/kWh)	Hydro/other Off-peak Rate ($/kWh)	Hydro/other On-peak Rate ($/kWh)
1	$0.03342	$0.04248	$0.03079	$0.03844	$0.03063	$0.08728
2	$0.03135	$0.04042	$0.02891	$0.03657	$0.02876	$0.08545
3	$0.03009	$0.03916	$0.02777	$0.03544	$0.02763	$0.08435
4	$0.03014	$0.03921	$0.02787	$0.03553	$0.02773	$0.08447
5	$0.03035	$0.03943	$0.02812	$0.03579	$0.02799	$0.08476
6	$0.03079	$0.03987	$0.02857	$0.03625	$0.02844	$0.08524
7	$0.03142	$0.04050	$0.02919	$0.03687	$0.02905	$0.08588
8	$0.03152	$0.04061	$0.02944	$0.03713	$0.02932	$0.08618
9	$0.03166	$0.04076	$0.02972	$0.03741	$0.02961	$0.08650
10	$0.03182	$0.04092	$0.03000	$0.03769	$0.02989	$0.08680
11	$0.03201	$0.04111	$0.03028	$0.03798	$0.03018	$0.08712
12	$0.03218	$0.04129	$0.03055	$0.03825	$0.03045	$0.08742
13	$0.03238	$0.04149	$0.03083	$0.03853	$0.03073	$0.08773
14	$0.03257	$0.04168	$0.03108	$0.03879	$0.03099	$0.08802
15	$0.03278	$0.04190	$0.03137	$0.03908	$0.03128	$0.08833

Payments: Rate x kWh metered during each Off-Peak Hours and On-Peak Hours period.

kWh = Metered kilowatt-hours supplied to the Utility for each Off-Peak Hours and On-Peak Hours period.

(continued)

Schedule No. QF-1

QUALIFYING FACILITY POWER PURCHASE

Option 1(b): Agreement lengths: 1 month to 18 months – short-term.

RATE:

Energy ($/kWh):

i. Agreement lengths up to 1 year use Year 1 rates from above table.

ii. Agreement lengths 1 year to 18 months use Year 2 rates from above table.

Payments: Hourly Rate x Hourly kWh

kWh = Metered kilowatt hours supplied to the Utility in each hour.

Option 2: Agreement length of up to 25 years.

Rate: This rate is equal to the published Intercontinental Exchange (ICE) Mid-C index price for Heavy Load Hours and Light Load Hours, less $.00162/kWh basis adjustment between Mid-C and Montana, and applied to the Heavy Load and Light Load metered sales and purchases of Seller. Another Mid-C price index may be substituted if necessary, if ICE is no longer available.

Payments: Daily Heavy Load Hour and Light Load Hour Rate x Heavy Load and Light Load kWh

kWh = Metered kilowatt hours supplied to the Utility in each daily Heavy Load and Light Load period.

(continued)

PUBLIC SERVICE COMMISSION MONTANA

QUALIFYING FACILITY POWER PURCHASE

SPECIAL TERMS AND CONDITIONS:

1) Definitions:

A. "Agreement" means the Power Purchase Agreement between Seller and the Utility for a term of not less than one month.

B. "Commission" means the Montana Public Service Commission.

C. "Contingency Reserves" are an amount of spinning and nonspinning reserves (at least half must be spinning reserve) sufficient to meet the North American Electric Reliability Council (NERC) Disturbance Control Standard BAL-002 consistent with Western Electric Coordinating Council and Northwest Power Pool requirements.

D. "Contract Length" means the length of a Seller's contract with NorthWestern measured in whole years. For contract terms not in whole years, the length of a Seller's contract will be rounded up to the next whole year for purposes of determining applicable rates.

E. "Heavy Load Hours" means the weekday and Saturday hours ending 7 and through hour ending 22 inclusive, Pacific Prevailing Time, except NERC defined holidays. For purposes of this Tariff, Heavy Load Hours correspond to Peak hours as used on the ICE web site.

F. "Intermittent" means generation resources with variable generation output from hour to hour. Specifically, wind and solar PV are considered to be Intermittent resources.

G. "Light Load Hours" means those hours not included in the definition of Heavy Load Hours. For purposes of this Tariff, Light Load Hours correspond to Off-Peak hours as used on the ICE web site.

H. "Network Upgrades" means additions, modifications, and upgrades to NorthWestern's transmission system required at or beyond the point at which the Small Generating Facility interconnects with the transmission system to accommodate the interconnection with the Small Generating Facility to NorthWestern's transmission system. Network Upgrades do not include Distribution Upgrades.

I. "Off-Peak Hours" means those hours in the year not included in the definition of On-Peak Hours.

J. "On-Peak Hours" means the Heavy Load hours for the months of January, February, July, August, and December.

(continued)

QUALIFYING FACILITY POWER PURCHASE

K. "Other QF" means QF facilities other than hydroelectric, wind or solar powered resources.

L. "RECs" means renewable energy credit. One megawatt hour of renewable energy generation gives rise to one REC, and this REC embodies all environmental attributes of that renewable energy generation.

M. "Regulating Reserve" is spinning reserve immediately responsive to Automatic Generation Control (AGC) to provide sufficient regulating margin to allow the Balancing Authority to meet NERC's Control Performance Criteria (BAL-001).

N. "Seller," for purposes of this schedule, is any individual, partnership, corporation, association, government agency, political subdivision, municipality or other entity that:

a. Operates a QF; and

b. Has entered into an Agreement(s) with the Utility stipulating the terms and conditions of the interconnection and separately the sale of electric power to the Utility.

O. "Utility" means NorthWestern Energy.

P. "Wind Integration Services" means those services necessary to integrate wind generation into the Utility's electric transmission and/or distribution system(s) in a manner such that all operational and reliability criteria are met. Wind Integration Services include, but are not limited to, Regulating Reserves, imbalance service, and scheduling.

2) Net Billing Option: If Seller contracts for Net Billing and the Seller's consumption kWh exceeds its production kWh, Seller shall be billed for power supply for the consumption kWh in excess of the production kWh in accordance with the Utility's applicable rate schedule. If Seller's consumption kWh is less than its production kWh, Seller shall receive a power supply payment (credit) for the production kWh in excess of the consumption kWh at the Rates specified above.

3) Disposition of RECs: QFs retain RECs but may still separately attempt to negotiate for the sale of RECs to NWE or other interested parties at any time that an Agreement remains in effect. Any such negotiation occurs separate from the Power Purchase Agreement and does not create a reopener that refreshes the rates in the Agreement.

(continued)

QUALIFYING FACILITY POWER PURCHASE

4) Wind Integration: Sellers of Wind Energy must contractually agree to the provision of wind integration services for the term of the Agreement and may either self-supply sufficient within-hour regulating reserves under terms acceptable to NorthWestern or pay the Utility for these services according to the Wind Integration Tariff (WI-1). Payment to the Utility for selection of service through WI-1 will result in a deduction from the total monthly payment made to the QF to reflect the provision of integration services.

5) Contingency Reserves: QFs must either self-supply contingency reserves, or purchase the needed reserves from NorthWestern at the rate as specified according to the Contingency Reserves Tariff (CR-1). If the QF purchases reserves from NorthWestern, the CR-1 rate for the appropriate resource type will be deducted from the total monthly payment made to the QF to reflect the provision of contingency reserves.

6) Hourly Metering: Sellers are required to install interval metering capability if necessary to support the Rate Option chosen.

SERVICE AND RATES SUBJECT TO COMMISSION JURISDICTION: All rates and service conditions under this Rate Schedule are governed by the rules and regulations of the Public Service Commission of Montana and are subject to revision as the Commission may duly authorize in the exercise of its jurisdiction.

How Long Does it Take for Photovoltaics To Produce the Energy Used?

BY VASILIS FTHENAKIS

In the July 2011 *PE* magazine article "Why We Need Rational Selection of Energy Projects," the author stated that "photovoltaic electricity generation cannot be an energy source for the future" because photovoltaics require more energy than they produce (during their lifetime), thus their "Energy Return Ratio (ERR) is less than 1:1." Statements to this effect were not uncommon in the 1980s, based on some early PV prototypes. However, today's PVs return far more energy than that embodied in the life cycle of a solar system (see Figure 1).

Their energy payback times (EPBT)—the time it takes to produce all the energy used in their life cycles—currently are between six months to two years, depending on the location/solar irradiation and the technology. And with expected life times of 30 years, their ERRs are in the range of 60:1 to 15:1, depending on the location and the technology, thus returning 15 to 60 times more energy than the energy they use. Here is a basic tutorial on the subject.

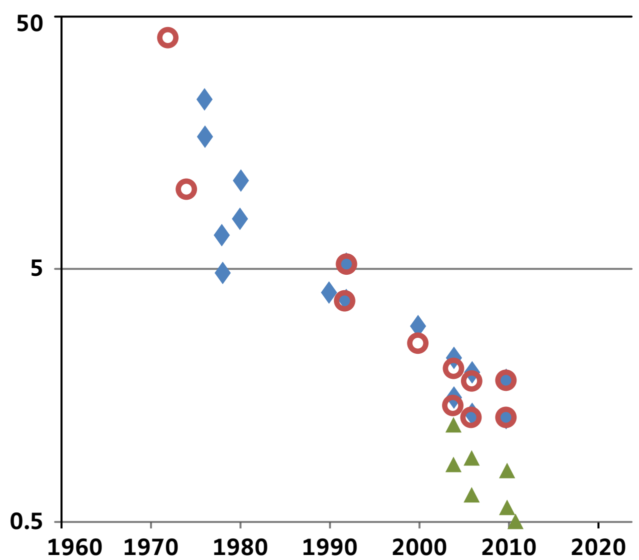
Life Cycle of PV and Energy Payback Times

The life cycle of photovoltaics starts from the extraction of raw materials (cradle) and ends with the disposal (grave) or recycling and recovery (cradle) of the PV components (Figure 2). The mining of raw materials such as quartz sand for silicon PVs, and copper, zinc, and aluminum ores for mounting structures and thin-film semiconductors, is followed by separation and purification stages. The silica in the quartz sand is reduced in an arc furnace to metallurgical-grade silicon, which must be purified further into solar-grade silicon (i.e., 99.9999% purity), requiring significant amounts of energy. Metal-grade cadmium and tellurium for CdTe PV is primarily obtained as a byproduct of zinc and copper smelters, respectively, and further purification is required for solar-grade purity. Similarly, metals used in CIGS PV are recovered as byproducts: indium and gallium are byproducts of zinc mining, while selenium is mostly recovered from copper production.

The raw materials include those for encapsulations and balance-of-system components, for example, silica for glass, copper ore for cables, and iron and zinc ores for mounting structures. Significant amounts of energy are required for the production, processing, and purification of all these materials, as well as for the manufacturing of the solar cells, modules, electronics, and structures, and for the installation, sometimes the operation, and eventually the dismantling and recycling or disposal of the system components. Thus, the EPBT is defined as the period required for a renewable energy system to generate the same amount of energy (in terms of primary energy equivalence) that was used to produce the system itself.

(FIGURE 1)

EPBT OF PV SYSTEMS HAVE BEEN REDUCED FROM ABOUT 40 TO 0.5 YRS FROM 1970 TO 2010



KEY ◆ mono-c-Si ○ multi-c-Si ▲ CdTe

Energy Payback Time =

$$(E_{mat}+E_{manuf}+E_{trans}+E_{inst}+E_{EOL}) / (E_{agen}-E_{aoper})$$

where,

E_{mat}: Primary energy demand to produce materials comprising PV system

E_{manuf}: Primary energy demand to manufacture PV system

E_{trans}: Primary energy demand to transport materials used during the life cycle

E_{inst}: Primary energy demand to install the system

E_{EOL}: Primary energy demand for end-of-life management

E_{agen}: Annual electricity generation in primary energy terms

E_{aoper}: Annual energy demand for operation and maintenance in primary energy terms

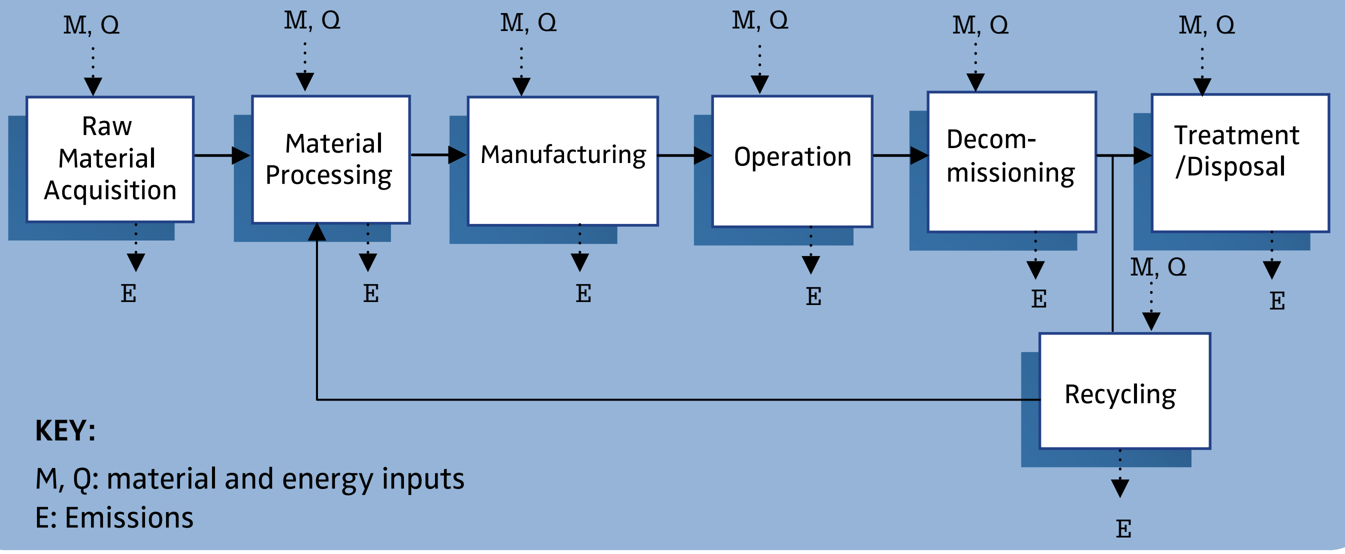
The traditional way of calculating the EROI of PV is EROI = lifetime/EPBT, thus an EPBT of one year and life expectancy of 30 years corresponds to an EROI of 1:30.

Results

Figure 3 gives the energy payback times of three major commercial PV module types: mono-Si, multi-Si, and cadmium telluride. These results are based on detailed process data obtained through collaborations with 13 European and U.S. PV manufacturers. The

(FIGURE 2)

FLOW OF THE LIFE-CYCLE STAGES, ENERGY, MATERIALS, AND EFFLUENTS FOR PV SYSTEMS



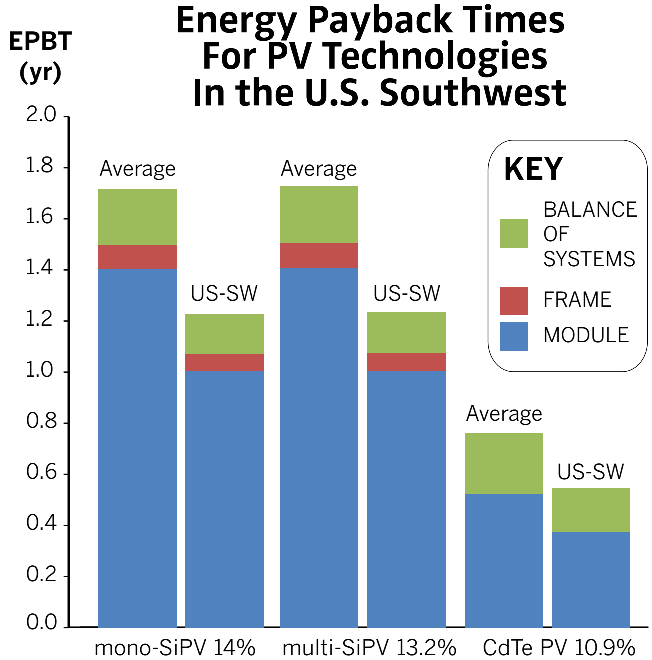
EPBT for the same type of systems installed in the U.S. Southwest are decreased in proportion to the solar irradiation ratio (1700/2380) between the U.S. average and Southwest solar conditions. Thus, for Southwest irradiation the EPBTs for the three PV technologies shown in Figure 3 are 1.2, 1.2, and 0.5 years and the corresponding EROIs are 0.04, 0.04, and 0.02, thus 50 times better than stated in the July *PE* article. And these EROI keep improving as systems and material utilization efficiencies continue to improve.

It is noted that several PV LCA studies with differing estimates can be found in literature. Such divergence reflects different assumptions about key parameters, like product design, solar irradiation, performance ratio, and lifetime. The estimates also differ because of the different types of installation used, such as ground mounts, rooftops, and façades. Also, assessments often are made from outdated information in the literature collected from antiquated PV systems.

To resolve these inconsistencies, the International Energy Agency PVPS Task 12 has published "Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity" (www.bnl.gov/pv). These guidelines reflect a consensus among experts in the U.S., Europe, and Asia for conducting balanced, transparent, and accurate life-cycle assessments. The results presented in Figure 3 are produced according to these guidelines.

(FIGURE 3)

Energy Payback Times For PV Technologies In the U.S. Southwest



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Producer Responsibility and Recycling Solar Photovoltaic Modules

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Abstract

Rapid expansion of the solar photovoltaic (PV) industry is quickly causing solar to play a growing importance in the energy mix of the world. Over the full life cycle, although to a smaller degree than traditional energy sources, PV also creates solid waste. This paper examines the potential need for PV recycling policies by analyzing existing recycling protocols for the five major types of commercialized PV materials. The amount of recoverable semiconductor material and glass in a 1 m^2 area solar module for the five types of cells is quantified both physically and the profit potential of recycling is determined. The cost of landfill disposal of the whole solar module, including the glass and semiconductor was also determined for each type of solar module. It was found that the economic motivation to recycle most PV modules is unfavorable without appropriate policies. Results are discussed on the need to regulate for appropriate energy and environmental policy in the PV manufacturing industry particularly for PV containing hazardous materials. The results demonstrate the need to encourage producer responsibility not only in the PV manufacturing sector, but also the entire energy industry.

Keywords: recycling; photovoltaic; manufacturing; manufacturing responsibility

1. Introduction

As the negative effects of anthropogenic climate destabilization become more pronounced (IPCC, 2008), greater attention is being paid to life cycle carbon emissions (Kenny *et al.*, 2010) and low emission renewable energy sources such as solar photovoltaic (PV) technology are experiencing rapid growth (EPIA, 2009). Many countries in Europe have already benefited from this strong PV growth both economically and environmentally, and have demonstrated to the rest of the world that PV technology is a promising (Jäger-Waldau, 2007) and a truly sustainable (Pearce, 2002) energy source. In addition to the clear environmental benefits (Frantzeskaki *et al.*, 2005; Castanas and Kampa, 2008), there is also a clear financial benefit for governments to encourage PV manufacturing in their region because of the concomitant large relative

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job creation to other energy-related industries (Pembina Institute, 1997; Branker and Pearce, 2010). These properties have enabled the PV industry to garner enormous public support, with a recent poll finding that 92% of U.S. citizens support the development and use of solar technology (Cheyney, 2009). However, with this rapid expansion of the PV industry buoyed by public support, it is anticipated that there will be a remarkably large challenge of waste disposal in 25 to 30 years (Fthenakis, 2000).

Often PV technology is considered an energy source that has very minimal waste because there is none produced during operation and the more traditional electricity sources are so environmentally damaging. Although, PV-related solid waste is minute in comparison to the waste associated with traditional energy sources, there is still waste that can not be ignored that is created by the decommissioning of the solar modules at the end of their lives. As the PV market continues to grow, so will waste, even if it only appears after a relatively long time delay. This is due to the fact that the industry generally provides 25-30 year warranties for the power produced, which consequently is the life cycle for a module to still perform at 80% of its initial energy output (Kazmerski, 2006). Additionally, with the recent increased cell efficiencies and decreasing production costs, the PV industry has grown tremendously. In 2000 the total world PV production was 278 MW compared to the 5,559 MW produced in 2008, and the 7,300 MW produced in 2009 (EPIA, 2009; Solar Buzz, 2010).

Unlike other industries, PV waste is unique because it has a long (approximately generational) lag time from the time it is produced to the time it is decommissioned. Figure 1 shows the global PV production in the decade between 1998 and 2008 (EPIA, 2009) and the concomitant expected waste until 2038 assuming the historical percentages and efficiencies of thin film and silicon-based technologies and an end of life matching the warranty lag. The amount of PV modules created for any one of these years will correlate to the amount of PV waste that will exist assuming that modules are retired after their warranty has expired as seen in Figure 1. As can be seen in Figure 1 the amount of waste (still quantified in installed power units) can vary dramatically after 2030 based on the actualized lifetime of the modules and the dramatic growth experienced in the PV industry in the last decade.

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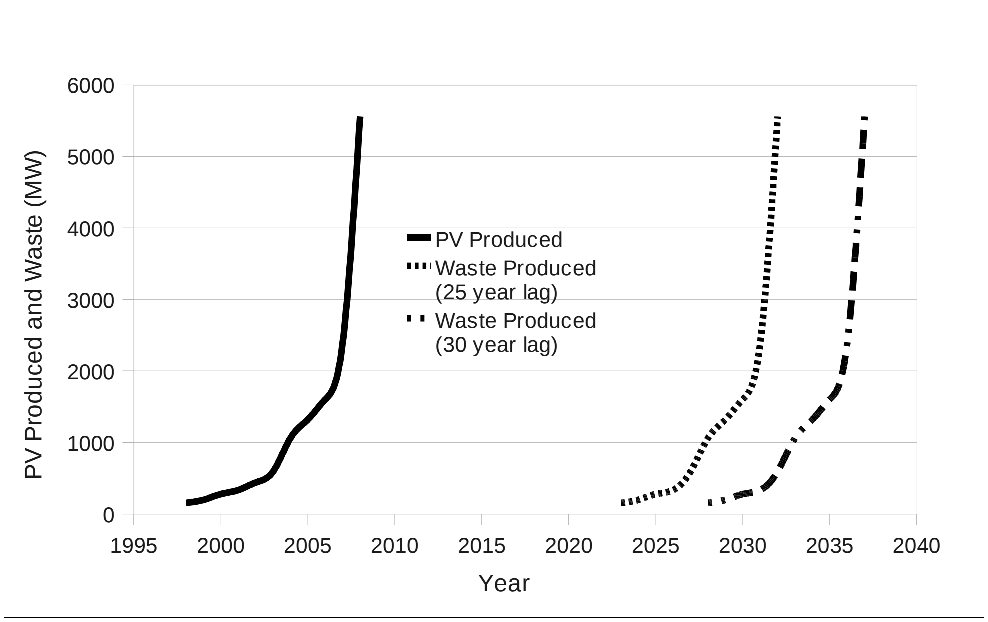

Figure 1: Global PV production and projected waste from 1998 to 2038

Additionally, some solar modules contain hazardous materials such as cadmium, tellurium, lead and selenium. Cadmium compounds are, for example, currently regulated in many countries because of their toxicity to fish and wildlife and because they can pass to humans through the food chain. In China the sale of some solar modules is prohibited because of the policies regulating cadmium in photoelectric semiconductor devices (Kaczmar et al, 2008). Cadmium has also been associated with numerous human illnesses particularly lung, kidney and bone damage and once absorbed in the body, cadmium can remain for decades (Bernard, 2008). It accumulates in the natural environment by leaching into ground water and surface water from landfills, and it can enter the atmosphere through incinerator smokestack emissions (Fthenakis, 2000; Fthenakis and Zweibel, 2003). Effective air pollution control equipment at incinerators traps Cd, which

ends up in the ash and thus causes problems of cadmium in ashfill leachate. Accordingly, it is important to realize that as solar waste is created over the next decades, some of this waste will contain hazardous material, and it will be the responsibility of governments to regulate the safe disposal of these materials. Consequently, this paper examines the potential need for PV recycling incentives and regulation through a review of the recycling protocols for modules using the five major commercialized photovoltaic materials. The results of this review provide the foundation for an analysis that will determine whether there is an economic motivation for manufacturers to voluntarily take responsibility for recycling solar modules, and if not, given the hazardous nature of some of the materials, should policy tools be used to ensure solar module recycling.

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2. Solar Photovoltaic Recycling Processes

In order to determine the economic viability of recycling solar modules, an analysis of the recycling process will be done for five of the largest volume commercialized types of solar cells including: copper indium gallium diselenide (CIGS), cadmium telluride (CdTe), amorphous silicon (a-Si), poly-crystalline silicon (p-Si) and mono-crystalline silicon (c-Si). These five cells can be broken up into two additional categories, conventional "1st generation" (c-Si and p-Si, which can be referred to as x-Si) and "2nd generation" thin-film solar cells (a-Si, CIGS, and CdTe) (Green, 2001).

x-Si based PV are the most common type of solar cell manufactured in the world. In 2008, 86-88% of solar cell production was that of mono and multi-crystalline silicon composition (European Commission, 2009). The recycling process for both types of x-Si solar cells is identical and involves pyrolysis, which recovers crystalline silicon wafers from the modules. In this process the ethylene vinyl acetate (EVA) lamination layer is vaporized by the inert atmosphere pyrolysis at about 500°C (Fthenakis, 2000).

Thin-film solar cells (CIGS, CdTe, and a-Si) have grown increasingly popular in recent years largely due to their decreased manufacturing costs. However, thin film PV only made up 12-14% of the total solar cells produced in 2008, but are expected to have a market share of about 25% by the end of 2010 (Brandsen *et al.*, 2007; European Commission, 2009). The production capacity for thin-film cells almost tripled from 2006 to 2008, growing from 282.4 to 890 MW_p (Brandsen *et al*., 2007; Solar Buzz, 2009).

The recycling process of CIGS solar cells involves putting the materials through a smeltering process or acid baths to recover the metals, including selenium (Se), indium (In) and gallium (Ga). The glass is processed through thermal decomposition, solvent or acid dissolution to remove any remaining PV layers and is recovered (Eberspacher *et al.*, 1998).

The CdTe PV recycling process involves chemical stripping of the metals and EVA and successive steps of electrodeposition, precipitation and evaporation to separate and recover the metals cadmium and tellurium. In addition, the EVA is skimmed from the chemical solution for potential re-use and the glass and frame are recovered (Fthenakis, 2000).

The semiconductor material in an a-Si solar cell is composed of silicon atoms whose microstructure exhibit no long-range order. Recent advances in controlling light induced degradation with the microstructural properties of the material have assisted in improving the stabilized efficiencies (Wronski *et al.*, 2002b; Pearce *et al.*, 2003; Ferlauto *et al.*, 2004; Konagai *et al.*, 2006). Thus, a-Si cells can now be manufactured with a 10% stabilized efficiency (Oerlikon, 2009; Osborne, 2010). Due to the high absorption coefficient of a-Si only a very thin layer is needed, which makes it viable for commercial use. As the amount of a-Si material is minute in a given module and of low value as a scavenged material, there is currently no literature explaining the recycling process of amorphous silicon solar cells. It is presumed a-Si based solar cell recycling would be primarily driven to reclaim the substrates using any of the techniques described above.

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3. Methodology

The comparative analysis performed for the recycling process of the five types of PV material-based solar cells first determines the amount of semiconductor material in a 1 m^2 area solar module and finds the amount of recoverable semiconductor material by recycling from the module. The semiconductor materials considered are: indium (In), gallium (Ga), silicon (Si), cadmium sulfide (CdS), cadmium (Cd) and tellurium (Te). Because the recycling process of p-Si and c-Si PV modules is identical, the two types of modules have been grouped together for the analysis. It has also been assumed that all modules use a standard glass substrate/cover, which can be recycled, and are frameless. It should be noted that in the event that a module has a frame (e.g. aluminum) it can be mechanically separated from the module and recycled using well established techniques.

By determining the thickness and density of the semiconductor in each module from literature, the mass of recovered semiconductor in each module after the recycling process can be found using:

$$m_{rs} = A \times t_s \times \rho_s \times z_s \qquad \text{[grams/module]} \qquad (1)$$

where A in cm^2 is the area of the solar module, t_s is the thickness in cm of the semiconductor in the solar module, ρ_s is the density of the semiconductor material in g/cm^3 and z_s is the percent of semiconductor material that can be recovered from a solar module, determined from literature.

Given the amount of recovered semiconductor material in each module, and data from the literature for the cost of recycling the solar modules, the profit P_s, made from re-selling the semiconductor is given by:

$$P_s = m_{rs} \times V_s \qquad \text{[\$/module]} \qquad (2)$$

where V_s is the resale value in dollars/gram of the semiconductor material, m_{rs} is determined from equation 1. All economic values are given in U.S. dollars. Additionally, the mass of recovered glass is given by:

$$m_{rg} = A \text{ x } t_g \text{ x } \rho_g \text{ x } z_g \qquad \text{[grams/module]} \qquad (3)$$

where t_g is the thickness in cm of all the glass in the solar module, the percent recovery, z_g, is assumed here to be 100% for the glass cullet, and ρ_g is the density of the glass in g/cm^3. Similarly using the results from equation 3, the profit, P_g, of recycling the glass can be found as:

$$P_g = V_g \times m_g \qquad \text{[\$/module]} \qquad (4)$$

where V_g is the resale value in dollars of the glass, m_{rg} is given by equation 3.

Finally, the cost of landfill disposal was found for each type of solar module. These results take into account the cost of disposing the whole solar module, including the glass and semiconductor. The total mass of waste per module was calculated using:

$$W = \frac{A \times E \times w}{N_p} \qquad \text{[kg/module]} \qquad (5)$$

Where E is the power per unit area of each module in W/m^2, w is the weight of the solar module in kg and N_p is the nominal power in W of the solar module.

The final disposal cost was found using:

$D = W \times T$ [\$/module] (6)

where W is the waste mass per module calculated in equation 5, and T is the tipping cost in \$/kg determined from the literature. Finally the total profit found from recycling is given by:

$P_T = (P_s + P_g) + D - C = P_t + D - C$ [\$/module] (7)

where C is the cost of recycling \$/module and P_t is the sum of P_s and P_g.

4. Results: PV Recycling Costs and Profits

A comparative analysis was done to determine the potential profit of recycling five types of solar modules. In the first step of this analysis, the mass of semiconductor material in a solar module was determined and compared to the amount which can be recovered from recycling. The input parameters and the mass of the recovered semiconductor material after the recycling process for a 1m^2 panel from equation 1 are outlined in Table 1 for the four types of solar modules: CIGS, CdTe, a-Si and x-Si.

Table 1: Amount of recovered semiconductor material for four solar modules

	CIGS		CdTe		a-Si	x-Si
	Ga	**In**	**Cd**	**Te**		
A (cm^2)	10,000[a]		10,000[a]		10,000[a]	10,000[a]
t_s (cm)	0.0004[b]		0.0003[c]		0.00005[d]	0.02[e]
ρ_s(g/cm^3)	N/A	N/A	6.2[f]		2.33[f]	2.33[f]
m_s (g)	6.54	10.77	9.07[g]	9.53[g]	1.165	466
z_s (%)	80		99[h]	96[h]	N/A	60[h]
m_{rs} (g)	5.23	8.62	8.98	9.15	< 1.17	279.6
Sources: (a) Assumed area of 1m^2 (b) Edoff (2004) (c) Fthenakis (2003) (d) Applied Materials (2009) (e) Boyeaux *et al.* (2001) (f) Angrist (1982) (g) Ahn *et al.* (1998) (h) Fthenakis (2000)						

There is currently no information in PV recycling literature to suggest that recycling a-Si solar modules is performed. This is likely because the mass of semiconductor material in an a-Si module is so minute and the value of a-Si is so small that the value is negligible. This conclusion is supported by the results in Table 1, which shows that the mass of semiconductor material in a 1m^2 a-Si solar module is about 1g. As a result, the value of the a-Si will not be used for further cost analyses here as the relative value will become clear when the value of the glass and avoided waste tipping fee are quantified below.

Next the amount of recovered glass after recycling is determined and the results are found in Table 2. As can be seen in Table 2 for all the types of modules the mass is between 16 and 17 kg per square meter.

Table 2: Determining mass of recovered glass for CIGS, CdTe, and c-Si PV modules

	CIGS	CdTe	c-Si
A (cm^2)	10,000[a]	10,000[a]	10,000[a]
t_g (cm)	0.68[b]	0.64[c]	0.64[d]

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ρ_g (g/cm^3)	2.6[e]	2.6[e]	2.6[e]
m_{rg} (g)	17,680	16,640	16,640
Sources: (a) Assumed area of 1m^2 (b) Xsunx (2009) (c) First Solar (2009b) (d) BP Solar (2009a) (e) Giancoli (1998)			

The third step in the comparative analysis was to use equations 2 and 4 to determine and compare the cost of recycling each of the three remaining solar modules and the financial return from re-selling the recovered semiconductor material and the glass in each. The results of this analysis are found in Table 3.

Table 3: Recycling cost and recycling profit for three solar modules

	CIGS		**CdTe**		**x-Si**
	In	**Ga**	**Cd**	**Te**	Si
V_s (\$/g)	3.00[a]	3.00[a]	0.026[a]	0.220[a]	0.027[b]
m_{rs} (g)	5.23	8.62	8.98[c]	9.15[c]	279.60[c]
P_s (\$/module)	15.70	25.85	0.23	2.02	7.54
V_g (\$/g)	3.72E-06 [d]	3.72E-06 [d]	3.72E-06 [d]	3.72E-06 [d]	3.72E-06 [d]
m_{rg} (g)	17,680 [e]		16,640 [e]		16,640 [e]
P_g (\$/module)	0.07		0.06		0.06
P_t (\$/module)	**41.62** [f]		**2.31** [f]		**7.54**[f]
C (\$/module)	20.24[g]		9.00[g]		32.11[h]
Sources: (a) Radiochemistry Society (2003) (b) Fero et al. (2010) (c) results from Table 1 (d) Three D and UWC (2008) (e) results from Table 2 (f) sum of P_s and P_g (g) Eberspacher (1998) (h) Fthenakis (2000)					

It is clear from Table 3 that the profit made by re-selling the recovered semiconductor material and glass, P_t, from CIGS solar modules greatly exceeds the cost of recycling these modules. However, in the case of CdTe and x-Si solar modules, the cost of recycling the module is more than the money made from re-selling the recovered materials. However, there is also an economic benefit from diverting panels from landfills. This economic benefit is only experienced by the manufacturers if there is an existing manufacturing responsibility legislation in place.

To calculate this benefit the cost of landfill disposal for each type of solar module from equation 6 is used and the results of this analysis are found in Table 4.

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Table 4: Landfill disposal cost of PV modules and total profitability of recycling

	CIGS	CdTe	c-Si	p-Si	a-Si
E (W/m^2)	100[a]	108[a]	144[a]	138[a]	90[a]
Weight (kg)	28[b]	12[c]	15.4[d]	19.4[e]	19.1[f]
Nominal Power (W)	160[b]	77.5[c]	180[d]	230[e]	128[f]
W (kg/module)	17.5[b]	16.72[c]	12.32[d]	11.64[e]	13.43[f]
T ($/kg)	0.05[g]	0.39[g]	0.05[g]	0.05[g]	0.05[g]
D ($)	0.87	6.45	0.61	0.58	0.67
$P_T = P_t + D - C$ ($)	22.25	-0.24	-23.96	-23.99	0.73-C
Sources: (a) Von Roedern (2009) (b) Xsunx (2009) (c) First Solar (2009b) (d) BP Solar (2009a) (e) BP Solar (2009b) (f) Sharp (2009) (g) Lee (1995)					

It is evident from Table 4 that the cost of landfilling the CdTe modules is considerably higher than the other types of modules because this module contains a substantial amount of cadmium, which is toxic heavy metal and considered a hazardous material. This is economically beneficial for the recycling mandate, but unfortunately the magnitude is not great enough to keep the total profitability of recycling CdTe modules from being negative. Thus the CdTe modules are not profitable to recycle, but the relatively small cost of recycling is likely worth the goodwill generated by being environmentally responsible.

In addition all the silicon-based modules are not profitable to recycle. The case of a-Si is not quantified but it is clear from the costs to recycle the other types of modules that P_T would be largely negative. Although it should be noted it may be possible to recycle the top glass as pre-deposited solar substrates with the transparent conducing oxide intact. Further work is required to determine the viability of this scheme, which would improve the economics considerably for all of the thin film modules.

Overall Table 4 indicates that there is no economic motivation for recycling, therefore because some materials are hazardous and recycling is critical, there is a need to provide policies to ensure recycling as the economic case for recycling using the current economic system, which ignores most environmental and social externalities. It should be pointed out that in the economically viable case of CIGS, because most CIGS modules contain a buffer layer of CdS, the recycling and landfilling may also be costly (Alsema *et al.*, 2005). Thus, the value in Table 4 must be considered a lower estimate and the economic incentive to recycle CIGS would be even greater than indicated. It can be drawn from comparing Table 3 and Table 4, that the cost of landfill disposal for each of the solar modules is extremely low when compared to the cost of recycling, which indicates that there may be a need for some non-market based approach to ensuring environmental sustainability – whether it be through corporate social responsibility or governmental regulations against disposal for industry to make an investment in recapturing the materials from PV modules, even if it is profitable as seen in Table 4.

5. Discussion

5.1 Existing Photovoltaic Recycling Initiatives

It can be assumed that based on the analysis above CIGS modules will be recycled due to the value of the materials they contain, but for the other modules some additional incentive is necessary. Therefore, it is essential that producer responsibility is developed among manufacturers to ensure the proper disposal methods are undertaken for solar PV modules. There are three main recycling initiatives that have already been voluntarily developed by PV manufacturers that may be generalized to be used as models: First Solar, SolarWorld Global, and PV Cycle.

First Solar is an American company that was formed in 1999, and launched production of CdTe-based PV commercial products in 2002. They have shown some commitment to the environment by ensuring that all stages of the PV manufacturing process, including end-of-life, create low carbon emissions. Consequently they claim that their carbon footprint is the lowest among available PV technologies, and compares well with wind technologies (Lincot, 2009). Additionally, in anticipation of potential negative backlash for using a toxic heavy metal in a 'green' product, more recently the company has undertaken a collection and recycling program (First Solar, 2009a; 2010). With the sale of each module, First Solar sets aside sufficient funds required for the estimated future cost of collection and recycling in custodial accounts in the name of a Trustee and the program, including the financing structure, is audited annually by an independent third party (First Solar, 2010). This collection and recycling program involves three steps: registering each module that the company sells, collecting these modules once they are decommissioned and recycling the modules to recover materials (First Solar, 2009a). The company also pays all packaging and transportation costs associated with the collection of the decommissioned modules. This program is a useful model as it covers the most environmentally dangerous photovoltaic-related solid waste and provides an example for other CdTe manufacturers. However, this program is only designed to recycle solar cells that First Solar has manufactured, so policy would need to ensure that each company also instituted such a program.

The second example program was developed by SolarWorld AG and their sub-division SolarMaterial, which focuses on many aspects of the PV module life cycle, including the recycling phase. Their program is designed to recycle modules of all designs and sizes that have undergone any type of damage (e.g. glass breakage, defective laminate, or electrical faults) (SolarMaterial, 2009). As a result of this project, and SolarWorld's overall environmental leadership, the company was ranked first overall among crystalline PV manufacturers in a report by the Silicon Valley Toxic Coalition because of their performance on environmental and social responsibilities (Santarris, 2010). Based on this award, clearly one of the benefits for SolarWorld is goodwill. However, because this program includes all types of solar modules, the economic analysis above indicates it may not be in the benefit of the company to maintain the program in the future.

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Unlike the two previous examples of company specific programs, PV Cycle is a program that was created by the European PV manufacturing industry. The program was founded in 2007 to implement the PV industry’s commitment to set up a voluntary take back and recycling program (PV Cycle, 2009). The manufacturers, which make up PV Cycle embrace the concept of producer responsibility and aim to offer a completely sustainable solar energy solution. However, this type of initiative only works if the industry is inclined to voluntarily participate in environmentally responsible manufacturing, which is not yet applicable globally. Without this type of initiative being regulated, manufacturing companies are free to withdraw from the program.

5.2 Producer Responsibility in PV Manufacturing

The initial cost of landfill disposal for all five solar modules is lower than the cost of recycling the modules, which will still make landfill more favorable than recycling for companies with short-term thinking even if the recycling is profitable overall. From the results above it is clear that: 1) CIGS PV will likely be recycled for profit, 2) CdTe manufacturing is dominated by First Solar, which has set a good example of a relatively low-cost recycling program for this technology, 3) some companies like SolarWorld may offer recycling programs for goodwill, but are unlikely to continue to provide economic loss leaders as the volume of waste PV increases, and 4) producer responsibility is needed to recycle Si-based PV as demonstrated by PV Cycle in Europe and to ensure that modules containing hazardous materials are disposed of appropriately. This final methodology of manufacturing responsibility, is the most generalizable as the first three are constrained by specific situations.

Although there are other policy techniques such as mandated consumer recycling to ensure products containing hazardous materials are disposed of appropriately, in the PV case there is clear advantage of using manufacturing responsibility because of the way government is supporting the industry to break into the energy market. For example, Abound Solar Manufacturing was recently offered a US$400 million loan guarantee to build two plants to manufacture CdTe-based solar panels during Obama's 4th of July announcement (Goossens, 2010). This will be the first time this technology for manufacturing solar panels is deployed commercially anywhere in the world, yet Abound will reach full manufacturing capacity in 2013, when they expect to produce more than 0.84 GW of PV modules annually (Goossens, 2010). To put that manufacturing capacity in perspective, consider that this relatively unproven company will be producing more PV panels than the aggregate of the entire global PV industry in 2003 only because of government assistance. Clearly, the government is in a position to demand extended manufacturing responsibility for such companies producing products containing hazardous materials. Utilizing manufacturing responsibility as a means to ensure proper disposal of PV-related hazardous waste will ensure that the burden is not foisted on consumers.

The concept of extended manufacturing responsibility states that the life cycle impacts of a product are viewed as the responsibility of the manufacturers and producers that create them (Larsen, 2009). In the manufacturing sector this concept is relatively

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well developed as compared to the energy sector. Larsen explains that this idea of extended manufacturing responsibility should involve testing new materials and processes, expanding recycling technologies, and designing products to be more easily recycled (Larsen, 2009). In the PV industry, a benefit of an environmentally responsible market is the possibility that materials from the decommissioned PV cells can be recovered and re-used, which may become important, as there has recently been discussion in the PV industry of declining amounts of cadmium, indium and tellurium (Larsen, 2009). This material shortage could lead to increased material prices and production costs of PV solar cells (Feltrin and Freundlich, 2006); and may make recycling solar modules more favorable because many of the semiconductor materials, can be recovered and re-used by recycling decommissioned solar cells. In a given region, if the PV manufacturing industry does not voluntarily adopt manufacturing responsibility as was done with PV Cycle, the government must assume its environmental responsibility and regulate the PV manufacturing industry to ensure recycling and avoid hazardous materials from entering local landfills. This will create a competitive advantage for companies that either work hard to avoid toxic materials (which entail a larger cost for recycling), or have already instituted recycling programs. Thus the environmentally most responsible companies are rewarded for their investments.

5.3 Producer Responsibility for Similar Hazardous Products

Regulation has been used in technology sectors across the world as a driver for recycling of hazardous products. Nickel-cadmium (NiCd) batteries and cathode ray tube (CRT) televisions and monitors contain materials similar to those found in some PV modules, and both saw increased recycling and take-back programs following government regulation. The PV industry can gain from observing past efforts to manage the recycling of similar hazardous products.

The amount of Cd contained in a 1 m^2 CdTe solar module is very similar to that in a size AA or size C NiCd battery (about 3-10g) (Fthenakis, 2003). The Mercury-containing and Rechargeable Battery Management Act was established in 1996 (EPA, 1996) to accomplish two goals: to phase out batteries that use mercury and to develop collection, transportation and most importantly recycling and proper disposal for NiCd batteries (Palchy, 2003). Additionally, in the U.S., eight states created legislation that mandated producer responsibility among NiCd battery manufacturers. Through this legislation, the NiCd industry instituted a national take-back program (Fishbein, 1996). Moreover, there have been independent NiCd recycling facilities and take-back programs that have been established to manage the hazardous cadmium waste in NiCd batteries (Palcy, 2003). For example Kodak developed a take-back and recycling program for their used cameras, which is currently recycling upwards of 1 billion cameras, and ensures that 90% of new cameras developed come from recycled cameras (Fishbein, 1996).

During the 1st International Conference on PV Module Recycling in Berlin, Germany, Döring argues that one can look at Germany's experience in recycling cathode ray tube (CRT) TV monitors, because the material composition is similar to PV modules (2010). One of the major drivers that led to CRT recycling in Germany was the regulation

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for electronic waste (Döring, 2010). This regulation stemmed from the Waste Electrical and Electronic Equipment (WEEE) Directive set forth by the European Commission in 2003, which utilizes the Polluter Pays Principle (Kibert, 2004). The Directive essentially mandates producers to be responsible for taking back and recycling products they manufacture at no cost to the consumer (Kibert, 2004), thereby creating extended producer responsibility within the electrical and electronic equipment industry.

5.4 Producer Responsibility in the Energy Industry

There is obviously a concern that regulating PV manufacturers to ensure they make the investment to recycle their products will have an un-intended consequence of providing a competitive advantage to other forms of electricity production. As most electricity is created from the combustion of fossil fuels or the fission of uranium it is clear that any disadvantage to the PV manufacturing industry caused by mandated recycling could actually increase environmental damage unless other members of the energy industry were similarly mandated. The concept of applying producer responsibility to the traditional energy industry is relatively unexplored and provides a rich area for future inquiry. Researchers have just begun to look at externalities in the nuclear industry such as the indirect subsidies inherent in nuclear energy insurance caps (Dubin and Rothwell, 1990; Heyes, 2003; Pearce, 2009) and work focused on quantifying the costs of externalities of fossil fuel use has started (Ambs and Roth, 2004; Eyre, 1997; Klaassen and Riahi, 2007; Owen, 2006), but rarely applied through mechanisms like carbon pricing and taxing (Flavin and Lenssen, 1992; Mathews, 2007; Sterner, 2007). It is clear that such work is imperative to correct for the current market failures that provide advantages to environmentally and socially irresponsible 'manufacturers' of energy.

6. Conclusions

This paper examined the potential need for solar PV recycling policies by analyzing existing recycling protocols for the five major types of commercialized PV materials. It was found that the economic motivation to recycle most types of PV devices does not outweigh the difference between recycling and landfill costs, thereby making recycling an unfavorable economic option without appropriate incentives. Nonetheless, some solar manufacturing companies have begun to voluntarily recycle solar modules, but such initiatives are driven by environmental responsibility rather than economic benefit. Therefore, as PV waste appears 25-30 years after the module is created and the PV industry is experiencing explosive growth, there will be increased need to recycle the large amount of decommissioned solar modules. Because recycling is economically unfavorable, this will ultimately lead to economic stress on voluntary initiatives. Consequently, unless recycling of solar modules is regulated in the future, it is likely that these types of voluntary initiatives will not be maintained and hazardous materials will begin to enter local waste streams However, it is critical that regulation of recycling in PV manufacturing does not provide a competitive advantage to the more environmentally destructive forms of electricity production. Therefore, it is imperative that appropriate policies are instituted taking the future into account and minimizing environmental

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pollution and solid waste from electricity production.

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2015 DEC 29 PM 1:10
LA PUBLIC SERVICE COMMISSION

BEFORE THE
LOUISIANA PUBLIC SERVICE COMMISSION

DOCKET NO. R-33929

LOUISIANA PUBLIC SERVICE COMMISSION,
EX PARTE

In re: Review of policies related to customer-owned solar generation and possible modification of the Commission's current net metering rules.

NOTICE OF PROPOSED RULEMAKING AND PROPOSED MODIFICATIONS TO THE COMMISSION'S CURRENT NET METERING RULES

PLEASE TAKE NOTICE that this rulemaking is being initiated in accordance with the actions of the Louisiana Public Service Commission ("LPSC" or "Commission") at its November and December 2015 Business and Executive Sessions ("B&E") in Commission Dockets No. X-33192 and U-32913 (consolidated). At its November 2015 B&E, the Commission confirmed that 3 electric cooperatives have reached the cap found in § 5.02 of the net metering rules.[1,2] At its December 2015 B&E, The LPSC adopted the proposal of Acadian Consulting to assist Commission Staff in conducting a 2-phase rulemaking to: 1) modify the Commission's current net metering rules in order to address how new solar customers should be compensated once a utility reaches the net metering cap found in § 5.02 of the rules; and 2) examine appropriate changes to solar policies in Louisiana.

[1] The Commission's current net metering rules are attached to the General Order issued July 26, 2013 (Docket R-31417).

[2] In Consolidated Order No. U-32913, the Commission verified that Northeast Louisiana Power Cooperative, Inc. ("Northeast"), Panola-Harrison Electric Cooperative, Inc. ("Panola-Harrison"), and Washington-St. Tammany Electric Cooperative, Inc. ("WST") had reached the cap found in § 5.02 of the Commission's rules.

Commission Staff is proposing certain changes to the Commission's current net metering rules, as shown on the attached redline of the rules. Commission Staff is requesting that this notice be published in the next official bulletin for a 20-day intervention and comment period. Parties should provide comments within the publication period regarding Staff's proposed changes as well as any other recommended changes to the net metering rules necessary to address Phase I post-cap remuneration issues. It is anticipated that a Phase I recommendation will be presented to the Commission in February or March 2016 and the Phase II rulemaking will commence thereafter. Should you wish to participate in either phase of this rulemaking, it is necessary to intervene during the intervention period.

Baton Rouge, Louisiana, this 29th day of December, 2015.

Respectfully Submitted:

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LOUISIANA PUBLIC SERVICE COMMISSION

GENERAL ORDER

LOUISIANA PUBLIC SERVICE COMMISSION, EX PARTE

~~Docket No. R-31417~~ -

***In re:** ~~Re-examination~~Review of policies related to customer-owned solar generation and possible modification **of the Commission's** ~~Net Energy Metering Rules found in General Order No. R-27558, dated November 30, 2005 (the "Net Metering Order")~~current net metering rules.*

(Decided at the ~~June 26, 2013~~_______ Business and Executive Session)

ATTACHMENT "A"

(Net Metering Rules)

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Appendix B

DEFINITIONS

Avoided Costs

The incremental cost to an electric utility for energy or capacity or both which, but for the purchase from the net metering facility, the utility would generate itself or purchase from another source.

Billing period

The billing period for net metering will be the same as the billing period under the customer's applicable standard rate schedule.

Biomass

(A) Any organic matter that is available on a renewable or recurring basis (excluding old-growth timber), including dedicated energy crops and trees, agricultural food and feed crop residues, wood and wood wastes and residues, aquatic plants, grasses, residues, fibers, and animal wastes, municipal wastes, and other waste materials.

(B) Biomass shall not include:

1. Wood contaminated with plastic or metals; exceptions such as construction debris may be allowed by the Commission after a docketed proceeding and only after the applicant has obtained any and all additional approval from other state and/or federal regulatory agencies.
2. Recyclable post-consumer waste paper; exceptions may be allowed on a case by case basis by the Commission after a docketed proceeding and only after the applicant has obtained any and all additional approval from other state and/or federal regulatory agencies.

Biomass facility

A facility that may use one or more organic fuel sources that can either be processed into synthetic fuels or burned directly to produce steam or electricity, provided that the resources are renewable, environmentally sustainable in their production and use, and the process of conversion to electricity results in a net environmental benefit. This includes, but is not limited to, dedicated energy crops and trees, agricultural food and feed crops, agricultural crop wastes and residues, wood wastes and residues, aquatic plants, animal wastes, and other accepted organic, renewable waste materials.

Commercial customer

A customer served under a utility's standard rate schedule applicable to commercial service.

Commission

The Louisiana Public Service Commission.

Electric utility/Utility

A public or investor owned electric utility, an electric cooperative, or any private power supplier or marketer that engages in the business of supplying electric energy to the ultimate customer or any customer class within the state. The electric utility must fall under the jurisdiction of the Commission in order to be required to comply with the provisions set out herein.

<u>Excess net metered energy</u>

<u>The kilowatt-hours (kWh) generated by the net metering facility and exported to the electric utility that exceed the kWhs supplied to the net metering customer by the electric utility during the billing period.</u>

Fuel cell facility

A facility that converts the chemical energy of a fuel directly to direct current electricity without intermediate combustion or thermal cycles.

Geothermal facility

An electric generating facility in which the prime mover is a steam turbine. The steam is generated in the earth by heat from the earth's magma.

Hydroelectric facility

An electric generating facility in which the kinetic energy is derived from moving water. The facility must meet all local, state, and Federal regulations that govern or effect the construction and operation of a hydroelectric power plant and must protect all users of the resource, including the plant, fish, and animal communities that utilize the water. Local, state, and Federal legal restrictions on the development of the hydroelectric site and the use of the water must be complied with

Interconnection costs

The reasonable costs of connection, switching, metering, transmission, distribution, safety provisions and administrative costs incurred by the electric utility directly related to the installation and maintenance of the physical facilities necessary to permit interconnected operations with a net metering facility, to the extent the costs are in excess of the corresponding costs which the electric utility would have incurred if it had not engaged in interconnected operations, but instead generated an equivalent amount of electric energy itself or purchased an equivalent amount of electric energy or capacity from other sources. Interconnection costs do not include any costs included in the calculation of avoided costs.

Micro turbine facility

A facility that uses a small combustion turbine to produce electricity.

Net metering

Measuring the difference between electricity supplied by an electric utility and the electricity generated by a net metering customer and fed back to the electric utility over the applicable billing period.

Net metering customer

Any customer who chooses to take electric service under the net metering tariff, as set out below. For commercial customers, this includes subsidiaries and affiliates.

Net metering facility

A facility for the production of electrical energy that:

(A) Uses solar, wind, hydroelectric, geothermal, or biomass resources to generate electricity including, but not limited to, fuel cells and micro turbines that generate electricity if the fuel source is entirely derived from renewable resources; and,

(B) Has a generating capacity of not more than twenty-five (25) kilowatts for residential or three hundred (300) kilowatts for commercial or agricultural use; and,

(C) Is located in Louisiana; and,

(D) Can operate in parallel with an electric utility's existing transmission and distribution facilities; and,

(E) Is intended primarily to offset part or all of the net-metering customer requirements for electricity or,

(F) Is designated by the Commission as eligible for net metering service pursuant to § 2.06 below, because it has applied for and is entitled to receive state or federal funding for all or part of the costs of its project, which the Commission finds to be in the public interest.

Parallel operation

The operation of on-site generation by a customer while the customer is connected to the utility's distribution system.

Renewable energy credit

The environmental, economic, and social attributes of a unit of electricity, such as a megawatt hour, generated from renewable fuels that can be sold or traded separately.

Residential customer

A customer served under a utility's standard rate schedules applicable to residential service.

Solar facility

A facility in which electricity is generated through the collection, transfer and/or storage of the sun's heat or light.

Wind facility

A facility in which an electric generator is powered by a wind-driven turbine.

SECTION 1. GENERAL PROVISIONS

1.01. Purpose

The purpose of these Rules is to establish rules for net energy metering and interconnection.

1.02. Statutory Provisions

A. Article IV, Section 21(B) of the Louisiana Constitution.

B. Legislative Act No. 653, Regular Session 2003.

C. Legislative Act No. 543, Regular Session 2008.

1.03. Other Provisions

A. These Rules apply to all jurisdictional electric utilities, as defined in these Rules.

B. The Net Metering Rules are not intended to, and do not affect or replace any Commission approved general service regulation, policy, procedure, rule or service application of any utility which address items other than those covered in these Rules.[1]

C. Net metering customers taking service under the provisions of the Net Metering Tariff may not simultaneously take service under the provisions of any other alternative source generation or cogeneration tariffs except as provided herein.

SECTION 2. NET METERING REQUIREMENTS

2.01. Electric Utility Requirements

A. An electric utility, subject to the jurisdiction of this Commission, that offers residential or commercial electrical service, or both, shall allow net metering facilities to be interconnected using a standard meter capable of registering the flow of electricity in two (2) directions. A two-channel meter or other type meter(s) which is capable of determining the net energy can be utilized, as well.

B. If the meter that is currently installed on the net metering facility is incapable of registering the flow of electricity in two directions, an additional meter or meters to monitor the flow of electricity in each direction may be installed by the electric utility. The cost of the meter shall not be borne by the net metering customer, unless the additional meter(s) is not required by the electric utility, but instead requested by the net metering customer. A customer charge for the any installations where the meter will not register in both directions may be assessed by the utility in conformity with Section 2.02(A) below.

C. If an additional meter or meters are installed, as described in 2.01(B) above, the net energy metering calculation shall yield the same result as when a single meter is used.

2.02. Metering Requirements

A. Metering equipment shall be installed to both accurately measure the electricity supplied by the electric utility to each net-metering customer and also to accurately measure the electricity generated by each net-metering customer that is fed back to the electric utility over the applicable billing period. Notwithstanding the provisions of Section 3.01 below, the cost of the meter is the responsibility of

[1] The issue of securitization non-bypassability and its applicability to net metering customers was raised by LEUG in its post technical conference comments and in discussions with Staff. Both LEUG and Entergy filed comments on this issue and both are in agreement with Staff that the non-bypassability provisions of the various Financing Orders approved by the Commission apply equally to all new self-generation resources regardless of size to the extent that such resources may displace electric load met by one of the Companies that existed at the time specified in those Orders.

the electric utility, but the utility will be allowed to assess a one-time customer charge to cover the installation costs. The utility may also assess a customer charge for any additional meter installations if the additional installations are requested by the net metering customer.

B. Accuracy requirements for a meter operating in both forward and reverse registration modes shall be defined in Appendix B. A test to determine compliance with this accuracy requirement shall be made by the electric utility either before or at the time the net metering facility is placed in operation in accordance with these Rules. The costs associated with the test may be included in the customer charge, as set out in Section 2.02(A) or it may be a separate customer charge, to be assessed to the net metering customer. The customer charge for testing may be assessed when the customer's meter is first tested, and the same fee may be charged by the utility each time the customer requests additional meter tests to be performed unless the test demonstrates that the meter does not comply with the accuracy requirements. If the meter is found to not comply with the accuracy requirements, then the net metering customer shall not be charged for the testing.

To the extent that a faulty meter has resulted in a net metering customer receiving insufficient credits or payments, pursuant to Section 2.04 (B) and (C) below, the utility shall make the appropriate credits or payments in the next billing cycle. If the faulty meter has resulted in the net metering customer receiving excess credits or payments, pursuant to Section 2.04 (B) and (C) below, then the utility shall reduce any future credits or payments by the excess amount in the next billing cycle. Nothing in this section shall supercede the provisions of the Commission's General Order dated April 21, 1993, in re: Computer glitches and billing errors.

2.03. New or Additional Charges

A. Any new or additional charge that would increase a net metering customer's costs beyond those of other customers in the rate class shall be filed by the electric utility with the Commission for approval. The filing shall be supported by cost/benefit analyses.

B. Following notice and opportunity for public comment, the Commission may authorize an electric utility to assess a net metering customer a greater fee or customer charge, of any type, if the electric utility's direct costs of interconnection and administration of net-metering outweigh the distribution system, environmental and public policy benefits of allocating the costs among the electric utility's entire customer base.

C. Net metering customers shall be obligated to pay any interconnection costs, as defined above. These costs shall be assessed on a nondiscriminatory basis with respect to other customers with similar load characteristics.

Electric utilities shall be reimbursed by the net metering customer for interconnection costs at the time the costs are incurred. Upon petition by any party involved and for good cause shown, the Commission may allow for reimbursement of the interconnection costs over a reasonable period of time and upon such conditions as the Commission may determine; provided, however, that no other customers of the utility shall bear any of the costs of interconnection.

2.04. Billing for Net Metering

A. On a monthly basis, the net metering customer shall be billed the charges applicable under the currently effective standard rate schedule and any appropriate rider schedules. Under net metering, only the ~~kilowatt-hour (~~kWh~~)~~ units of a customer's bill are affected.

B. If the kWhs supplied by the electric utility exceeds the kWhs generated by the net metering facility and are fed back to the electric utility during the billing period, the net metering customer shall be billed for the net kWhs supplied by the electric utility in accordance with the rates and charges under the customer's standard rate schedule.

C. Where the electricity generated by the net metering customer exceeds the electricity supplied by the electric utility, the net metering customer shall be credited, during the next billing period, for the excess kilowatt hours generated in the same manner as Section 2.04(B) above., except in instances where Section 5.02 below is applicable. For the final month in which the net metering customer takes service from the electric utility, the electric utility shall issue a check to the net metering customer for the balance of any credit due in excess of amounts owed by the customer to the electric utility. The payment for any remaining credits shall be at the electric utility's avoided cost. That avoided cost shall be clearly identified in the electric utility's net metering tariff, as set out below in Section 5.01.

D. Customers with multiple accounts may not apply any credits from a net metering account to any other account or premise.

E. Net metering tariffs are not available for temporary services or commercial customers from an underground electrical network system.

2.05. Renewable Energy Credits

This section is not needed at this time due to the fact that no Renewable Energy Credit ("REC") program has been established. The Commission reserves the right to revisit this section if a REC program is established.

2.06. Large Net Metering Projects

A. The Commission may allow projects greater than 300kW for a commercial net metering customer, if the customer's project is found to be in the public interest.

B. Projects approved under this section shall meet all of the requirements of this rule, including the limitations set forth in paragraphs A,C,D, and E, found in the definition of net metering customer herein.

C. Large net metering customers shall reimburse the utility for reasonable and necessary engineering analyses and/or studies performed prior to project approval.

D. Large net metering customers shall compensate the utility for necessary upstream and/or downstream system infrastructure improvements triggered by the net metering project.

E. Utilities may request to recover lost base revenues associated with net metering facilities greater than 300kW through appropriate proceedings and/ or mechanisms.

F. All projects requested hereunder shall be docketed and published in the Commission's official bulletin prior to Commission approval. Expedited treatment may be allowed upon a showing of good cause by the applicant.

G. All projects hereunder are bound by all rules regarding interconnection and must continue to follow interconnection policies and procedures in the same manner as a non-net metering entity.

H. The Commission reserves its rights to determine on an individual basis the appropriate pricing on projects larger than 300kW.

SECTION 3. INTERCONNECTION OF NET METERING FACILITIES TO EXISTING ELECTRIC POWER SYSTEMS

3.01 Requirements for Initial Interconnection of Net Metering Facility

A. A net metering customer shall execute a Standard Interconnection Agreement for Net Metering Facilities (please see Appendix A) prior to interconnection with the utility's facilities. The Standard Interconnection Agreement shall set forth the expenses for which the net metering customer shall responsible.

B. A net metering facility shall be capable of safely operating in parallel prior to commencing the delivery of power into the utility system at a single point of interconnection. A net metering facility shall have a visibly open, lockable, manual disconnection switch that is accessible by the electric utility and clearly labeled, unless this requirement is waived by the electric utility pursuant to Section 4 of the Standard Interconnection Agreement.

C. The customer shall submit a Standard Interconnection Agreement to the electric utility at least forty-five (45) days prior to the date of the customer intends to interconnect the net metering facilities to the utility's facilities. Part I, Standard information, Sections 1 through 4 of the Standard Interconnection Agreement must be completed for the notification to be valid. The customer shall have all equipment necessary to complete the interconnection prior to such notification. If mailed, the date of notification shall be the third day following the mailing of the Standard Interconnection agreement. The net metering customer will be required to provide documentation indicating the date upon which the notification was mailed to the electric utility. The electric utility shall provide a copy of the Standard Interconnection Agreement to the customer upon request.

D. Following notification by the customer as specified in Section 3.01.C, the electric utility shall review the plans of the facility and provide the results of its review to the customer within 45 calendar days from the date of notification. Any items that would prevent parallel operation due to violation of safety standards and/or power generation limits shall be explained along with a description of the modification necessary to remedy the violations.

E. The net metering facility, at the net metering customer's expense, shall meet all safety and performance standards established by local and national electric codes including the National Electric Code (NEC), the Institute of Electrical and Electronics Engineers (IEEE), the National Electrical Safety Code (NESC), and Underwriters Laboratories (UL).

F. The net metering facility, at the net metering customer's expense, shall meet all reasonable safety and performance standards adopted by the utility and filed with and approved by the Commission pursuant to these rules that are necessary to assure safe and reliable operation of the net metering facility when connected to the utility's system.

G. If the electric utility's existing facilities are not adequate to interconnect with the net metering facility, any changes will be performed in accordance with the electric utility's Extension of Facilities Tariff.

H. Provided that no modifications have been made to the net metering facility which would render it no longer in compliance with the above safety and performance standards, valid interconnection agreements signed pursuant to this section shall be transferable to a purchaser of the property on which the net metering facility is located, regardless of whether the utility has reached the cap found in Section 5.02 of these rules.

Rule 3.02. Requirements for Modification or Changes to a Net Metering Facility

Modifications or changes made to a net metering facility shall be evaluated by the electric utility prior to being made. The net metering customer shall provide detailed information describing the modifications or changes to the electric utility in writing prior to making the modifications to the net metering facility. The electric utility shall review the proposed changes to the facility and provide the results to its evaluation to the customer within forty-five (45) days of receipt of the customer's proposal. Any items that would prevent parallel operation due to violation of applicable safety standards and/or power generation limits shall be explained along with a description of the modifications necessary to remedy the violations.

SECTION 4. STANDARD INTERCONECTION AGREEMENT FOR NET METERING FACILITIES.

4.01. Standard Net Metering Interconnection Agreement.

Each electric utility shall file, for approval by the Commission, a Standard Interconnection Agreement for Net Metering Facilities (please see Appendix A). The electric utility may submit a Standard Interconnection Agreement with proposed modifications, however, the proposed modifications will only become effective upon approval by the Commission or its Staff. The Standard Interconnection Agreement shall describe any and all interconnection expenses, and other customer charges in conformity with Sections 2.02 and 2.03 above, for which the net metering customer shall be responsible.

SECTION 5. STANDARD NET METERING TARIFF FOR NET METERING FACILITIES

5.01 Net Metering Tariff.

Each electric utility shall update its tariff on file with the Commission within thirty (30) days from the effective date of these rules. The Net Metering Tariff shall be filed with and maintained by the Commission. The tariff shall specify standard rates for purchases from net metering facilities with a design capacity of 300 kilowatts or less. The Net Metering Tariff must comply with the Section 204 (a)(c) and (e), regarding standard rates for purchases at avoided costs, of the Commission's General Order dated February 27,1998. Electric utilities may include seasonally differentiated avoided cost rates for purchases from net metering customers, to the extent that avoided costs vary by season. The net metering tariff may include customer charges or interconnection charges as set forth in Sections 2.02, 2.03, and 2.06 above.

5.02 Cap on Net Metering Installations

A. ~~When a utility determines that its~~Each utility's net metering ~~purchases exceed~~program will be capped at 0.5% of its monthly LPSC-jurisdictional retail peak load~~.~~. When a utility determines that the ~~affected~~installed net metered generation exceeds this cap, the utility is no longer required to ~~accept net metering applications.~~credit excess net metered energy at full retail rates as identified in Section 2.04(C).

B. Any utility invoking this provision shall advise the Commission by making a filing with the Secretary. A claim by a utility that it has met the cap in paragraph A is subject to verification by the Commission.

C. The Commission shall verify the claim in accordance with Order No. U-32913 (consolidated).

D. Once a filing has been made pursuant to Section 5.02(B), above (provided however, that the claim has not been rejected by the Commission pursuant to Section 5.02(C), above, the utility shall credit customers for excess energy delivered to the grid at the utility's avoided cost rate, as set forth in Section 5.01 above.

E. Alternative avoided cost rates such as seasonally differentiated avoided cost rates or average avoided cost rates that reflect upward adjustments for avoided line losses and daytime, on peak generation may be approved on a utility-specific basis. Unless otherwise specified in the order approving the rate, if the Commission allows such adjustment, hereinafter referred to as a net metering alternative avoided cost adjustment, the rate shall be updated bi-annually and all amounts collected shall be eligible for recovery pursuant to the LPSC's General Order No. U-21497, which governs the types of costs that may be recovered through a utility's monthly Fuel Adjustment Clause.

5.03 Filing and Reporting Requirements.

Each electric utility shall file a net metering annual ~~reports~~report no later than March 1 of each year~~, listing all existing net metering facilities~~. The report shall be in Excel format, on the form attached hereto as Appendix C and ~~the generator rating and, where applicable, the inverter power rating of each net metering facility~~shall include information as of the end of the previous calendar year. ~~When the filing is made, the title of the filing shall reference Docket Number R-31417.~~The form will be available on the Commission's website (http://www.lpsc.org/electricannualreports.aspx).

5.04 Commission Review.

The Commission may revisit this rule at any time.

Appendix A

STANDARD INTERCONNECTION AGREEMENT FOR NET METERING FACILITIES

I. STANDARD INFORMATION

Section 1. Customer Information

Name:____
Mailing Address:____
City:_______________ State:______________ Zip Code:__________________
Facility Location (if different from above):_________________________________
Daytime Phone: Evening Phone:____
Utility Customer Account (from electric bill):________________________________

Section 2. Generation Facility Information

System Type: Solar Wind Hydro Geothermal Biomass Fuel Cell Micro turbine
Generator Rating (**kW**): AC or DC (circle one)
Describe Location of Accessible and Lockable Disconnect:_________________________
Inverter Manufacturer: Inverter Model:_______________________________________
Inverter Location: Inverter Power Rating:____________________________________

Section 3. Installation Information
Attach a detailed electrical diagram of the net metering facility.
Installed by:_______________________Qualifications/Credentials :______________________
Mailing Address:____
City:________________ State:________________ Zip Code:______________________
Daytime Phone:____________________Installation Date:___________________________

Section 4. Certification

1. The system has been installed in compliance with the local Building/Electrical Code of (City/Parish)
____

Signed (Inspector):_________________________________Date:_____________________
(In lieu of signature of inspector, a copy of the final inspection certificate may be attached.)

2. The system has been installed to my satisfaction and I have been given system warranty information and an operation manual, and have been instructed in the operation of the system.
Signed (Owner):_____________________________________Date:_____________________

Section 5. Utility Verification and Approval

1. Facility Interconnection Approved:________________ Date:___________________________
Metering Facility Verification by:____________________Verification Date:__________________

Appendix A

II. <u>INTERCONNECTION AGREEMENT TERMS AND CONDITIONS</u>

This Interconnection Agreement for Net Metering Facilities ("Agreement") is made and entered into this _____ day of ______, 20__, by ________________("Utility") and ________________("Customer"), a _____ __________ (specify whether corporation or other), each hereinafter sometimes referred to individually as "Party" or collectively as the "Parties". In consideration of the mutual covenants set forth herein, the Parties agree as follows:

Section 1. The Net Metering Facility

The Net Metering Facility meets the requirements of "Net Metering Facility", as defined in the Louisiana Net Metering Rules.

<u>Section 2. Governing Provisions</u>

The terms of this agreement shall be interpreted under and subject to Louisiana Law. The parties shall be subject to the provisions of Act No. 653, the terms and conditions as set forth in this Agreement, the Net Metering Rules, and the Utility's applicable tariffs.

Section 3. Interruption or Reduction of Deliveries

The Utility shall not be obligated to accept and may require Customer to interrupt or reduce deliveries when necessary in order to construct, install, repair, replace, remove, investigate, or inspect any of its equipment or part of its system; or if it reasonably determines that curtailment, interruption, or reduction is necessary because of emergencies, forced outages, force majeure, or compliance with prudent electrical practices. Whenever possible, the Utility shall give the Customer reasonable notice of the possibility that interruption or reduction of deliveries may be required. Notwithstanding any other provision of this Agreement, if at any time the Utility reasonably determines that either the facility may endanger the Utility's personnel or other persons or property, or the continued operation of the Customer's facility may endanger the integrity or safety of the Utility's electric system, the Utility shall have the right to disconnect and lock out the Customer's facility from the Utility's electric system. The Customer's facility shall remain disconnected until such time as the Utility is reasonably satisfied that the conditions referenced in this Section have been corrected.

Section 4. Interconnection

Customer shall deliver the as-available energy to the Utility at the Utility's meter.

Utility shall furnish and install a standard kilowatt-hour meter. Customer shall provide and install a meter socket for the Utility's meter and any related interconnection equipment per the Utility's technical requirements, including safety and performance standards. Customer shall be responsible for all costs associated with installation of the standard kilowatt-hour meter and testing in conformity with Sections 2.02 of the Net Metering Rules.

The customer shall submit a Standard Interconnection Agreement to the electric utility at least forty-five (45) days prior to the date the customer intends to interconnect the net metering facilities to the utility's facilities. Part I, Standard Information Sections 1 through 4 of the Standard Interconnection Agreement must be completed for the notification to be valid. The customer shall have all equipment necessary to complete the interconnection prior to such notification. If mailed, the date of notification shall be the third day following the mailing of the Standard Interconnection agreement. The net metering customer will be required to provide documentation indicating the date upon which the notification was mailed to the electric utility. The electric utility shall provide a copy of the Standard Interconnection Agreement to the customer upon request.

Following notification by the customer as specified in Rule 3.01.C, the utility shall review the plans of the facility and provide the results of its review to the customer within 45 calendar days. Any items that would prevent parallel operation due to violation of applicable safety standards and/or power generation limits shall be explained along with a description of the modifications necessary to remedy the violations.

To prevent a net metering customer from back-feeding a de-energized line, the customer shall install a manual disconnect switch with lockout capability that is accessible to utility personnel at all hours. This requirement for a manual disconnect switch may be waived if the following three conditions are met: 1) The inverter equipment must be designed to shut down or disconnect and cannot be manually overridden by the customer upon loss of utility service; 2) The inverter must be warranted by the manufacturer to shut down or disconnect upon loss of utility service; and 3) The inverter must be properly installed and operated, and inspected and/or tested by utility personnel. The decision to grant the waiver will be at the Utility's discretion, however, any decision will be subject to review by the Commission.

Customer, at his own expense, shall meet all safety and performance standards established by local and national electrical codes including the National Electrical Code (NEC), the Institute of Electrical and Electronics Engineers (IEEE), the National Electrical Safety Code (NESC), and Underwriters Laboratories (UL).

Customer, at his own expense, shall meet all safety and performance standards adopted by the utility and filed with and approved by the Commission pursuant to Rule 3.01.F that are necessary to assure safe and reliable operation of the net metering facility to the utility's system.

Customer shall not commence parallel operation of the net metering facility until the net metering facility has been inspected and approved by the Utility. Such approval shall not be unreasonably withheld or delayed. Notwithstanding the foregoing, the Utility's approval to operate the Customer's net metering facility in parallel with the Utility's electrical system should not be construed as an endorsement, confirmation, warranty, guarantee, or representation concerning the safety, operating characteristics, durability, or reliability of the Customer's net metering facility.

Modifications or changes made to a net metering facility shall be evaluated by the Utility prior to being made. The Customer shall provide detailed information describing the modifications or changes to the Utility in writing prior to making the modifications to the net metering facility. The Utility shall review the proposed changes to the facility and provide the results of its evaluation to the Customer within forty-five (45) calendar days of receipt of the Customer's proposal. Any items that would prevent parallel operation due to violation of applicable safety standards and/or power generation limits shall be explained along with a description of the modifications necessary to remedy the violations.

Section 5. Maintenance and Permits

The customer shall obtain any governmental authorizations and permits required for the construction and operation of the net metering facility and interconnection facilities. The Customer shall maintain the net metering facility and interconnection facilities in a safe and reliable manner and in conformance with all applicable laws and regulations.

Section 6. Access to Premises
The Utility may enter the Customer's premises to inspect the Customer's protective devices and read or test the meter. The Utility may disconnect the interconnection facilities without notice if the Utility reasonably believes a hazardous condition exists and such immediate action is necessary to protect persons, or the Utility's facilities, or property of others from damage or interference caused by the Customer's facilities, or lack of properly operating protective devices.

Section 7. Indemnity and Liability
Each party shall indemnify the other party, its directors, officers, agents, and employees against all loss, damages expense and liability to third persons for injury to or death of persons or injury to property caused by the indemnifying party's engineering design, construction ownership or operations of, or the making of replacements, additions or betterment to, or by failure of, any of such party's works or facilities used in connection with this Agreement by reason of omission or negligence, whether active or passive. The indemnifying party shall, on the other party's request, defend any suit asserting a claim covered by this indemnity. The indemnifying party shall pay all costs that may be incurred by the other party in enforcing this indemnity. It is the intent of the parties hereto that, where negligence is determined to be contributory, principles of comparative negligence will be followed and each party shall bear the proportionate cost of any loss, damage, expense and liability attributable to that party's negligence.

Nothing in this Agreement shall be construed to create any duty to, any standard of care with reference to or any liability to any person not a party to this Agreement. Neither the Utility, its officers, agents or employees shall be liable for any claims, demands, costs, losses, causes of action, or any other liability of any nature or kind, arising out of the engineering, design construction, ownership, maintenance or operation of, or making replacements, additions or betterment to, the Customer's facilities by the Customer or any other person or entity.

Section 8. Notices
All written notices shall be directed as follows:

Attention:
[Utility Agent or Representative]

[Utility Name and Address]

Attention:
[Customer]
Name:________________
Address:______________
City:_________________

Customer notices to Utility shall refer to the Customer's electric service account number set forth in Section 1 of this Agreement.

Section 9. Term of Agreement
The term of this Agreement shall be the same as the term of the otherwise applicable standard rate schedule. This Agreement shall remain in effect until modified or terminated in accordance with its terms or applicable regulations or laws.

Section 10. Assignment

This Agreement and all provisions hereof shall inure to and be binding upon the respective parties hereto, their personal representatives, heirs, successors, and assigns. The Customer shall not assign this Agreement or any part hereof without the prior written consent of the Utility, and such unauthorized assignment may result in termination of this Agreement.

IN WITNESS WHEREOF, the parties have caused this Agreement to be executed by their duly authorized representatives.

Dated this _________ day of ___________, 20__.

Customer:	Utility:
____________________________	____________________________
By:__________________________	By:__________________________
Title:________________________	Title:________________________
Mailing Address:	Mailing Address:
____________________________	______________________
____________________________	______________________

Appendix B

<u>Accuracy Requirements for Service Watt-Hour Meters, Demand Meters, and Pulse Recorders:</u>

A. Initial and Test Adjustments:

(1) No watt-hour meter that has an incorrect register constant, test constant, gear ratio or dial train, or that registers upon no load ("creeps"), shall be placed in service or allowed to remain in service without adjustment and correction. An in-service meter "creeps" when, with potential applied to all stators and with all load wires disconnected, the moving element makes one complete rotation in 10 minutes or less.

(2) No watt-hour meter that has an error in registration of more than the limits allowed in Rule 7.05.B. (1) shall be placed in service or be allowed to remain in service without adjustment. When meter error is found to exceed any one of the test limits in Rule 7.05.B.(1), it must be adjusted and a correction made to the customer's bill.

(3) Meters must be adjusted as closely as practicable to the condition of zero error by no greater than +/- 0.5 percent.

B. Acceptable Performance

(1) Watt-Hour Meter Accuracy

The average error of the watt-hour meter shall not exceed +/- 2 percent.

	Test Current	Power Factor	Accuracy
Heavy Load	100% Test Amperes	1.0	+/- 2%
	100% Test Amperes	0.5	+/- 2%
Light Load	10% Test Amperes	1.0	+/- 2%

(2) Demand Meter Accuracy

The error of the demand register shall not exceed +/- 4% of the full scale value when tested between 25 percent and 100 percent of full scale value.

(3) Pulse Recorders

Pulse recorders shall not differ by more than +/- 2 percent from the corresponding kilowatt hour meter registration. The timing error shall not exceed +/- 2 minutes per day.

(4) Time of Use Meters

The timing element of time of use meters shall not be in error with central standard/daylight savings time by more than +/- 15 minutes.

C. Average Error

(1) The average error of a service watt-hour meter shall be determined as follows:

$$WA = LL + 4HL / 5$$

Where:

Where:	WA	=	weighted average error of a service watt-hour meter
	LL	=	error at light load for 100 percent power factor
	HL	=	error at heavy load for 100 percent power factor

(2) The average error of the watt-hour portion of a demand meter shall be determined as follows:

$$WA = LL + 4HL + 2HHL / 7$$

Where:	WA	=	weighted average of error of the watt-hour portion of a demand meter.
	LL	=	error at light load of 100 percent power factor
	HL	=	error at heavy load for 100 percent power factor
	HHL	=	error at heavy load with 50 percent lagging power factor.

Appendix C

LPSC Net Metering Annual Report

Utility Name: ____________________

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Residential													
1 Number of Solar Unit Installations													
2 Solar Generation Capacity, kW (DC)													
3 Solar Inverter Capacity, kW (AC)													
4 Number of Wind Unit Installations													
5 Wind Generation Capacity, kW (DC)													
6 Wind Inverter Capacity, kW (AC)													
7 Number of Biomass Unit Installations													
8 Biomass Generation Capacity, kW (DC)													
9 Biomass Inverter Capacity, kW (AC)													
10 Number of Other Unit Installations (Microturbine, Fuel Cell)													
11 Other Generation Capacity, kW (DC)													
12 Other Inverter Capacity, kW (AC)													
13 Total Number of Installations													
14 Total Generation Capacity, kW (DC)													
15 Total Inverter Capacity, kW (AC)													
Commercial													
16 Number of Solar Unit Installations													
17 Solar Generation Capacity, kW (DC)													
18 Solar Inverter Capacity, kW (AC)													
19 Number of Wind Unit Installations													
20 Wind Generation Capacity, kW (DC)													
21 Wind Inverter Capacity, kW (AC)													
22 Number of Biomass Unit Installations													
23 Biomass Generation Capacity, kW (DC)													
24 Biomass Inverter Capacity, kW (AC)													
25 Number of Other Unit Installations (Microturbine, Fuel Cell)													
26 Other Generation Capacity, kW (DC)													
27 Other Inverter Capacity, kW (AC)													
28 Total Number of Installations													
29 Total Generation Capacity, kW (DC)													
30 Total Inverter Capacity, kW (AC)													
Total													
31 Number of Solar Unit Installations													
32 Solar Generation Capacity, kW (DC)													
33 Solar Inverter Capacity, kW (AC)													
34 Number of Wind Unit Installations													
35 Wind Generation Capacity, kW (DC)													
36 Wind Inverter Capacity, kW (AC)													
37 Number of Biomass Unit Installations													
38 Biomass Generation Capacity, kW (DC)													
39 Biomass Inverter Capacity, kW (AC)													
40 Number of Other Unit Installations (Microturbine, Fuel Cell)													
41 Other Generation Capacity, kW (DC)													
42 Other Inverter Capacity, kW (AC)													
43 Total Number of Installations													
44 Total Generation Capacity, kW (DC)													
45 Total Inverter Capacity, kW (AC)													

Utility Name: ______________________

Utility	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
46 Utility Peak Load (MW)													
47 Retail Portion													
48 Percent of System Peak ((line 44/1,000)/line 47)													
49 Energy Purchased from Net Metered Customers (kWh)													
50 Average Rate Paid for Energy Purchased from Net Metered Customers ($/kWh)													
51 Cost of Energy Purchased from Net Metered Customers ($)													
52 Utility Avoided Cost Rate ($/kWh)													
53 Utility Fuel Clause Rate ($/kWh)													

ID	Address	City	Zip	x_coord	y_coord	Customer Class	Customer Class (Standardized)	Capacity (DC)	Capacity (Inverter AC)	Voltage

Installation	Installatio	Installation	Fuel	Prime Mov	h. metered	i. Participat e in NM?	j. Eligible but no NM?	k. Rejected from NM?	usage

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TECHNICAL PAPER

Recovering valuable metals from recycled photovoltaic modules

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Recovering valuable metals such as Si, Ag, Cu, and Al has become a pressing issue as end-of-life photovoltaic modules need to be recycled in the near future to meet legislative requirements in most countries. Of major interest is the recovery and recycling of high-purity silicon (>99.9%) for the production of wafers and semiconductors. The value of Si in crystalline-type photovoltaic modules is estimated to be ~$95/kW at the 2012 metal price. At the current installed capacity of 30 GW/yr, the metal value in the PV modules represents valuable resources that should be recovered in the future. The recycling of end-of-life photovoltaic modules would supply >88,000 and 207,000 tpa Si by 2040 and 2050, respectively. This represents more than 50% of the required Si for module fabrication. Experimental testwork on crystalline Si modules could recover a >99.98%-grade Si product by HNO_3/NaOH leaching to remove Al, Ag, and Ti and other metal ions from the doped Si. A further pyrometallurgical smelting at 1520°C using CaO–CaF_2–SiO_2 slag mixture to scavenge the residual metals after acid leaching could finally produce >99.998%-grade Si. A process based on HNO_3/NaOH leaching and subsequent smelting is proposed for recycling Si from rejected or recycled photovoltaic modules.

Implications: The photovoltaic industry is considering options of recycling PV modules to recover metals such as Si, Ag, Cu, Al, and others used in the manufacturing of the PV cells. This is to retain its “green” image and to comply with current legislations in several countries. An evaluation of potential resources made available from PV wastes and the technologies used for processing these materials is therefore of significant importance to the industry. Of interest are the costs of processing and the potential revenues gained from recycling, which should determine the viability of economic recycling of PV modules in the future.

Introduction

To reduce the impact of global warming, several countries around the world have developed and used renewable energy resources to reduce greenhouse gas emissions. In this respect, the European Union (EU) has taken a leading role by adopting a 20% carbon reduction by 2020, a high target to be followed by most developed countries. One of the many options adopted is by replacing fossil fuels with solar energy. Electricity can be generated by capturing solar energy via a thermal mass or via photovoltaic (PV) devices (Desideri et al., 2013). According to a White Paper presented by the U.S. Department of Energy (U.S. DOE, 2010), the PV technology has improved markedly over the last decade, significantly reducing the cost of solar cell fabrication from USD ($) 8/W in the late 1990s for utility-scale systems to below $3.50/W in 2010 in the United States. The installation costs for Europe ($5.00/W), China ($4.42/W), and Japan ($5.02/W) are comparable to those in the United States for utility-scale projects, although it is generally more expensive for smaller scale residential applications (Branker et al., 2011). According to Razykov et al. (2011), the PV market is dominated (>40%) by grid-connected residential systems at present. Module prices are in the range of $3.0–4.5/peak watt (system prices $5–7/W). The U.S. DOE forecasts that the cost of solar energy will be reduced to $0.06/kWh for utility, $0.08/kWh for commercial, and $0.10/kWh for residential applications by 2015 (Razykov et al., 2011). This should encourage many other countries to supplement their energy needs with solar energy-based electricity generation (Dincer, 2011; Solangi et al., 2011; Wang and Qiu, 2009; Tour et al., 2011; Liou, 2010). The European Photovoltaic Industry Association (EPIA) predicted that by 2040, PV energy might contribute up to 14% of the world’s electricity need (Marwede and Reller, 2012).

The world’s PV installed capacity has increased rapidly over the last 15 years. The total world production of PV modules produced was equivalent to 7.3 GW in 2009 according to McDonald and Pearce (2010), on par with 7.437 GW predicted in other studies (Shiue and Lin, 2012; EPIA, 2012). China and Taiwan have been the main producers of modules, accounting for more than 49% of all manufactured PV cells since 2009. China produced more than 3.5 GW in 2009, while Taiwan’s production reached nearly 1.5 GW in the same year (Bio Intelligence Service, 2011). Most of this production has been exported to Germany and other countries in the EU. However, the projected

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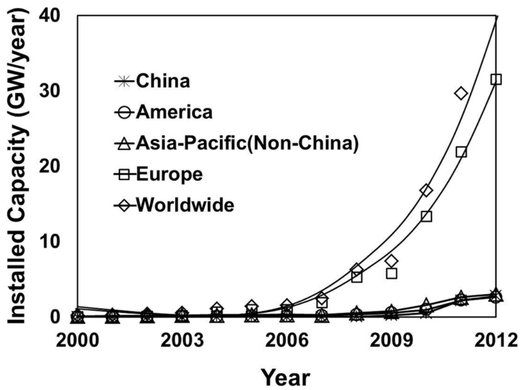

Figure 1. Solar energy installed—yearly capacity (data from EPIA, 2012). Europe has 27 countries using solar energy, with Germany and Italy as leaders. and Asia-Pacific (non-China) includes Japan, Australia, Korea, and India.

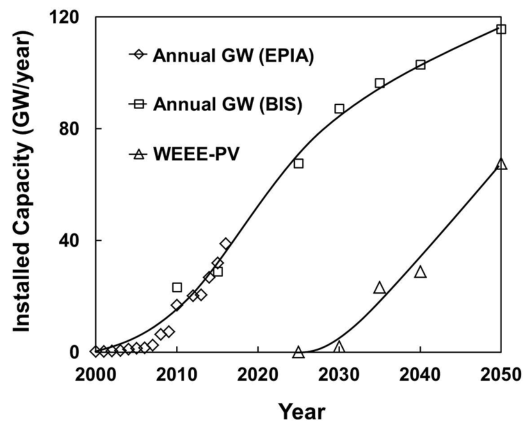

Figure 2. Long-range forecast of annual installed capacity and waste generated (PV under EU's WEEE classification). Data from EPIA (2012) and Bio Intelligence Service (2011).

use of solar energy would rise significantly over the next two decades in the main markets (Germany and Italy as leaders in EU, the United States, Japan, and China) as shown in Figure 1. These data seem to fit well with those collected by the European Association for Recycling of PV Modules (PV Cycle), formed by companies representing 90% of solar cell production/use in Europe (PV Cycle, 2011). By the end of 2011, the yearly installation of PV had reached nearly 30 GW. The new installations are projected to increase annually by 25% to 2020, then 12.5% yearly to 2025, then 9.5% to 2030 (Bio Intelligence Service, 2011).

Although this represents significant amounts of PV modules to be installed in the future, and consequently, wastes generated by the industry, there is a lag of time for the end-of-life decommissioning of PV modules. Most experts believe that the installed PV modules would last for a minimum of 25 years, although some predicted shorter life spans of 20 years (Zuser and Rechberger, 2011). There is no doubt that solar energy has expanded rapidly due to the acceptance by the public. However, public concern over the handling of metallic wastes such as Cd, Se, Pb, and others used in PV modules is growing, which prompted the industry and government to look at their safe disposal or recycling in the future. As an example, the EU (Neidlein, 2012) has issued a directive, which will be enforced by laws in all member countries, to implement protocols for the collection and recycling of PV panels by their suppliers. PV modules are now classified as electrical and electronic equipment (WEEE) and have to be collected by suppliers at their end of life. Recycling of PV modules for recovering metal values and at the same time minimizing the wastes generated has become a major concern now for the solar energy industry. Figure 2 shows the rapid expansion of the current annual new installed capacity (23.28 GW in 2010) to the projected 103 GW within 20 yr (to 2040), according to the forecast by EU agencies (Bio Intelligence Service, 2011; EPIA, 2012). The WEEE-PV waste has already been collected and accumulated, to be treated in the future when its tonnage warrants economic viability.

Another issue related to waste minimization and Si recovery worth considering is the processing of kerf loss slurry. During the cutting of Si ingots for the production of Si wafers, 30–40% of Si is lost. The separation and recovery of high-purity Si from SiC and other sawing materials has been recently evaluated (Tomono et al., 2012; Wang et al., 2012; Tsai, 2011a, 2011b). The recovery of high-purity Si from kerf loss is as attractive as PV module recycling, as close to 50% of this metal is lost during wafer production.

This paper evaluates the key issues related to PV recycling, aiming to reflect the scenario that the world and in particular, the Korean solar energy industry will face in the future. Emphasis is placed on the estimation of metal value that can be recovered from Si-based modules. Tests were conducted to confirm the leachability of all metal dopants using chemicals and to determine the grade of Si that can be recovered from acid etching and purification smelting.

Critical Evaluation of Photovoltaic Waste Recycling

The industry has recognized two major factors that affect the recycling of PV modules in the years to come. Of utmost concern are environmental issues due to the generation of waste and old modules (which since 2012 are classified as WEEE by the EU and have to be collected by suppliers at end of life) due to contamination of Cd, Pb, and so on. The potential shortage of raw materials has also drawn a great deal of attention by the industry. According to experts, recycling of PV modules is not viable at the present time due to the fact that the volume of wastes generated is still too small to be economically viable for recycling. However, by 2030, the waste generated from PV modules is expected to reach over 130,000 tpa, the level that is sustainable for its recycling, according to the European Association for the Recovery of PV Modules (PV Cycle, 2011).

Value of contained metals in PV modules

The PV technology has advanced rapidly using silicon and other metals that are rare or produced in small quantities (Paridaa et al., 2011). The recycling of thin-film PV modules based on CdTe and CIGS (copper, indium, gallium, germanium, and selenium) is considered worthwhile to recover high-value metals used, as they have been produced only in small quantities annually (<2,000 tpa for Se, <600 tpa for In, and <150 tpa for Te), according to Berger et al. (2010). The market for both of these thin film types is expected to grow from <5% now to 25% after 2020 (Bio Intelligence Service, 2011) and 50% by 2040 (Zuser and Reshberger, 2011). However, the production of crystalline silicon-based (c-Si) PV modules has been dominant (>90% of the market) for more than a decade due to their lower cost and higher efficiency (EPIA, 2012; Kang et al., 2012). It is safe to assume that in the period 2030–2050 the metals that will be recovered from PV module recycling are predominantly Si, Ag, Cu, and Al; all are metal components of crystalline (c-Si) solar cells.

The raw material cost, mainly of Si for (c-Si) PV modules, can be estimated from the quantity used for producing each peak watt of solar energy. The Advanced Research Projects Agency of the U.S. Department of Energy summarized the cost component for making 1 W of solar energy in its White Paper reported at a workshop in Washington, DC (U.S. Department of Energy, 2010). According to this report, although there is a push to reduce the cost of 1 W of solar energy to \$1.00/W by 2017, the production cost as of 2010 was \$1.70/E, of which the chemicals and metals were the main contributors to the raw material components (Si, Cu, Al, dopants, chemicals), estimated at \$0.54/W.

Based on the world production of solar energy at 12 GW in 2010 (Figure 1), the cost for Si raw material, dopants, and chemicals (\$0.54/W $\times$ 12 $\times$ 10^9 W/yr) could easily reach \$6.5 billion. With the target of 85% of PV wastes to be recycled from now on as set by the EU (Neidlein, 2012; Bio Intelligence Service, 2011), this represents a major resource of Si and other rare metals that should be recovered in the future.

Table 1 gives the breakdown of all metals used in the production of crystalline (c-Si) and amorphous (a-Si) PV modules, the two major types produced over the last 15 years. It can be easily recognized that the greatest potential for metal recovery is from (c-Si) PV modules, as they contain more metal value compared to other thin film types. From data summarized in Table 1 and the current (2012) metal prices, these major metal components (Si, Cu, Al, and Ag) contribute to a value of \$126.54/kW if 4N Si is used in the fabrication process. All metal values, of which Si represents the highest contribution, therefore constitute ~25% of the raw material and chemical cost of \$0.54/W reported by the U.S. DOE (2010) for (c-Si) PV modules.

It is worth noted that the high-purity Si (4N–5N) used for producing wafers is ~9 tonne/MW (Shiue and Lin, 2012), although only ~3.07 tonne/MW ends up in the PV modules, as shown in Table 1. This indicates that a significant amount of Si is lost due to breakage or attrition during cutting and fabrication, and this can also be recycled in the same recycling plant in the future. In this respect, the loss of high-purity Si to sawing waste (containing SiC) and so on during wafer production could be 40% of the starting material. The processing of the resulting kerf loss from wafer fabrication has also been a topic of much research lately (Wang et al., 2012; Tomono et al., 2012; Tsai, 2011a, 2011b; Lin et al., 2010).

The EU is aiming to collect and recycle 85% of end-of-life PVs. Combining this with standard total metal process recoveries from primary or secondary resources (at 80–90%), it is expected that 70–75% of the metal value (\$126/kW for 4N-c-Si PV) from PV wastes could be recovered. This represents a minimum recovered metal value of \$95/kW PV-energy produced at the 2012 4N Si metal price.

Figure 3 shows the world installation of PV energy, yearly from 2000 to 2011 with projected expansion into 2016 (EPIA, 2012). The cumulative installed capacity up to 2016 has reached 274.19 GW, representing a metal value of \$26.05 billion (based on the existing metal value of \$95/kW at 2012 for 4N Si prices estimated earlier).

Supply of raw materials and potential for metal recovery from PV waste

Marwede and Reller (2012) predicted that the industry has to rely on all Te recycled by 2038 to meet its need of new thin-film CdTe installations. Zuser and Rechberger (2011) proposed a model to predict the utilization of all metals in the fabrication

Table 1. Types of metals that can be recovered from PV modules

Materials recovered	Price, USD/kg	kg/MW (for c-Si)	kg/MW (for a-Si)	Types of PV panels
Aluminum (Al)	2.252+	10,700	100	Mainly c-Si
Copper (Cu)	8.034^	583		c-Si
Silicon (Si)	30.119–77.429*	3,069	18	c-Si or a-Si
Silver (Ag)	1,043	5.115		c-Si
Indium (In)	500	300	900**	a-Si, CIS, CIGS
Gallium (Ga)	300			CIGS, CPV and emerging technologies
Germanium (Ge)	1,600		Counted above with indium	a-Si, CPV and emerging technologies

Notes: Data from Table 38, 39, and 44 of Report by Bio Intelligence Service (2011). Prices for In, Ga, and Ge are from the website: http://www.minormetals.com. Others are from USGS Mineral Industry Survey (2012, accessed 8 November 2013). +Aluminium price in the United States, average first 8 months of 2013 at 100.54 U.S. cents per pound. ^Copper price in the United States, average first 7 months of 2013, at 303.57 U.S. cents per pound. *Average price of \$30,119/tonne for 99.99% (4N) Si (exported from the United States) for the first 5 months of 2013. **Counted for indium and germanium in a-Si PV modules.

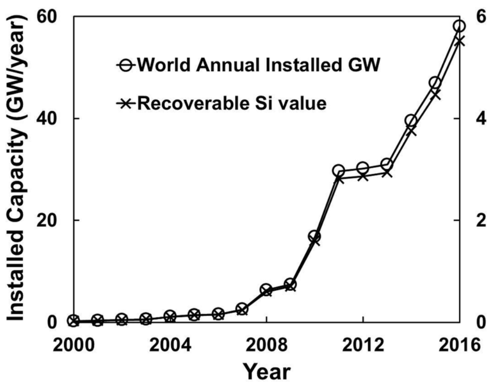

Figure 3. Annual PV installed capacity worldwide and recoverable metal value (based on 2012 average metal prices).

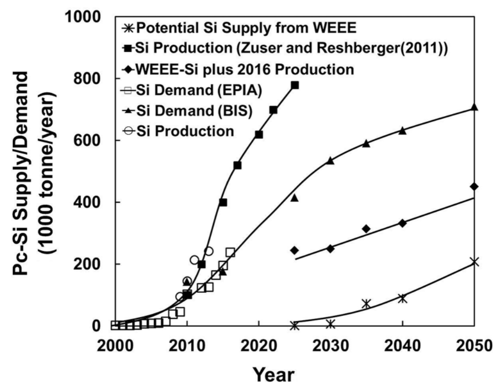

Figure 5. Long-term demand and supply for c-Si from EU's WEEE-PV recycling and current/short-term Si production from mineral resources.

of PV modules in the period 2010–2040. For non-Si thin-film PV, apart from Te, other metals required (Cd, Cu, In, Ga, Se) seem to be of adequate supply to meet the demand. However for both c-Si and a-Si PVs the "realistic" prediction for maximum Si demand reaches 445,543 tonne/yr by 2040, which should be mostly met by recycled Si.

The short-term forecast for the Si demand and supply until 2016 can be determined from published data. Using the figures reported by Bio Intelligence Service (2011) on behalf of the EU (summarized in Table 1), the requirement for (c-Si) PV modules is 3.069 tonne Si/MW installed. The forecast of polycrystalline Si demand for 2016 as shown in Figure 4 would reach 178,000 tonne Si/yr, corresponding to an annual installation of 58.04 GW capacity. The supply of polycrystalline Si at this stage, as tabulated by the U.S. Geological Survey (USGS) in its "Mineral Yearbook for Si" (2010), shows more than twice the amount contained in c-Si PV cells up to then. Taking into account the kerf loss (at 30–40%) and breakage of Si wafers/cells during production at maximum 50% (Tomono et al., 2012; Wang et al., 2012; Tsai, 2011a, 2011b; Lin et al., 2010), the demand for

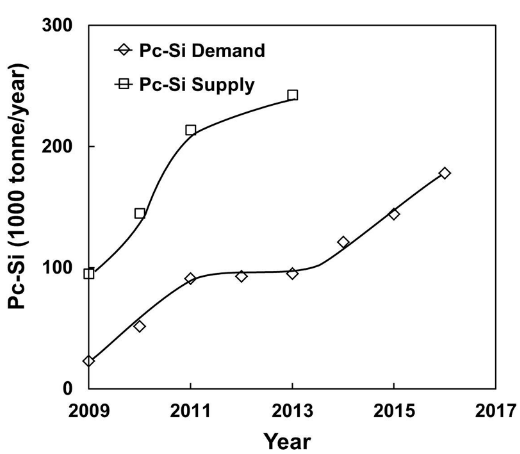

Figure 4. Short-term supply and demand for polycrystalline Si until 2016 calculated from data from Bio Intelligence SErvie (2011) Report for the EU and supply data from USGS (2010) Mineral Yearbook for Si.

polycrystalline Si up to 2016 should be easily met. According to the USGS Mineral Industry Survey (USGS, 2012), the resources for Si (high purity silica) are abundant around the world and the supply for Si should be more than adequate to meet the demand for all types of Si. The increasing cost of production, if any, for c-Si is the only concern for the industry. At the present stage, there seems to be a surplus of high-purity polysilicon (7N–9N) used for the fabrication of PV cells, which leads to the significant price drop lately (Wicht, 2012; Glenn, 2012).

Based on the current and future installation forecast by EPIA (2012) and Bio Intelligence Service on behalf of the EU (2011), the long-term demand for c-Si is plotted in Figure 5, together with the potential supply from end-of-life WEEE-PV modules targeted in the EU and the total Si production. The demand for Si is based on twice the contained c-Si in PV modules (2×3.069 tonne/MW), counting 50% kerf loss and breakage during wafer fabrication. Results are also tabulated in Table 2 for current and projected demand of c-Si and its supply from mine production and recycled PV.

It should also be of top priority to develop new technology now for the separation and recovery of high purity c-Si from SiC, grinding material, and so on in the kerf loss (40%), rather than waiting for the recycled PV modules to build up to a significant level from 2030 onward.

The PV industry in Korea, however, is modest, compared to those reported earlier in this paper. Data from the Korea Photovoltaic Industry Association (2012) are plotted in Figure 6, showing less than 200 MW of PV panels has been installed yearly since 2007, except for 2008, which saw the installation peak at 273 MW. In the short-term projection until 2016, Korea would only install 200–280 MW/yr. The total solar cell production capacity reached a level as high as 1.3 GW/yr in 2010, but most of this has been exported. The outlook for the solar energy industry is encouraging with the government's announcement that from 2015, the country would investment USD20 billion to expand the use of PV in Korea (KOPIA, 2012).

The recycling of PV modules in Korea has a potential to recover only \$25–30 million/yr of metal values contained from 2030 onward (at \$95,000/MW using 4N Si feed and

Table 2. Current and projected long-term demand and supply (tonnes per year) of c-Si from EU's WEEE-PV recycling and current/short term production. Data from EPIA-2012 and Bio Intelligence Service (2011)

Year	(c-Si in PV), tonnes/yr	Production, tonnes/yr	Poly-Si demand(*)	Recycled, tonnes/yr	Shortfall, tonnes/yr	Note
2009	45,648	95,000				
2010	103,222	145,000				
2011	115,000	213,600	205,000			
2012			196,000			
2013	126,166	242,600				
2021	184,133	—			120,000	Shortfall: 2 × (184,133–126,166), requiring new Si ingot plants
2025	414,370	—		576	177,191	Shortfall increases slowly until its peak from about 2040.
2030	535,921	—		6239	287,082	
2040	632,527	—		88,595	301,331	
2050	709,890	—		207,685	259,605	

Notes: Data from EPIA-2012 and Bio Intelligence Service (2011).

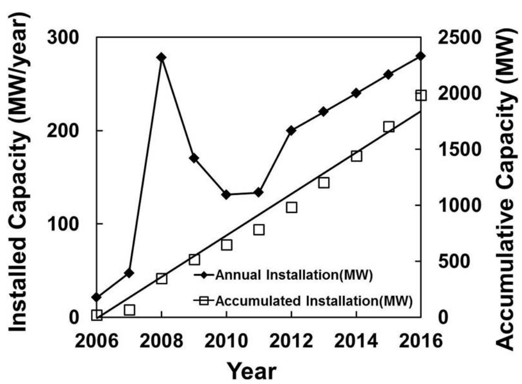

Figure 6. Annual installed capacity in Korea (data from EPIA, 2012).

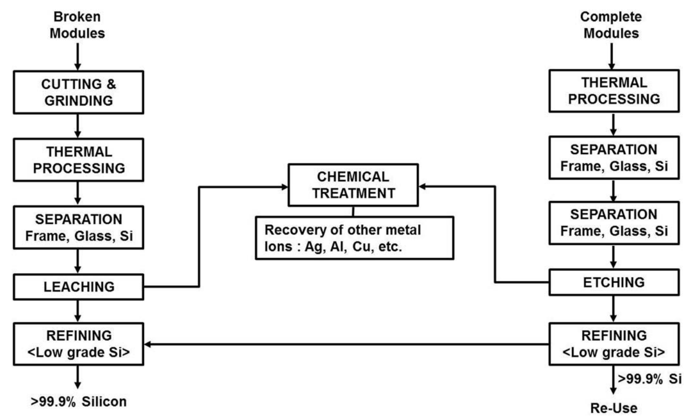

Figure 7. Typical process adopted for recycling Si modules incorporating thermal treatment to remove the ancillary materials before chemical treatment.

annual installation of 250–300 MW) unless there is a significant expansion of solar energy application in the next decade. No cost is yet anticipated at this stage for the recovery of this described metal value until a proven recycling process flow sheet is determined.

Proposed PV module recycling processes

There are several processes currently being developed to recover valuable metal components from PV wastes (Berger et al., 2010; Kang et al., 2012; Klugmann-Radziemska et al., 2010; Klugmann-Radziemska and Ostrowski, 2010). Several process steps need to be incorporated to separate the metal frame, back sheet, EVA resins, and the protective tempered glass sheet before the PV modules can be recovered. These modules are then subjected to chemical leaching to produce >99% Si for recycling. A typical flow sheet for Si module recycling is shown in Figure 7.

Experimental Procedures

The materials tested were collected from Symphony Solar (Korea) as broken PV cells that have been manually dismantled from their modules at the plant. The separation of frame–glass–Si wafers was completed at the plant and is not the focus of this research. Both monocrystalline Si and polycrystalline Si cells were tested. All copper wiring to the cells was cut off but the conducting strips were left "as-is" for treatment. All cells were crushed to pieces of 1–2 cm^2 before weighed samples were subjected to leaching tests. The Si content of the original material was assayed in the range of 97–98% Si.

As crushed pieces of Si cells were used for the leaching tests, they could not be suspended properly for effective leaching. An ultrasonic bath (KODO, model NXP-5030) was therefore used to create microstirring and to promote the leaching of doped metal ions such as Ag, Al, Cu, and others and the conducting strips from the cell material. Self-heating of the solution by ultrasound raised the temperature to 40°C in most cases, providing also favorable conditions for leaching. Known weight samples were added to the leachants (1–3 *M* HCl or H_2SO_4 or HNO_3 and NaOH) at a weight ratio for solid/leachant of 1:5 and leached for 2 hr. Leached solution samples (2 mL) were taken to determine the percentage of metal recovered by mass balance calculations. Solutions were analyzed for metal concentrations using inductively coupled plasma–mass spectroscopy (ICP-MS; Agilent 5500). In some cases, leached material was also subjected to scanning electron microscopy (SEM) with energy-dispersive spectroscopy (EDS) analysis to check the composition of the Si surface and more. For the smelting tests, acid-leached Si cells were then ground and mixed with a ($CaO + CaF_2 + SiO_2$) mixture at a Si cell/slag mixture weight ratio of 5:1, 7:1, and 10:1 and melted at 1520°C for 6 hr. The slag mixture was prepared with equal weights of CaO, CaF, and SiO_2.

Results and Discussion

Leaching/etching of metal ions from Si cells

In this study the etching and/or leaching of metal additives from broken Si cells was conducted in batches to optimize the conditions for high-purity Si recovery. Broken PV wafers were subjected to leaching at 20–40°C, using either hydrochloric, sulfuric and nitric acid, or caustic NaOH, under ultrasonic treatment to enhance the leaching rate. The concentration of the acids used was varied from 1 to 3 *M* and treatment time was within 2 hr. The results for these leaching tests are summarized in Figures 8 and 9, showing the effect of time and acid concentration, respectively, for different types of leachants. Only typical results for Ag and Al additives for both single-crystal and poly-crystal Si cells are shown, as the other components were also mostly removed. The removal (%) of a metal was calculated from the available mass in the original sample used and the metal content in the leached solution.

The chemical etching/leaching of metals with nitric acid (oxidizing acid) can be represented by the chemical equation

$$\mathrm{Ag(or\ Al)} + 2\mathrm{H}^+ + \mathrm{NO}_3^- \rightarrow \mathrm{Ag}^+(\mathrm{or\ Al}^{3+}) + \mathrm{NO}_2 + \mathrm{H_2O} \qquad (1)$$

Both sulfuric acid and hydrochloric acid are not effective for Ag dissolution due to formation of insoluble salts of silver sulfate or chloride. As later shown in the Stabcal modeling and SEM analysis, Al could only be fully dissolved with NaOH after acid leaching due to possible formation of Al–Si compounds during acid treatment.

The use of nitric acid as an oxidizing acid is more effective in dissolving most metals, including silver. The etching efficiency increases with concentration of the acid used for Al extraction, whereas nitric acid leaching only partly removes aluminum, which requires a subsequent treatment with NaOH. The chemical etching process would yield up to 99.98% Si after treatment typically, as shown in Table 3.

The chemical leaching could produce 3N Si as shown in Table 3, although the treatment could remove critical components of P and B to less than the specification for 5N Si ingots (<5 mg/kg P and <3 mg/kg B; Symphony Silicon Ltd, Korea). However, the total metal content is still higher than specification (<2 mg/kg total metal) for 5N Si.

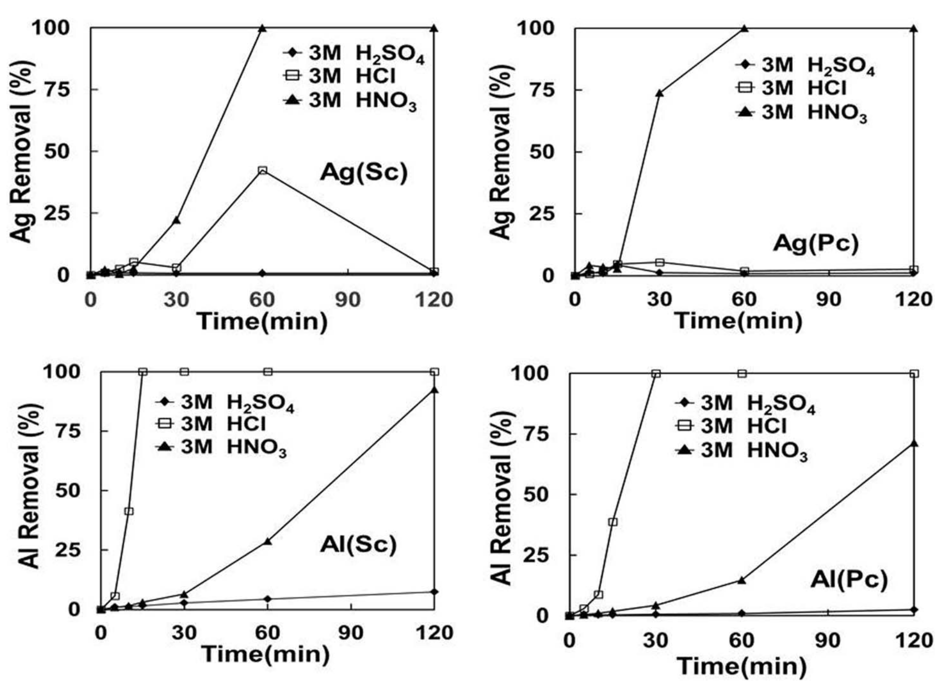

Figure 8. Effect of time on acid leaching of Al and Ag for both single-crystal (Sc) and poly-crystal (Pc) Si modules.

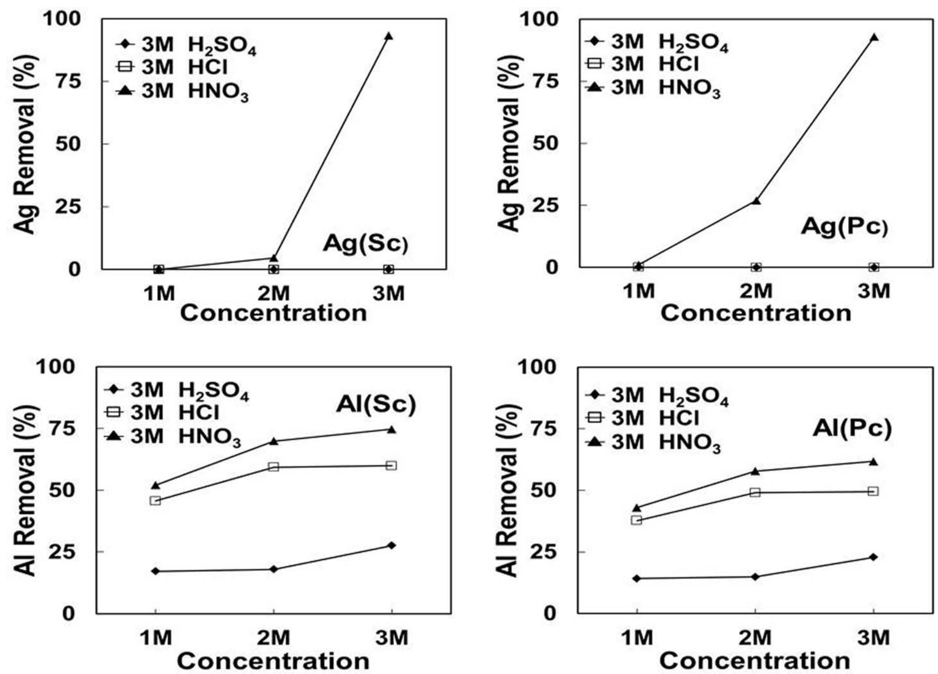

Figure 9. Effect of concentration of different acids (HNO_3, H_2SO_4, and HCl) on the extraction of Al and Ag.

Table 3. Composition of Si wafers before and after chemical treatment using 3 *M* nitric acid and 3 *M* sodium hydroxide (all are in mg/kg except Si)

	Single-crystal type		Poly-crystal type	
Element	Before	After	Before	After
Ag	11920	4.23	5659	21.97
Al	8070	162.5	8733	137
B	21.68	0.31	25.29	0.5
Ca	0.04	1.12	0.04	1.02
Cr	1.46	0.05	1.38	0.04
Cu	18.06	0.07	2.57	0.11
Fe	44.72	0.68	35.45	0.8
Li	0.4	0.07	5.13	0.03
Mg	0.04	0.47	0.05	0.33
Na	0.54	62.50	10.32	40.4
Ni	2.23	0.14	0.97	0.35
p	78.5	<0.1	29.01	3.41
Sn	0.31	0.04	1147	<0.01
Ti	10110	0.25	4439	0.35
Zn	274	0.21	87.1	0.17
Si (%)	96.94	99.98	97.98	99.98

Smelting with ($CaO + CaF + SiO_2$) slag mixture

A subsequent pyrometallurgical treatment using a ($CaO + CaF + SiO_2$) slag mixture to scavenge residual metals or metal oxide remaining in the Si material was also found effective in removing residual metal additives. The addition of this slag mixture corresponded to 5:1, 7:1, and 10:1 weight ratio with respect to the acid-leached Si material (containing minimum 3N Si). The smelting at 1520°C for 6 hr of the acid-leached Si and the slag mixture would yield >99.998% Si final product. This smelting step is believed to also remove residual SiO_2 from the oxidation of Si when nitric acid is used. Typical compositions of Si materials before and after pyrometallurgical treatment are shown in Table 4.

SEM-EDS analysis of the front and back of random samples of polycrystalline and single-crystalline cells (before and after chemical treatment) shows elements detected as shown in Table 5. Areas (A–G) correspond to the SEM images presented in Figure 10.

The SEM-EDS analysis confirms the process chemistry, which needs to be understood before the leaching scheme was devised. As shown before in Figures 8 and 9, HCl and H_2SO_4 are not effective in dissolving precious metals (Ag), and HNO_3 as oxidizing acid is more suitable for leaching. In this respect, chemical speciation modeling based on Stabcal (Huang, 2008), which has been used effectively in predicting metal dissolution and precipitation characteristics (An et al., 2012), was carried out to also confirm the chemical leaching of Si cells. Simulation of conditions where 100 g of Si cells (front and back Al-SiN and Ag-Al-Si materials) was leached in 500 mL of leachant shows stability of various Si, Ag, and species at different pH values in the pH range 0–14 (Figure 11). The results indicate that most critical to the dissolution processes is the use of caustic NaOH to dissolve Al, as solid $Al_2SiO_7{\cdot}H_2O$ could be formed at low pH to passivate the dissolution process. The use of NaOH in the

Table 4. Compositions of materials before and after pyrometallurgical treatment at different $CaO–CaF_2–SiO_2$ slag mixture/Si cell ratios (all are in mg/kg except Si)

Element	Starting material	5:1	7:1	10:1
B	0.5	0.41	0.46	0.55
P	3.41	1.36	1.41	2.59
Al	92	1.58	0.56	6.79
Ca	1.02	0.15	0.3	0.37
Fe	0.8	0.22	0.2	0.16
Ag	82	1.35	0.77	4.68
Cu	16	0.07	0.09	0.10
Ti	21	0.19	0.15	0.25
Cr	0.04	0.01	0.04	0.02
Sn	0.03	0.02	0.03	0.01
Li	0.03	0.01	0.02	0.02
Mg	0.33	0.3	0.05	0.02
Na	40	1.25	0.09	0.49
Ni	0.35	0.03	0.02	0.03
Zn	0.17	0.03	0.04	0.29
Si (%)	99.9741	99.9988	99.9996	99.9983

Table 5. Composition (%) of different areas of Figure 10 determined by SEM-EDs

Poly-crystalline Si cell		Area	O	Si	Ag	N	Al
	Before etching	A	8.16	2.50	86.9		2.41
		B	14.12	85.88			
	After HNO_3 etching	C	2.38	79.47		18.15	
Front	After NaOH etching	D		100			
	Before etching	E	7.68	26.6			65.7
Back	After HNO_3 etching	F	3.38	95.44			1.19
	After NaOH etching	G		100			
Single-crystalline Si cell		Area	O	Si	Ag	N	Al
	Before etching	A	9.30	2.47	88.22		—
		B	13.39	85.25	1.36		—
Front	After HNO_3 etching	C	16.28	80.76	0.8		
	After NaOH etching	D		100			
	Before etching	E	11.27	19.01			69.72
Back	After HNO_3 etching	F	25.1	68.84			6.06
	After NaOH etching	G		100			<0.01

second stage of leaching also removes SiO_2 coating, as most should be solubilized at high pH. This finding allows caustic to be effectively used to dissolve antireflection coating materials (SiO_2 and silicon nitride) and avoids toxic HF being used in the leaching process for such a task.

Outotec's HSC (HSC Chemistry, n.d.) software was used to predict the processes of removing residual impurities from the acid-treated Si by smelting with a (CaO + CaF + SiO_2) slag mixture. Typical results (CaO + CaF + SiO_2)/Si mass ratio 10:1 are shown in Figure 12 for major impurities left in the treated Si (Ti, Ag, Al). At the smelting temperature 1500–1600°C, Ti would be incorporated into the slag as Ca-titanate or TiO_2. For Al, apart from aluminum silicate, which would be transferred to the slag form, an AlF_3 gas phase is predicted. The gaseous phase also contains Ag(g) and other fluorides of Ag, Na, Al, and Si. The smelting process therefore has to incorporate a fluoride treatment step to handle this gas emission.

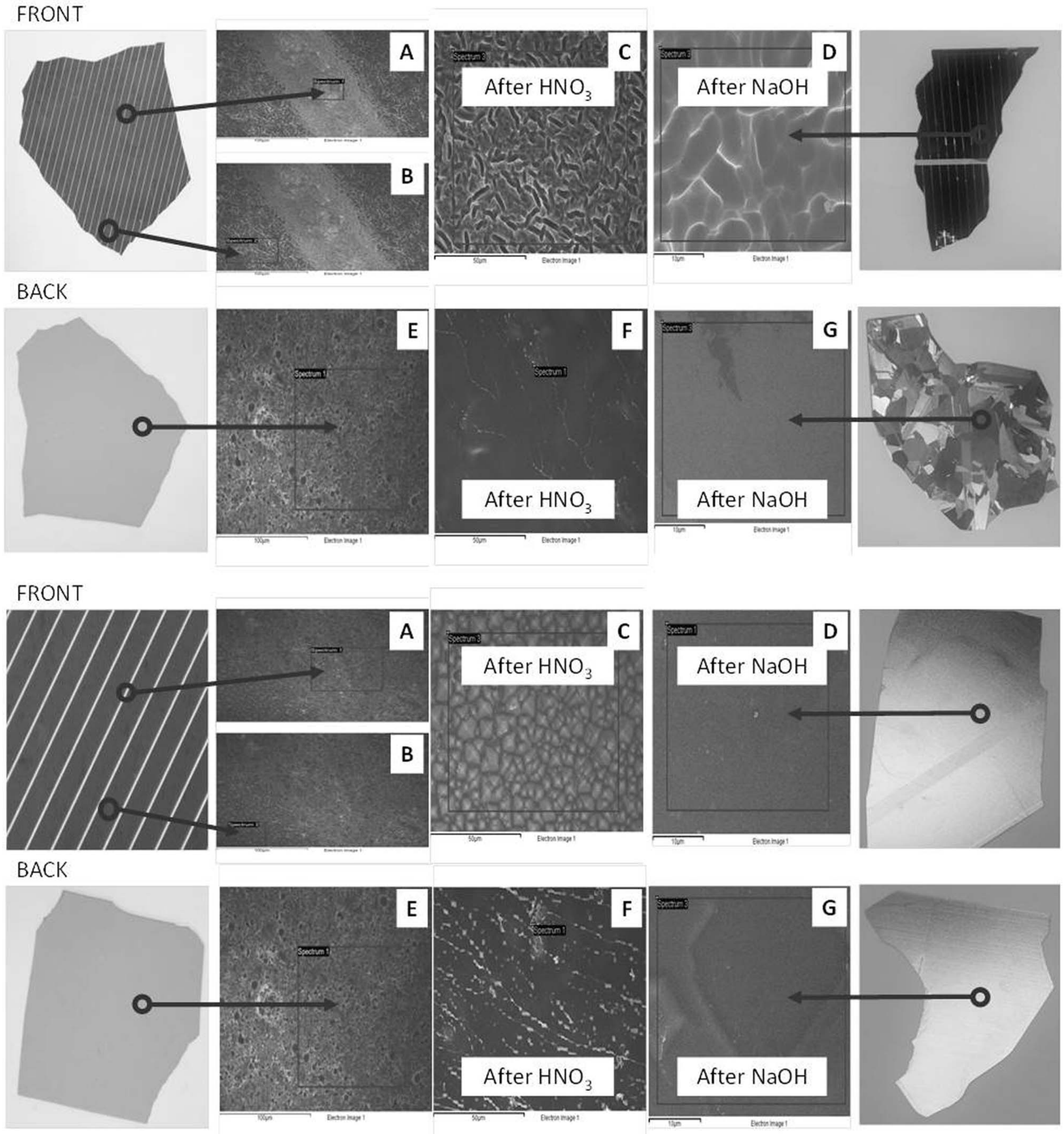

Figure 10. SEM-EDS analysis of a polycrystalline (top) and monocrystalline (bottom) Si cell samples.

Conclusions

It is technically feasible to recycle PV modules to recover Si, the main and most costly component of crystalline-Si cells. Si cells could be first leached in nitric acid, then caustic sodium hydroxide. Although nitric acid (initial 3 *M*) could remove all Ag, it cannot completely remove Al or N. Subsequent leaching in NaOH would remove N and Al completely to yield 99% Si. Subsequent smelting of the (HNO_3 + NaOH)-treated materials at 1520°C with CaO–CaF_2–SiO_2 is used to scavenge all metal impurities to produce >99.998% Si.

Although the cost benefit of recycling depends also on other aspects of recycling, including collection and sorting, to separate the Si cells from other ancillaries, recycling of PV modules is necessary to fit in with the regulatory requirements of several countries around the world. The industry should benefit from the corporate and social responsibility point of view by handling and

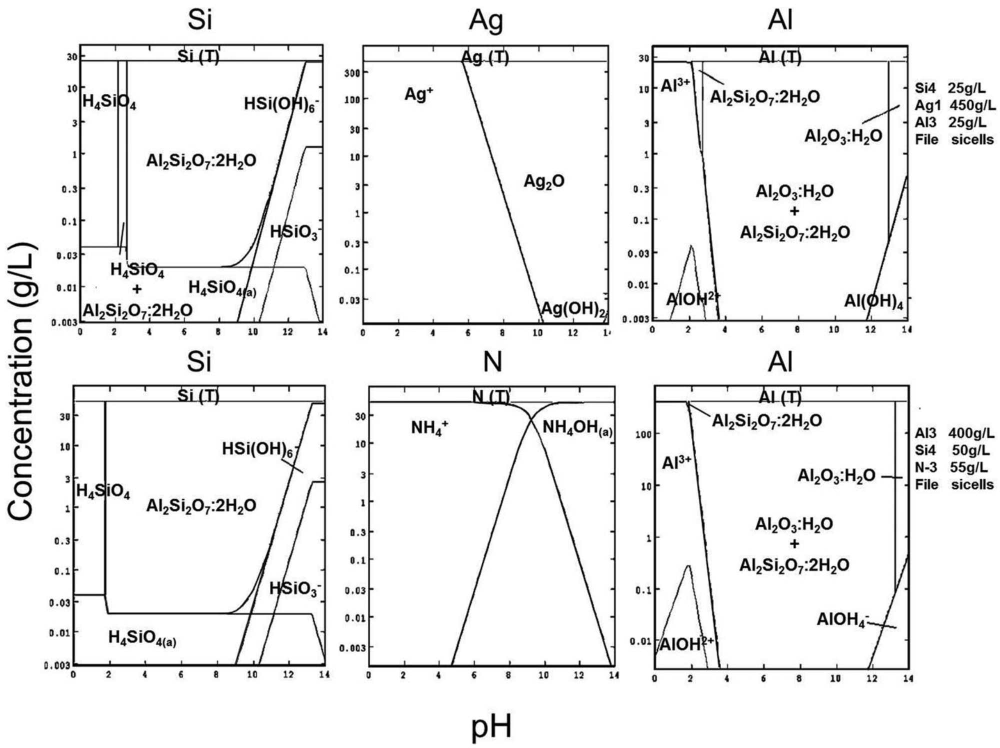

Figure 11. Stabcal speciation modelling showing the stability of different species formed during leaching (shaded area: solid species).

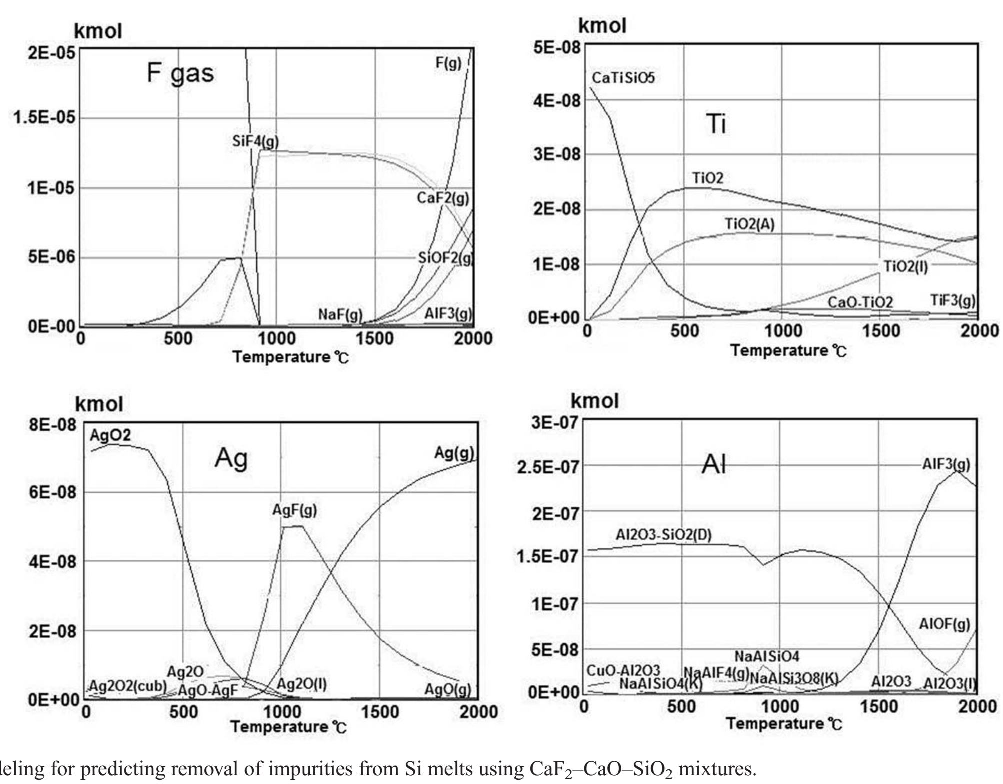

Figure 12. HSC modeling for predicting removal of impurities from Si melts using CaF_2–CaO–SiO_2 mixtures.

recycling its wastes in a way to fit in with the "green energy" image PV systems are presenting.

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Photovoltaic waste assessment of major photovoltaic installations in the United States of America

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A B S T R A C T

During the last decade, photovoltaic capacity in the United States has grown annually by 65% on average. Such rapid growth in capacity is naturally followed by an equally rapid growth of PV waste generation. This paper quantifies the future PV waste from the 69.7 GW reported as major PV projects (≥1 MW) in the U.S. at the end of 2015, including not only the modules but also the balance of system (BOS). Considering an average module lifetime of 30 years, 9.8 million metric tons (Mt) of PV waste are expected between 2030 and 2060. Of this, 6.6 Mt are PV modules, 2.7 Mt are BOS, 0.3 Mt are inverters, and 0.2 Mt are transformers. PV panel waste alone will grow from 1.3 Mt in 2040 to 5.5 Mt by 2050. The material value of metal in all PV installations is worth nearly 22 billion dollars, with aluminum, silicon, gold, steel, and copper making up 75% of the total value. It is estimated that 9.2 Mt of the metals contained in the PV systems can be recovered, including 1816 tons (t) of silver, 27 t of gold, 1073 t of gallium, 515 t of indium and 2010 t of tellurium.

1. Introduction

Photovoltaic (PV) deployments are currently increasing worldwide, partially due to their significant contribution to climate policy goals [1,2]. The United States has the potential of leading the global transition towards renewable energy, as it possesses some of the best wind, solar, geothermal, hydro, and biomass resources in the world according to the International Renewable Energy Agency (IRENA). The west and southwest regions of the United States have solar irradiance levels above 5 kWh/m^2 per day, which indicates that these regions are ideal to exploit solar energy. However, even the rest of the U.S. has solar resources that are above those from countries with high PV deployment, such as Germany (2.7–3.3 kWh/m^2 per day), Italy (3–5 kWh/m^2 per day), Japan (3–4.4 kWh/m^2 per day) and China (2.4–6.3 kWh/m^2 per day), meaning that PV energy can be exploited almost everywhere in the U.S.

In the last ten years, the U.S. has experienced an accelerated growth of PV deployment with an average annual growth rate of 65%. By the end of 2016, the cumulative installed capacity in the U.S. was 42 GW, making it the fourth largest PV market worldwide after China, Germany, and Japan [3]. Fig. 1 shows the installed U.S. PV capacity from 2000 to 2016 with projections until 2030. The curves from different sources all show exponential growth of PV technology since the year 2000. The Photovoltaic Power Systems Program (PVPS) of the International Energy Agency (IEA) has published annual trend reports of global PV market development; the IEA reported the U.S. cumulative PV capacity as 40 GW by the end of 2016 [4]. The data from the U.S. Solar Market Insight Reports published by the Solar Energy Industry Association (SEIA) and GTM Research matches with the data published by the IEA [5,6]. The data from SEIA and IEA is presented in Fig. 1, which includes all market segments nationwide (utility, residential and non-residential).

Utility-scale PV installations (>1MW_p capacity) are economically favorable in comparison to other models of PV deployments [8]. The scope of this study is a comprehensive list of all ground-mounted solar projects of 1 MW and above provided by SEIA (see Fig. 1). This list covers approximately 50% of all PV installations in the U.S. in 2016 and yields a total of 69.7 GW by 2030. The U.S. PV market growth in 2016 implies that PV could reach, or even exceed, the 135 GW of cumulative PV capacity (utility-scale and distributed) originally forecasted for the U.S. in the Roadmap 2030 for Renewable Energy Future (REmap) by IRENA [7]. This would also be approximately twice the amount of ground-mounted major installations that form the basis of this study.

The focus of this study is on major ground-mounted PV projects

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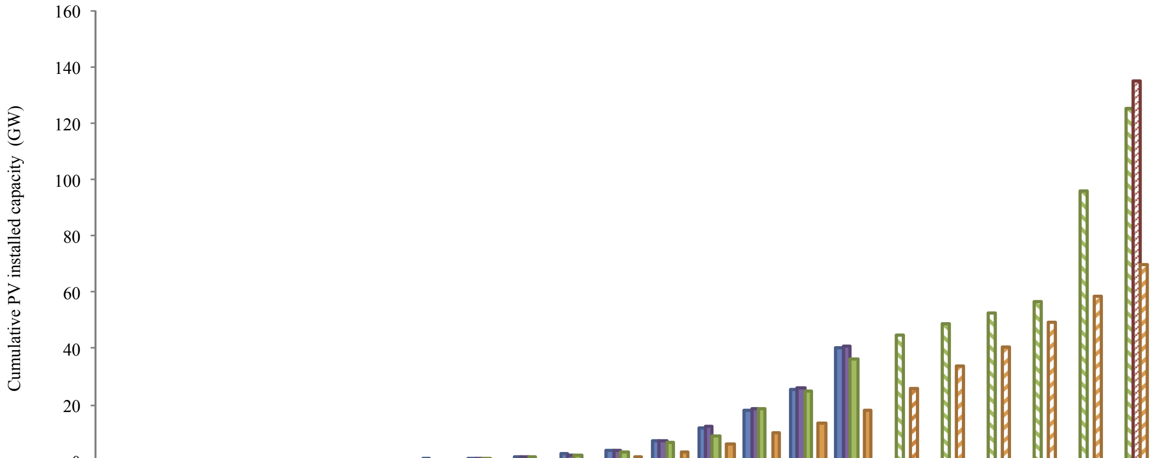


	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2025	2030
IEA [4]	0.14	0.17	0.21	0.27	0.4	0.5	0.6	0.8	1.2	1.6	2.5	3.9	7.2	12	18	26	40						
SEIA [5]	0.14	0.16	0.18	0.22	0.28	0.36	0.47	0.63	0.92	1.3	2.2	4.1	7.5	12.2	18.5	26	40.7						
US EIA [6]								0.5	0.8	1.5	2.3	3.5	6.5	9	19	25	36	45	49	53	57	96	125
IRENA REmap 2030 [7]																							135
This study					0.01	0.02	0.04	0.08	0.14	0.3	0.6	1.6	3	6.3	10	13.6	18.3	25.8	33.8	40.5	49.3	58.5	69.8

Fig. 1. Overview and projections of the PV installed capacity in the U.S.

(≥1 MW) in the United States. Another source of PV waste are rooftop installations; however, their assessment requires an estimate of the future growth of solar rooftop PV with suitable methodologies [9]. Installed PV capacity is the main input into the PV-waste model. Assuming a 30-year life span for modules and BOS (inverters, mounting structure and cabling) [10], high volumes of end-of-life (EOL) PV waste can be expected around 2030 from large-scale PV deployment in the U.S., which began around the year 2000. According to an end-of-life PV panel report by the IRENA and the IEA, the U.S. is expected to have the second largest cumulative waste of end-of-life PV panels by 2050, surpassed only by China (see Fig. 2) [3]. The report assesses two scenarios regarding cumulative waste of end-of-life PV panels worldwide: a regular-loss scenario and an early-loss scenario, which includes damage and failure before the 30-year average panel life span. It estimates that between 7.5 and 10 Mt of end-of-life PV panels will be generated by 2050 in the U.S. alone. In the regular-loss scenario, the model predicts an estimate of 170,000 t of end-of-life PV panels by 2030 and 1.7 Mt by 2040. The results of this study are benchmarked against the IRENA/IEA report, which presents the first projections for future PV panel waste volumes. The importance of developing PV-waste models to forecast end-of-life PV panel generation has been highlighted in previous studies, such as the PV-waste assessments conducted for Italy, Spain and Mexico [11–13]. There are four major differences between these previous analyses and the one presented in this paper: First, with the exception of the analysis of Mexico, previous models only account for PV modules; here, the BOS is included in the model, which represents 45% of the material contained in PV systems. Second, this study accounts for 21 metals, including critical metals (e.g. gallium, indium and tellurium), precious metals (e.g. gold), and toxic metals (e.g. cadmium and selenium). Previously conducted studies only assess four to six metals —aluminum, silicon, copper, silver, tin, lead and zinc, respectively. Third, this analysis includes an economic assessment of the metals contained in the PV system waste. Fourth, this study estimates the recoverability of raw materials through the

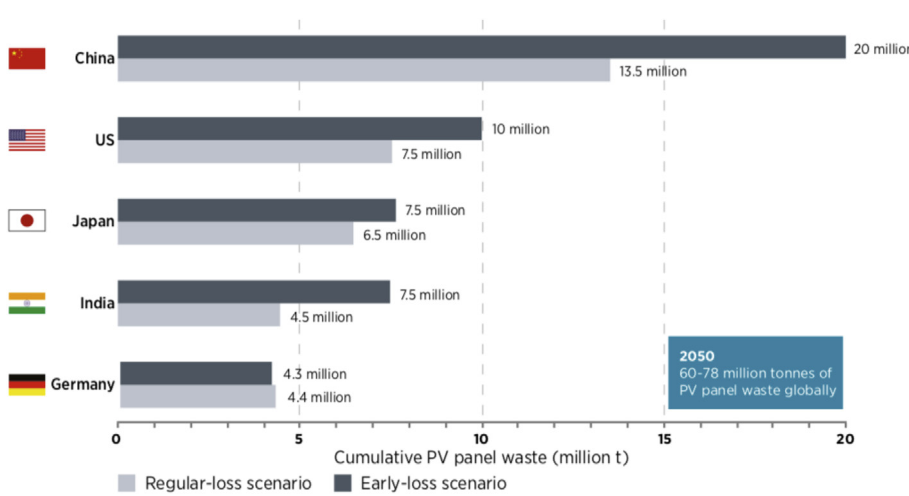


Fig. 2. Cumulative waste volumes of top five countries for end-of-life PV panels in 2050 [3].

integration of recycling yields.

The main objectives of this study are (1) to present a projection for future PV waste (module and BOS) in the U.S., derived from the 69.7 GW reported as major PV projects (≥1 MW) in the U.S. by the end of 2015 and (2) to estimate the amount and kind of materials that could be recovered from it. To achieve these objectives, the paper is structured according to Fig. 3. First, historical and future PV growth from 2000 to 2030 has been analyzed. Data from SEIA [14] is the main input to estimate future waste generation from end-of-life PV systems in the U.S. The resulting PV waste is quantified using the methodology summarized in Section 2. The methodology was first applied to the case of Mexico in a previous study, and it has been expanded for this study [8]. The model estimates the material amounts contained in PV installations, which will become PV waste, along with their economic value. Next, recycling yields of the metals contained in the PV systems were collected and applied to the PV-waste projections with the aim of obtaining the amount of metals that could be recovered from the PV waste. The effects of market share of PV technology, recycling yields, metal composition of transformers, use of tracking systems, and the reduction of silver content in c-Si PV modules were assessed through sensitivity analysis.

The main contributions of this work include: (1) overview and projections of the PV installed capacity in the U.S. based on four different sources, (2) a comprehensive methodology to estimate the metal inventory of PV waste (modules and BOS), including timing and location of waste generation, (3) an estimate of the metals that could be recovered from PV waste using an extensive list of recycling yields for metals, (4) an economic evaluation of PV waste, (5) identification and measurement of critical, precious and toxic metals found in PV systems, (6) a comparison of the U.S. production of critical metals with the amount contained in PV modules, (7) sensitivity of the metal inventory with respect to changes in PV technology market share (8) and an estimate of the cumulative PV waste volumes by 2040 and 2050 in the U.S.

2. Methodology to assess PV waste

An analysis of how much, when and where the PV systems will reach their end-of-life will help to plan for PV waste management. This section explains the PV-waste assessment methodology (see Fig. 4) and how it can be used to: (1) estimate the total metal inventory of PV installations that will become PV waste and (2) determine the amount of metals contained in the PV-waste projections that could be recovered. The PV-waste model is applied to U.S. PV installations (1 MW and above). However, this methodology can be applied to any set of PV installation data (e.g. regional, state

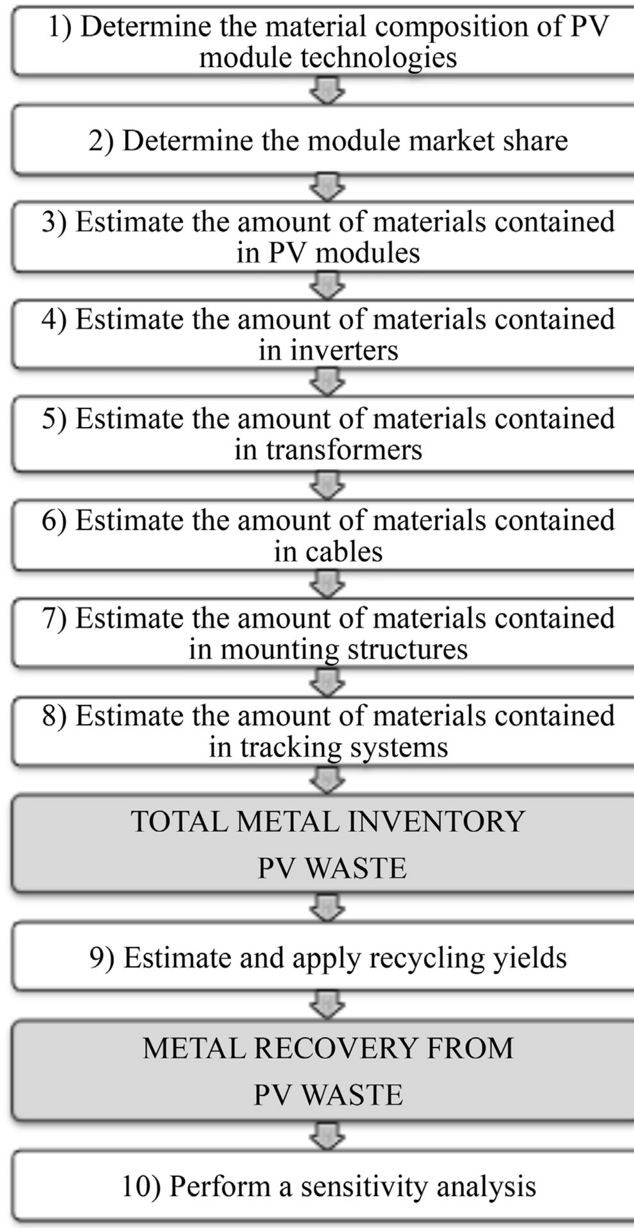


Fig. 4. Methodology to estimate PV waste.

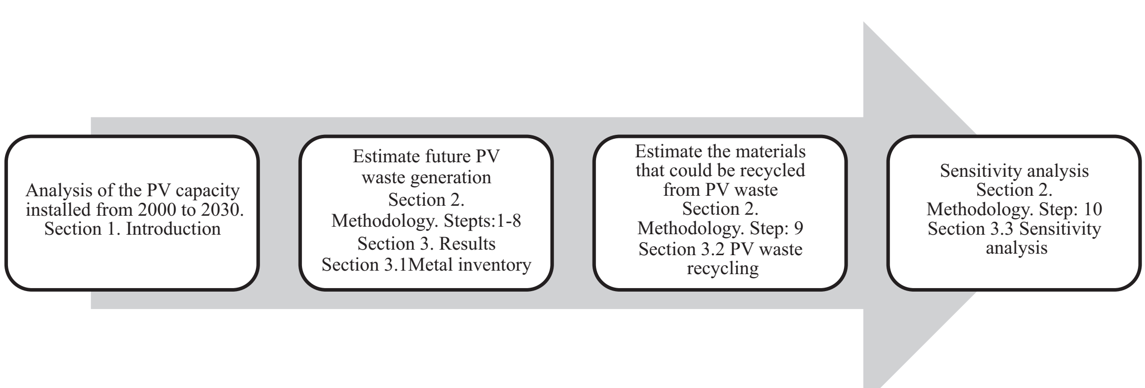


Fig. 3. Overview of the PV waste assessment in the U.S.

or nationwide) through the following ten steps.

1) *Determine the material composition of PV module technologies.* The first step to assess PV waste is to define the material composition of the PV installations under study (modules and BOS). The main material composition of the four different PV module technologies (c-Si, a-Si, CdTe and CIGS) analyzed in this study is presented in Table 1. Units are kg/m^2 of PV panel, unless indicated otherwise. Table 1 also includes the metal composition of the BOS (inverters, transformers, cabling and mounting). Extensive research on material contained in PV installations can be found in the previous study: PV waste assessment in Mexico [13]. Additional PV material composition data can be found in Refs. [3,15–20]. Since PV technologies are under continuous development, changes regarding the amount and type of materials contained in PV modules are expected. Hence, it is important to update the material composition as new technologies emerge.

Data on material content of the different PV module technologies as well as the BOS is mostly based on the Photovoltaics Report of the Swiss Centre for Life Cycle Inventories [24]. This report was used since it contains the most recent information about the production of different PV modules. Care has been taken to use material content rather than production input data. Furthermore, for each PV technology the resulting total module mass was calculated and benchmarked against the actual weight of commercial PV modules.

2) *Determine the module market share.* The second step is to determine the market share of the PV module technologies used on the PV installations analyzed. For the U.S., the market share used in this study is presented in Table 2. It is important to mention that the market share will vary by region and change over time.

In order to estimate the material inventory of the PV installations under study, it is necessary to estimate the amount of material contained in PV modules, inverters, transformers, cabling, mounting structures, and tracking systems. The method used to perform these estimates is presented in step 3 (for PV modules) and steps 4–8 (for the BOS).

3) *Estimate the amount of materials contained in PV modules.* The third step is to estimate the amount of material contained in PV modules based on the material composition presented in

Table 1
Main metal composition of PV systems. Units: kg/m^2 of PV panel.

Component	Precious metals	Base and special metals	Toxic/hazardous metals[a]	Other metals	Critical materials[b]
PV technology					
c-Si	Ag: 8.89E-03	Al: 2.54E+00 Cu: 1.13E-01 Fe: 1.47E+00	Pb: 7.20E-04	Si: 1.22E-01	Mg: 8.02E-02
a-Si		Al: 3.24E+00 Cu: 7.00E-02 Fe: 3.10E+00	Cd: 4.00E-04	Si: 2.00E-04	Mg: 1.02E-01 Te: 5.00E-04
CdTe		Al: 1.50E-02 Cu: 5.00E-01 Fe: 2.00E-01	Cd: 2.00E-02 Pb: 7.00E-04	Si: 5.00E-02	Te: 2.00E-02
CIGS		Al: 1.51E+00 Cu: 5.00E-02	Cd: 3.00E-02 Se: 1.00E-02		Mg: 4.70E-02 Ga: 1.00E-02 In: 5.00E-03
Inverter[c]	Ag: 0.37 Au: 0.51	Al: 131 Cu: 339 Fe: 1438 Zn: 0.4	Pb: 1.8		Mg: 0.01
Transformer[d]					
Copper winding		Fe: 0.63 Cu: 0.32			
Aluminum winding		Fe: 0.63 Al: 0.14			
Cabling		Cu: 0.64			
Mounting Structure		Al: 3.9 Zn: 0.27 Fe: 7.5			
Tracking system		Al: 4.29 Zn: 0.4 Fe: 11.25			

[a] According to the U.S. Environmental Protection Agency [21].
[b] According to the European Union's Critical raw materials and the U.S. Department of Energy's Critical Material Strategy [22,23].
[c] Units: kg/inverter.
[d] Units: kg/kg.

Table 2
Photovoltaic module specifications [24] and market share [3].

PV technology	Area [m^2]	Nominal Power [W_p]	Weigh [kg]	Market share [%]
c-Si	1.46	224	23	91
a-Si	2.3	128	18.86	2
CdTe	0.72	65	12	5
CIGS	0.72	80	12.6	2

Table 1. The number of PV modules can be calculated using Eq. (1). Total PV capacity in this study is 69.7 GW. Dividing this capacity by the product of the respective market share and the nominal power, the number of PV modules is estimated as 330 million. This is equivalent to 6.6 Mt of PV modules. Once the number of modules is known, the total material contained in those modules can be estimated by multiplying the material composition (kg/m^2) from Table 1 by the respective module area (m^2) shown in Table 2 (Eq. (2)).

$$\text{Number of modules} = \frac{\text{PV Capacity (W)}}{\sum[\text{Market share (\%)} * \text{Nominal power (Wp)}]} \tag{1}$$

$$\text{Material contained in PV (kg)} = \text{Material composition}\left(\frac{\text{kg}}{\text{m}^2}\right) * \text{Area}\ (\text{m}^2) \tag{2}$$

4) *Estimate the amount of materials contained in inverters.* The material composition of a 500 kW string inverter is applied and scaled to all PV installations through Eq. (3) [13]. The inverter sizing ratio is assumed to be 1.15 [25].

$$\text{Number of inverters} = \frac{\text{PV Capacity (W)} * \text{Inverter sizing ratio}}{\text{Inverter Capacity (W)}} \tag{3}$$

5) *Estimate the amount of materials contained in transformers.* The material composition of 1.6 kVA transformers made of copper (see Table 1) is applied and scaled to all PV installations, using a power factor of 0.8 and Eq. (4) [13].

$$\text{Number of transformers} = \frac{\text{PV Capacity (W)} * \text{Transformer power factor}}{\text{Transformer Capacity (W)}} \tag{4}$$

6) *Estimate the amount of materials contained in cables.* It is assumed that 0.64 kg of Cu per m^2 of PV module are required [26].
7) *Estimate the amount of materials contained in mounting structures.* The material required for open ground mounting is calculated based on [24] and presented in Table 1.
8) *Estimate the amount of materials contained in tracking systems.* The materials contained in tracking systems is taken into account when it is known that the PV installations have them.

Once the eight steps above are carried out, the complete material inventory of a PV installation can be calculated. This study is focused on the recycling of metals; therefore, in order to estimate the amount of metal that can be recycled from the end-of-life PV installations, there are two more steps that need to be accomplished.

9) *Estimate and apply recycling yields.* In order to estimate the amount of secondary materials that can be recycled from PV waste, it is necessary to multiply the amount of each metal estimated in the previous steps 3–8 by their respective recycling yield. Expansive research on the current and future recycling yields of each metal was performed and is presented in Table 3.
10) *Sensitivity analysis.* The last step of this methodology is to perform sensitivity analysis. This includes changes in the market share of the different PV-module technologies, the recycling yields, the metal composition of the transformer, the increased use of tracking systems, and the reduction of silver content in c-Si PV modules.

Technological advances will change the material composition and reduce the total mass of PV panels. For instance, metallization pastes or inks containing silver and aluminum are the most expensive and process-critical non-silicon materials used in c-Si technologies. Therefore, paste consumption will likely be reduced in the future. Currently, c-Si modules contain 8.8 g of silver per square meter of module. A reduction of silver down to 1.6 g/m^2 is expected by 2026 [44]. In order to assess this reduction of silver in PV modules, a sensitivity analysis is performed in Section 3.3.5. Material substitution (e.g. aluminum instead of copper) to achieve cost reductions is also anticipated. In addition, due to environmental constraints, the use of lead in pastes is expected to be eliminated.

3. Results

Future cumulative waste volumes from end-of-life PV systems in the U.S. were estimated taking into account all major solar projects in the U.S. according to the SEIA. This list includes 4062 projects, which add up to 69.7 GW of ground-mounted solar power plants of 1 MW and larger. The PV installations are divided into three categories: 1892 operating projects, 96 projects under construction with an expected on-line date of 2016, and 2076 projects under development [14]. Some of the projects began operating in 2003 with some of these being expected to be decommissioned by 2030. The list includes information such as: project name, status, developer, owner, electricity purchaser, city, county and state, as well as the technology and capacity of each solar project.

The projects analyzed in this study account for roughly 50% of the cumulative installed PV capacity. This means that compared with the amount of PV waste estimated in this model, a similar amount of PV waste will be produced by installations smaller than

Table 3
Recycling yields of metals contained in PV systems.

Metals	Recycling yields (%) from several sources	Recycling yield (%) for this study
Precious	Ag: 30–50 [11]; 95 [19]; 100 [27]; 22 [28]; 32 [29]	95
	Au: 36 [28]; 29 [29]	36
Base and special	Al: 100 [19]; 100 [27]; 14 [28]; 36 [29]; 100 [30]	100
	Cu: 78–100 [11]; 100 [19]; 94–99 [23]; 41 [28]; 30 [29]; 78 [30]; [31]; 85 [32]; 78–100 [33]	100
	Cr: 20 [29]	20
	Fe: 90 [34]	90
	Mn: 37 [29]	37
	Mo: 18 [28]; 33 [29]	18
	Ni: 41 [29]	41
	Sn: 32 [28]	32
	Ti: 52 [29]	52
	Ta: 21 [29]; 10–20 [35]	21
	Zn: 27 [29]	27
Toxic	Cd: 95 [17]; 85–96 [18]; 20–100 [23]; 27 [28]; 14 [29]; 85–96 [34]; 95 [36]; 90 [37]; 80–95 [38]; 95 [39]	95
	Pb: 96 [28]; 63 [29]	98
	Se: 88–90 [23]; 38 [28]; 62 [32]	89
Critical	Ga: 33 [28]; 40 [35]; 80–99 [40]	90
	In: 15 [34]; 80–99 [40]	90
	Mg: 33 [29]	33
	Te: 80–95 [11]; 85–96 [18]; 80–100 [23]; 85–96 [34]; 35-90 [35]; 95 [36]; 90 [37]; 80–97 [38]; 95 [39]; 80-99 [40]; 80 [41]	95
Other	Si: 76–86 [11]; 74 [23]; 100 [27]; 95 [28]; 90 [42]; 86 [43]	100

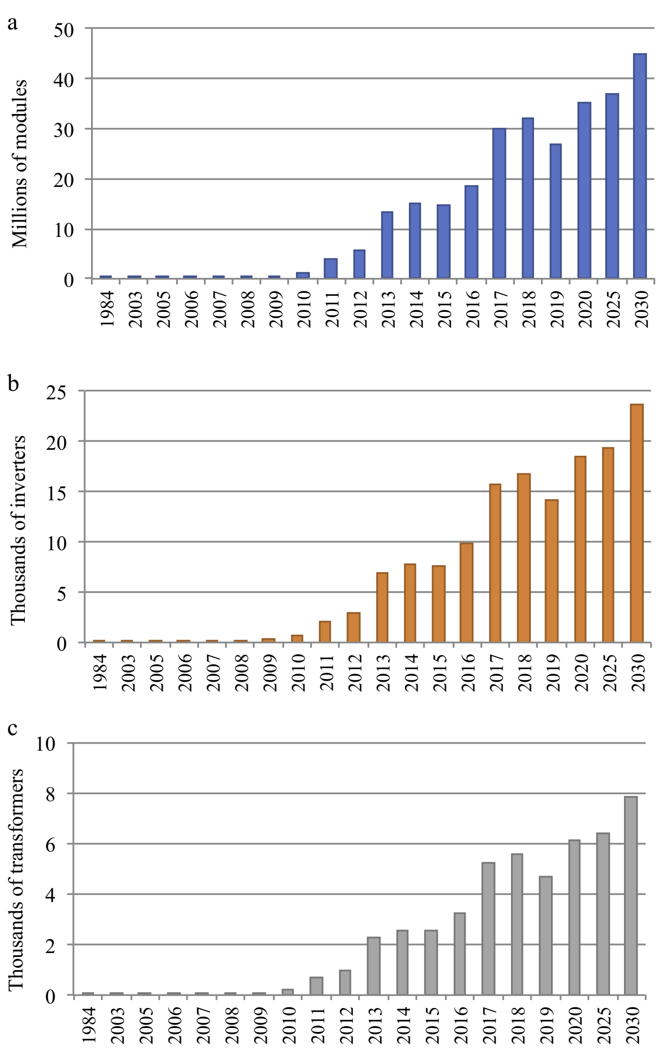


Fig. 5. PV equipment requirement for the U.S. PV installations: (a) modules, (b) inverters and (c) transformers, according to their installation year.

Table 4
PV projects approved in the U.S. up to April 2016. Data from Ref. [14].

State	Capacity [MW]	Share [%]	State	Capacity [MW]	Share [%]
CA	41,180	59.08	AR	81	0.12
NC	6954	9.98	PA	78	0.11
NV	4857	6.97	WA	76	0.11
AZ	4442	6.37	VT	61	0.09
TX	1838	2.64	TN	53	0.08
UT	1517	2.18	MS	53	0.08
NJ	1419	2.04	IL	50	0.07
FL	1416	2.03	CT	43	0.06
MA	947	1.36	SC	38	0.06
NM	850	1.22	DE	37	0.05
ID	651	0.93	MO	34	0.05
VA	585	0.84	PR	30	0.04
HI	585	0.84	OR	19	0.03
GA	560	0.80	MI	14	0.02
CO	405	0.58	RI	12	0.02
IN	181	0.26	KY	7	0.01
OH	147	0.21	WI	3	0.004
NY	144	0.21	OK	3	0.004
MD	134	0.19	KS	1	0.001
MN	114	0.16	NH	1	0.001
AL	83	0.12	NE	0	0.000
			Total	**69,704**	**100.00**

1 MW, which is an even greater challenge due to the management requirements for this size of PV installations.

Considering the PV installations reported by SEIA (1 MW and above), the main PV equipment requirements for the U.S. in the forthcoming years are estimated and shown in Fig. 5. Knowing the year of installation makes it possible to estimate the year of disposal of this equipment and thus plan for end-of-life management.

In order to estimate the metal content of the 69.7 GW PV systems already installed or planned in the U.S., the total mass of PV modules, inverters and transformers of each installation is calculated and shown by state in Table 4. California leads the solar market in the U.S. with around 60% of the PV installations in the country, followed by North Carolina (10%), Nevada (7%) and Arizona (6%).

One of the objectives of this study is to know when the PV systems will become PV waste. Therefore, Table 5 shows the year of

Table 5
PV projects approved in the U.S. up to April 2016.

Installation year	Annually installed [MW]	Cumulative capacity [MW]	Modules [t]	Inverters [t]	Transformers [t]	Disposal year
2003	15	15	1420	60	40	2028
2005	9	24	815	34	23	2030
2006	15	39	1415	60	39	2031
2007	40	78	3743	158	104	2032
2008	58	136	5524	233	154	2033
2009	128	264	12,077	509	337	2034
2010	321	585	30,366	1280	846	2035
2011	978	1563	92,591	3902	2580	2036
2012	1397	2960	132,313	5575	3687	2037
2013	3306	6266	313,082	13,193	8725	2038
2014	3722	9988	352,394	14,849	9821	2039
2015	3660	13,648	346,518	14,602	9657	2045
2016	4669	18,297	442,116	18,630	12,322	2046
2017	7504	25,801	710,566	29,942	19,803	2047
2018	7985	33,786	756,038	31,858	21,070	2048
2019	6739	40,524	638,087	26,888	17,783	2049
2020	8789	49,314	832,227	35,069	23,194	2050
2025	9230	58,544	873,960	36,827	24,357	2055
2030	11,249	69,792	1,065,138	44,883	29,685	2060
Total			**6,610,391**	**278,552**	**184,227**	

Table 6
Metal inventory of PV installations in the U.S.

Metal	Mass share [%]	Amount [t]	Commodity price [$/kg]	Economic value [$]	Economic value share [%]
Ag	0.02%	1911	646.55	$1,235,642,904	5.7%
Al	30.21%	2,966,684	1.9	$5,768,654,859	26.7%
Au	0.001%	75	37,616	$2,828,195,844	13.1%
Cd	0.05%	4704	1.1	$5,174,729	0.02%
Cr	0.003%	272	9.9	$2,695,950	0.01%
Cu	4.45%	436,723	6.1	$2,664,012,172	12.3%
Fe	46.34%	4,550,002	0.6	$2,730,001,454	12.6%
Ga	0.01%	1192	295	$351,749,221	1.6%
In	0.01%	573	460	$263,378,103	1.2%
Mg	0.32%	31,226	4.7	$146,761,966	0.7%
Mn	0.0001%	7	0.005	$37	0.0000002%
Mo	0.01%	966	17.8	$17,191,147	0.1%
Ni	0.001%	57	12.6	$718,082	0.003%
Pb	0.005%	468	2.05	$959,239	0.004%
Se	0.01%	966	50.3	$48,579,478	0.2%
Si	17.22%	1,691,432	2.998	$5,070,913,334	23.5%
Sn	0.01%	970	15.9	$15,415,807	0.1%
Ta	0.00003%	3	194	$625,532	0.003%
Te	0.02%	2116	89	$188,323,855	0.9%
Ti	0.000004%	0	0.64	$229	0.000001%
Zn	1.32%	129,382	2.1	$271,703,044	1.3%
Total	**100%**	**9,819,732**		**$21,610,696,986**	**100%**

installation as well as the estimated year of disposal. This information can help to plan PV-waste management across the U.S. in the coming years. A total of 6.6 Mt of PV modules, 278,552 t of inverters and 184,227 t of transformers will reach end of life between 2030 and 2060.

3.1. *Metal inventory and economic analysis of PV installations in the U.S.*

The metal inventory of PV installations in the U.S. is a comprehensive compilation of the metals contained in the PV systems. Table 6 displays the amount of metals contained in the U.S. PV installations in metric tons of metals. Results show that 69.7 GW PV installations in the U.S. will produce approximately 9.8 Mt of metal waste. This waste includes BOS components, such as inverters, transformers, cabling, and mounting, and will be generated between 2030 and 2060.

The percentages of the metals used in PV installations are shown in Fig. 6. These metals are mainly steel for mounting structures (46%), aluminum for module frames (30%), silicon for c-Si PV modules (17%) and copper for cabling (4%). From an economic point of view, the main contributors are aluminum (27%), silicon (23%), gold (13%), steel (13%), copper (12%), and silver (6%). It can be observed that the base and precious metals make up most of the economic value of the PV metal waste. When the metal inventory is assessed by economic value rather than mass, the importance of critical metals such as gallium (1.6%), magnesium (0.7%), tellurium (0.9%) and indium (1.2%) is also noticeable.

The major metals used in PV systems include abundant base metals such as iron, aluminum, copper, zinc, and silicon. However, there are precious, toxic or hazardous, and critical metals that require special focus (see Fig. 7). Precious metals, rare and with high economic value, such as silver, are used in the c-Si solar cells of PV modules. Gold, another precious metal, is used in small amounts in inverters. 75 t of gold are used in the inverters analyzed in this study. Toxic or hazardous metals such as cadmium, selenium, and lead are used mainly in thin-film modules (CdTe and CIGS).

Critical metals are used in small quantities, mainly in the PV

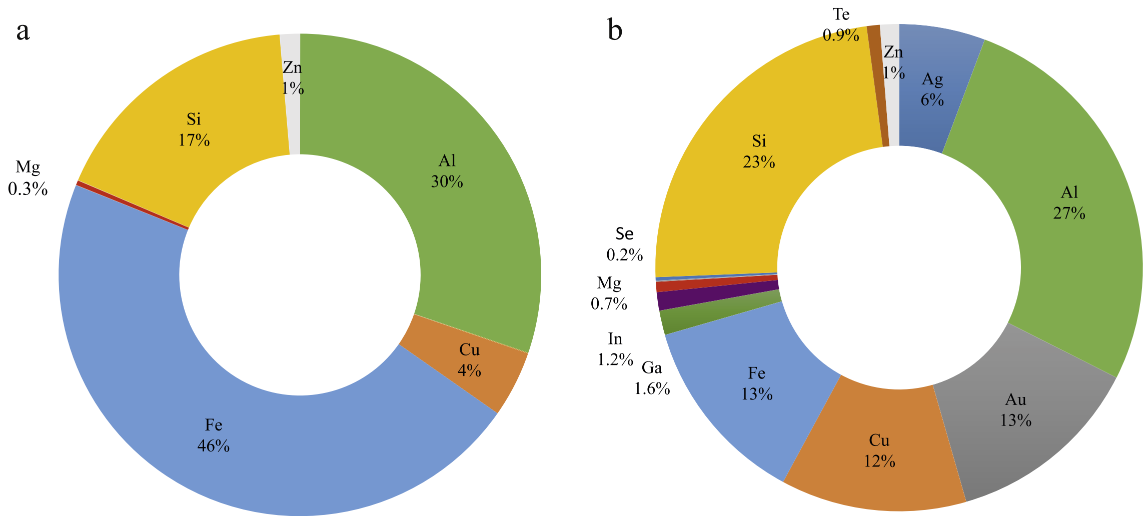


Fig. 6. (a) Mass and (b) economic value shares of metals in PV systems.

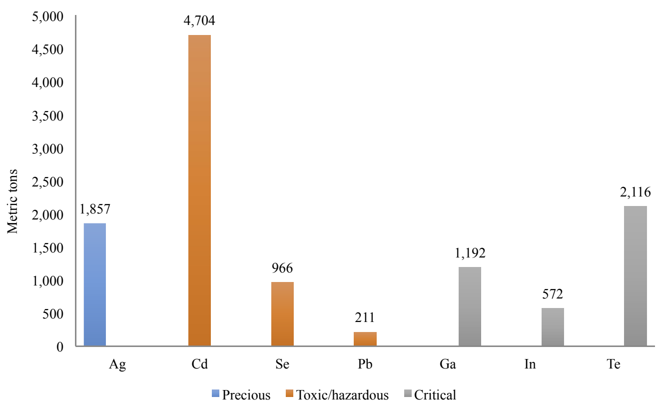


Fig. 7. Use of metals in PV systems in the U.S.

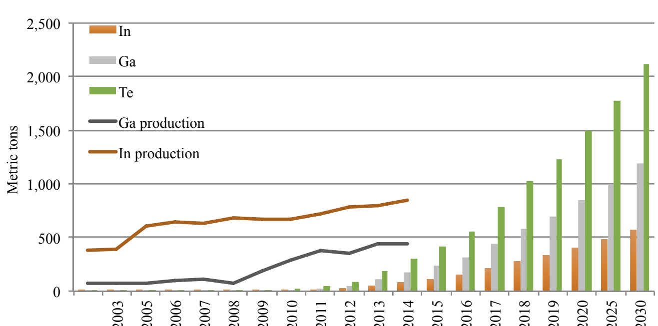


Fig. 8. Requirements of critical material in PV systems in the U.S. and global production of Ga and In.

modules, but have availability constraints due to their political or economic fluctuations in supply. These metals include gallium, indium, and tellurium, and are obtained as by-products during aluminum, zinc, lead, copper, and gold mining. Fig. 8 shows the requirements of these three metals for the PV installations in the U.S. from 2003 to 2030. The historical world production of indium and gallium is also presented according to the U.S. Geological Survey. It can be seen, that the production of these metals needs to be increased in order to meet the demand by the PV sector. A recent study revealed that if PV deployment growth would be based on thin-film technologies such as CIGS or CdTe, the required growth rates for the production of indium and tellurium would exceed historically-observed ones [45]. The same result can be observed in Fig. 7 for gallium. Another study identifies germanium, platinum, indium, and silver as the most critical materials for silicon-based and thin-film photovoltaics in the U.S. [46]. Recycling these metals is an alternative to ensure their availability. The recycling of critical metals to ensure sustainable growth of different PV technologies has been analyzed by Anctil and Fthenakis. They conclude that recycling is necessary, regardless of the type of materials used and that the cost of PV should include end-of-life management options [47].

3.2. PV-waste recycling in the U.S.

The U.S. does not have any legislation regarding collection and recycling of end-of-life PV panels. Currently, PV panels are disposed of in accordance with the Resource Conservation and Recovery Act (RCRA), the legal framework for the management of hazardous and non-hazardous solid waste [48]. The U.S. Environmental Protection Agency (EPA) developed an international research initiative to perform sustainable materials management (SMM),[1] which is a systematic approach to using and reusing materials more productively over their entire life cycles. In California, the Department of Toxic Substances Control is developing regulations to designate end-of-life PV modules that are identified as hazardous waste[2] as universal waste and subject them to universal waste management. Some of the advantages of managing PV waste as universal wastes are: reduction of the generator regulatory requirements, accumulation of waste for up to one year, no need for a hazardous manifest, and reduction of the amount of labeling and recordkeeping [50].

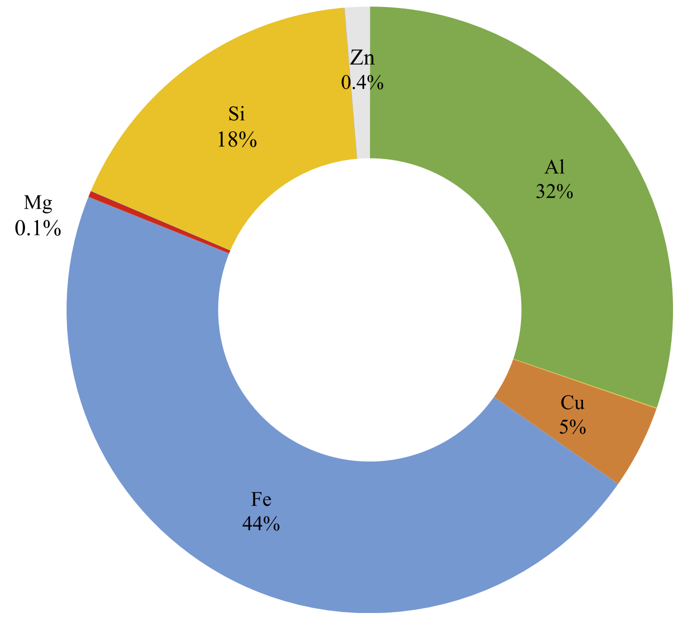
Recycling PV panels together with the components used in the PV installations is preferable to disposal. Recycling, and the

[1] SMM, which the OECD has defined as an approach to promote sustainable material use, integrating actions targeted at reducing negative environmental impacts and preserving natural capital throughout the life cycle of materials, taking into account economic efficiency and social equity [49].

[2] A hazardous waste is a waste with a chemical composition or other properties that make it capable of causing illness, death, or some other harm to humans and other life forms when mismanaged or released into the environment, according to the California Department of Toxic Substances Control [50].

Table 7
Recycling yields and estimated amount of metal in PV waste in the U.S.

Metal	Recycling yield [%]	Quantity [t]	[%]
Ag	95	1816	0.02
Al	99.97	2,965,794	32.08
Au	36	27	0.0003
Cd	95	4469	0.05
Cr	20	54	0.001
Cu	100	436,723	4.72
Fe	90	4,095,002	44.3
Ga	90	1073	0.01
In	90	515	0.01
Mg	33	10,305	0.11
Mn	37	3	0.00003
Mo	18	174	0.002
Ni	41	23	0.0003
Pb	96	449	0.005
Se	89	860	0.01
Si	99.9	1,689,741	18.28
Sn	32	310	0.003
Ta	21	1	0.00001
Te	95	2010	0.02
Ti	52	0.2	0.000002
Zn	27	34,933	0.38
Total		**9,244,283**	**100**



resulting material recovery, creates a secondary value chain with substantial environmental and economic benefits. Thus, identifying and quantifying the amount of metals that can be recovered from PV waste is the next logical step. To estimate the amount of recoverable secondary materials, expansive research on current and future recycling yields of each metal in the metal inventory shown on Table 6 was performed. Twenty-one metals are analyzed in this study. Recycling yields are estimated to be around 90% for eleven metals and between 18% and 52% for the other nine metals. The recycling yield reported for entire solar cells varies from 60% to 97% [27,51,52], while the total recycling yield for silicon modules is around 90% [47,53]. A 90% yield is also reported for the BOS [54]. It is important to highlight that some recycling yields were taken from general recycling industries that are not specialized in PV waste.

Table 7 shows the recycling yields as well as the amount of metals that could be recovered. The (non-weighted) average recycling yield of all metals contained in the PV systems is 86%. In total, around 9.2 Mt of secondary metal could be obtained. The recycling processes of aluminum, copper and iron are well-known and achieve yields close to 100%. These metals can be easily recovered from PV end-of-life components due to their bulk use as mounting structures, frames and cables. Nevertheless, there are metals that are contained in small amounts within the solar cells, transformers, and inverters, which require more complex recycling processes.

3.3. Sensitivity analysis

The estimates for the amount of metals contained in PV waste can be affected by different factors such as market share of PV technologies, recycling yields, metal composition of transformers, and the inclusion of tracking systems. Therefore, sensitivity analyses for these parameters were conducted.

3.3.1. Effect of market share of PV module technology

The metal inventory of PV waste depends on the solar cell material used in the PV modules. Likewise, the waste regulations and the waste treatment applied to end-of-life PV panels will depend on their metal composition. In this model, the metal composition is defined by the market share of different PV technologies and can be changed. For the U.S., the solar cell market share was assumed as 91% for c-Si, 2% for a-Si, 5% for CdTe and 2% for CIGS [3]. However, the silicon-based modules that currently dominate the market, will be replaced in the next decades by thin-film based PV technologies, advanced c-Si PV panels, and other technologies (e.g. organic PV, dye-sensitised cells, etc.), while a-Si technology will be discontinued due to low efficiencies [3,15]. By 2030, the market share of other PV technologies will be 44.1%. Since the metal composition of other technologies is currently not well known, their market share was allocated between three technologies, c-Si, CdTe and CIGS, proportionally to their market share in 2014. Therefore, 85.8% will be c-Si, 6.9% CdTe, and 7.3% CIGS.

Fig. 9 shows the change in metal inventory due to a change in the market share of PV modules. It can be seen that silicon (−6%), aluminum (−9%), and magnesium (−9%) will decrease because fewer c-Si modules with aluminum alloy ($AlMg_3$) frames will be produced and/or could be replaced by plastic frames or frameless modules. Otherwise, the increase of CIGS thin-film PV modules will greatly increase the use of selenium (265%) and critical metals, such as gallium (265%) and indium (175%). If more CdTe thin-film panels are used, then the amount of tellurium (36%) and cadmium (100%) required will increase.

3.3.2. Effect of recycling yields for target materials

Developments in recycling technology will change the recycling yields shown in Table 7. Current research in recycling of some metals such as silver, cadmium, gallium, indium, and selenium, mainly used in thin film technologies, shows very high levels of recovery (89–95%); however, these technologies are relatively new. The optimistic high recycling yields shown on Table 7 could be lower, and the amount of material recovered would be different, as shown in Fig. 10. The low recycling yields considered are: silver 30%,

Fig. 9. Change in metal inventory according to forecast market share of PV modules.

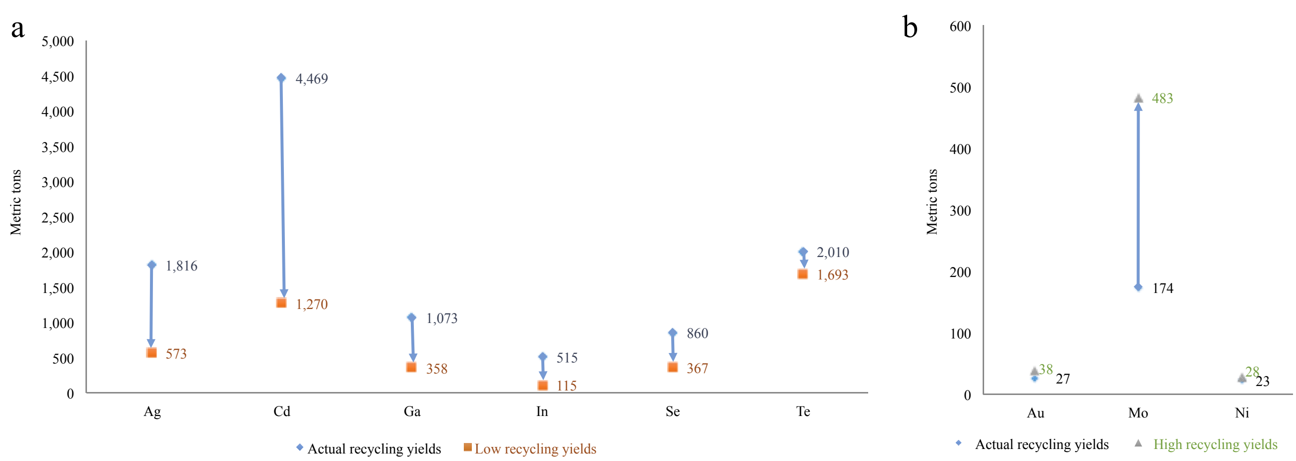


Fig. 10. Change in material recovery according to: (a) low recycling yields and (b) high recycling yields.

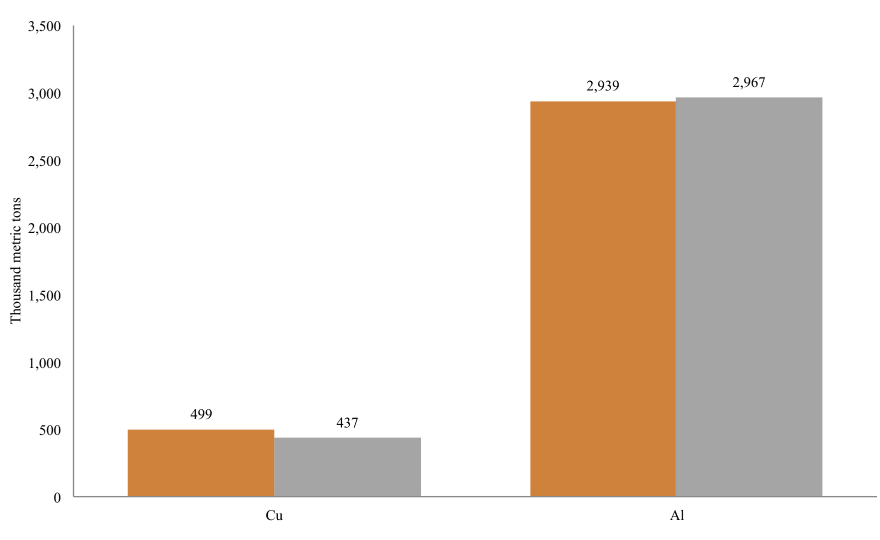


Fig. 11. Change in material requirements depending on the metal used in transformers.

cadmium 27%, gallium 30%, indium 20%, selenium 38% and tellurium 80% [11,28,52].

Moreover, valuable metals such as gold, or others like molybdenum and nickel, with very low recycling yields (18–41%) may experience an improvement in their recovery. Fig. 10 shows the increase of metal recovered if high recycling yields (50%) could be achieved for metals such as gold, molybdenum or nickel. For instance, a recycling yield of 50% for gold, instead of the actual 36%, means that an additional 40% of gold would be recovered [27].

3.3.3. Effect of metal composition of transformers (Al vs. Cu)

The choice of copper or aluminum as conductor used in transformer windings is based on technical (conductivity, density, connectivity, thermal and mechanical properties), economic (Cu is currently more expensive than Al), and resource constraints (copper reserves are limited). The material inventory presented in Table 6 assumes that transformers are made only of copper. Nevertheless, transformers with aluminum windings have become a more viable option because of their technical feasibility and economical advantage [55]. When aluminum is selected as winding material, the amount of copper used in the overall PV system will decrease by 62,000 t (12.4%), while aluminum will increase by 28,000 t (0.9%) (see Fig. 11). Considering the price of copper (6.1 $/kg) and aluminum (1.9 $/kg), the economic advantage of using aluminum instead of copper is clear [56]. The difference in material cost is approximately 325 million dollars.

3.3.4. Effect of tracking system

According to the International Technology Roadmap for Photovoltaic (ITRPV) in 2015, there is a long-term trend for large-scale PV systems to increase tracking up to 20% by 2026 [13]. Tracking systems increase the use of metals in mounting structures as follows: An additional 10% for aluminum, 50% for steel and zinc, and 30% for copper. Hence, the metal inventory would increase by around 2.1 Mt of metals.

3.3.5. Effect of silver reduction in PV modules

There is a trend of material reduction in PV modules. Due to the high economic value of silver, it is interesting to analyze the effect of silver content reduction in PV modules. For instance, c-Si modules currently use 8.8 g of silver per square meter of module, but this could go down to 1.6 g/m^2 by 2026 [12]. A gradual reduction of silver content, from current rates down to 1.6 g/m^2, would lead to a total reduction of 82% of silver use in the PV modules considered in this study. In other words, only 334 t of silver would be contained in c-Si PV modules, instead of the original 1816 t (considering 8.8 g/m^2). The economic value of this reduction would be 1.8 billion dollars.

4. Discussion

The estimated cumulative waste volume of end-of-life PV panels can be compared with the results in the report End-of-life Management Solar Photovoltaic Panels by IRENA/IEA [3]. The first step in both models is the analysis of growth in PV capacity. The IRENA/IEA model covers the years 2000–2050, while our model analyzes data from 2000 to 2030. The models make the conversion of capacity in GW to PV panel mass (in t) in a different way. The IRENA/IEA model uses an exponential regression function to calculate the annual conversion ratio (PV panel weight-to-power ratio [t/MW]). The resulting ratio decreases from 107 t/MW in 2000 to 60 t/MW by 2030. Our model converts GW to t, based on the market share of PV technology and using the available data on panel weight and nominal power. These ratios range from 102 t/MW for c-Si PV modules to 184 t/MW for CdTe. Since our research is focused on metal recovery, the Ecoinvent database 3.3 was used to identify all metals contained in each PV module technology. The IRENA/IEA model analyzes two scenarios, the regular-loss scenario (30 years lifetime) and the early-loss scenario, which includes loss, damage, and failure before the 30-year average panel lifetime. Our model only takes into account the regular-loss scenario. The input data for both models are the cumulative PV installed capacity. The IRENA/IEA model takes into account all segments of PV installations in the U.S., while our model only takes into account the PV installations of 1 MW or larger. This means that small installations have been excluded from our calculations. However, as the utility sector has been the main contributor to PV capacity in the last decade, results are in agreement with those estimated by the IRENA/IEA model. Results of estimated cumulative waste volumes of end-of-life PV panels for both models are presented in Table 8. Both results have the same order of magnitude and the differences mainly rely on the input factor of cumulative installed PV capacity. What was observed in the Mexican case is that many of the international reports underestimate installed PV capacity and actual PV deployment in Mexico. Our research suggests that more PV is being installed in Mexico, therefore PV waste will exceed projections. For the U.S., our model accounts only for the major solar projects reported by SEIA. Thus, PV-waste estimations are below the IRENA/IEA model predictions, but not by much.

The main differences between the IRENA/IEA model and this model can be summarized as follows: (1) The IRENA/IEA model takes into account all segments of the PV market, while the model presented in this study analyzes only PV installations of 1 MW and larger. (2) The conversion ratio (t/MW); the IRENA/IEA model uses an exponential regression function, while this model performs this conversion based on the PV module technology specifications. (3) The calculation of an early-loss scenario. However, this model has advantages, such as the BOS-waste estimates, the recycling analysis, and the economic assessment. Recycling of PV waste enables the recovery of material and its reintroduction into the economy, whether it is to produce new PV panels and components or any other products.

This paper is an important first step that will serve as the basis for further socio-economic and environmental analyses. Once the PV waste is quantified, the size of the potential economic benefits of PV recycling becomes evident. For instance, once it is known that the PV systems analyzed in this study contain 1911 metric tons of silver, it is possible to estimate the value of this amount of metal as $1600 million. This data helps to assess the economic feasibility of PV waste recycling. The same is true for environmental assessments of different disposal and recycling options available for end-of-life PV systems. Once it is known how much material can be recovered from the PV waste, it is possible to compare the environmental burdens of PV waste recycling with the benefits of secondary material recovery.

Table 8
Estimated cumulative waste volumes of end-of-life PV panels.

Country	Year	IRENA/IEA [3] [t]	This study [t]
USA	2040	1,700,000	1,290,000
	2050	7,500,000	5,500,000
Mexico [13]	2040–2050	55,000–630,000	691,000

5. Conclusions

As no federal regulations regarding the collection, disposal, and/or recycling of end-of-life PV panels currently exist in the U.S., it is important to provide data on the challenges and opportunities that

PV waste represents. Regardless of the regulatory framework, or lack thereof, responsible management of PV waste is an indispensable part of the transition to renewable energy.

This study presents the estimated cumulative waste volumes from end-of-life PV systems in the U.S. During this decade PV growth in the U.S. was mainly driven by the development of the PV utility segment. This document thus analyzes 69.7 GW of PV installations of 1 MW, or larger, which covers about 50% of all PV installations in the U.S. in 2016. The main results of this study are:

- Generation of 9.8 Mt of PV waste, consisting of 6.6 Mt of PV modules, 2.7 Mt of BOS, 0.3 Mt of inverters, and 0.2 Mt of transformers.
- 9.2 Mt of metals contained in the PV-waste stream can be recovered. This includes precious metals – 1816 t of silver and 27 t of gold – and critical metals – 4469 t of cadmium, 1073 t of gallium, 515 t of indium, and 2010 t of tellurium.
- It is estimated that 1.3 and 5.5 Mt of end-of-life PV panels will be generated in the U.S. by 2040 and 2050, respectively.
- The material inventory consists mainly of steel for mounting structures (46%), aluminum for module frames (30%), silicon for c-Si PV modules (17%), and copper for cabling (4%).
- When the metal inventory is assessed by economic value, rather than mass, the economic value shares of metals contained in PV waste are as follows: aluminum (27%), silicon (23%), gold (13%), steel (13%), copper (12%), and silver (6%). Base and precious metals make up most of the economic value in the PV metal waste. Next are the critical metals: gallium (1.6%), magnesium (0.7%), tellurium (0.9%) and indium (1.2%).
- California leads the solar market in the U.S. with around 60% of the PV installations, followed by North Carolina (10%), Nevada (7%), and Arizona (6%).
- If PV deployment growth would be based on thin-film technologies, such as CIGS, the required growth rates for the production of gallium would exceed historically-observed global production growth rates.
- Tracking systems would increase the metal inventory by around 2.1 Mt of metals.
- A reduction of 82% of silver content in c-Si modules represents a reduction in economic value of approximately 1.8 billion dollars.

The future challenges of PV waste recycling are: the development of recycling processes for all kinds of PV technologies, the coordination of waste management companies, and the creation of a network of PV recyclers throughout the U.S. The PV waste recycling model presented in this analysis provides decision-makers with information needed to develop and implement policies and strategies that will better address future PV waste management. This study will support the development of a comprehensive PV waste management plan, which includes dismantling, collection, transportation, and treatment of PV waste produced in these major installations. This, in turn, will pave the way for the management of PV waste arising from smaller PV installations.

Accurate and readily accessible waste composition data is a first step, but not enough. In addition, techno-economic and environmental analyses are needed to identify and solve the waste challenges that the rapid growth of PV energy entails. The better the connection between international agencies, governments, institutions, and industries, the better policy-makers and PV stakeholders will be able to plan for the responsible management of PV waste.

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Environmental and economic evaluation of solar panel wastes recycling

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Abstract

Owing to rising population and increasing energy demand, renewable energy resources become the most convenient and promising solution. Hence, solar power plant investments and photovoltaic module numbers have risen sharply. Turkey is one of the tight followers of the energy trends, thanks to its rising energy demand and economic power. However, the consequences of the massive plant wastes importance in term of economically and environmentally have not been understood yet. Almost 70% of the modules are formed by glass and the rest accumulates economically valuable metal materials, which are silver, aluminium and copper. These three main materials are substantially important in the overall waste. Not only the economic value, but also the environmental impacts of the mining effluents to excavate these metals are causing emission problems. As a chain reaction, the higher energy demand triggers a search for new and renewable energy resources. This is why popularity of solar energy has increased. Solar energy can be absorbed and transformed through photovoltaic modules, which contain glass and three main metals. In order to respond for the production of modules, metals are fundamental. This need triggers the need of metals mining excavations and emissions. In this respect, in the near future, thanks to the rising investments on photovoltaic modules and the CO_2 emissions coming from mining, the wastes of photovoltaic modules and the need of recycling will become more important. That is why, in this study it is aimed to present environmental benefits and economic recoveries of recycling photovoltaic module in Turkey.

Keywords

Photovoltaic, PV module, waste management, recycle, renewable energy

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Introduction

Fast-growing energy demand and high-carbon releasing fossil energy resources have become the main challenge of the world. Limited amounts and greenhouse gases (GHG) emissions are the two important aspects of conventionally used fossil energy resources (Ozlu and Dincer, 2016). Hence, replacing fossil-based resources with renewable energy-based implementations and applications have emerged as a promising and alternative energy resource all around the globe. These implementations had started mainly with solar and wind energy applications and recently continued with biomass, geothermal and hydropower (Pramanik and Ravikrishna, 2017; Sherwani et al., 2010). However, the solar energy applications, which transforms sun radiation to electric power, took the major interest by academics and industry, owing to solving the energy demand problem both in renewable and sustainable ways thanks to its lower GHG release (Luo et al., 2018; Wai et al., 2008). The productivity and efficiency improvements on photovoltaic solar panels and pay-off period of panels decreased tremendously and the governmental subsidies in the recent years have pushed the investors for solar panel applications (Dinçer, 2011). There are several commercial types of photovoltaic (PV) solar panels: Crystalline silicon (c-Si) solar panels that include single-crystalline silicon solar cells and polycrystalline silicon solar cells, and thin film photovoltaic solar panels (TFSC). The majority of residential applications are based on crystalline silicon PV owing to its higher efficiency yields, lower manufacturing cost and its basic formation. In 2015, from the overall solar panel manufacturing, crystalline silicon PVs value the 93% and the major part of these crystalline silicon type was accounted from polycrystalline silicon-based applications. Yet, the increasing level of efficiency on thin film PVs and growing market potential of them in the recent years indicates a new competitor especially for residential applications. Compared to the overall PV solar panel market, thin film PVs captured 8% of the applied modules, for residential applications (D'Adamo et al., 2017; Domínguez and Geyer, 2018).

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Table 1. PV module components and their weight percentages.

PV module material name	PV module component name	Weight percentage (%)
Glass	Cover of PV	70.00
Aluminium	PV frame	18.00
Adhesive (polymer based)	Encapsulation layer	5.10
Silicon metal	Solar cell	3.65
Polyvinyl fluoride	Back sheet layer	1.50
Copper and polymers	Cables	1.00
Aluminium	Conductor	0.53
Copper	Conductor	0.11
Silver		0.053
Tin and lead		0.053
Total		100

PV: photovoltaic.

The International Energy Agency showed that the total installed capacity of PV was 75 GW in 2016, which was mainly accumulated in Asia Pacific (includes the Turkey market too). However, this capacity only covers the 1.8% of the total electricity generation. Plus, Germany, Japan and Italy weights the highest ratios in solar panel PV per head in the population (IEA, 2016b).

On the other side, Turkey is ranked as 29th on solar power in 2016 with 832.5 MW installed capacity that covers less than 1% of the overall electricity demand. The legislation of Turkey allows unlicensed electricity power up to 1 MW, that is why the licensed plants cover only 1.5% of the overall installed solar panel capacity. However, 819.6 MW installed capacity is in the segment of without licensed (IEA, 2016a, 2016b; Republic of Turkey Ministry of Energy and Natural Resources, 2017a).

PV importance and weight to supplement the electricity demand is increasing tremendously, especially in the last 10 years. The installed capacity of panels has risen more than 50 times. Consequently, higher demand on solar energy brings two important facts: The efficient lifetime of the modules and the evaluation potentials at the end of their life. The aim of this study is creating a future looking vision for the installed PV solar modules at their end-life periods and projecting their value for the Turkish market based on their economic and environmental perspective.

Materials and methods

As a commercial energy supply, PV systems are broadly installed in the Turkish Market. Most widely, the crystalline silicon types are used, which includes valuable metals inside, such as aluminium, silver and copper.

Methodology state of mind

In order to understand the long-term economic and environmental impact of the PV solar panels, in the following part, PV module content information will be given with the ratios at the Table 1 (Latunussa et al., 2016). Later, for understanding the total installed PV module in the Turkish market, the average *unit energy capacity per panel module* will be calculated. Installed panels have limited lifetimes and need to be disposed after a decent time. However, using the wastes of PV modules as a recycling material would create a significant contribution to the economy and to the development of the country and also help for environmental precaution.

PV module content. As previously mentioned, most commonly applied types of PVs are crystalline silicon ones in Turkey. Thanks to the innovation, there are strong newcomers to the market, but still crystalline silicon PVs are the most widely preferred ones in the Turkish market. Commonly, depending on the silicon content ratio and processes, three methods of recycling methodologies are used for PV modules: Implementations of thermal (chemical process), mechanical and laser. The mechanical process, which is the basic and lower cost methodology, is the more convenient one, especially for splitting the layers of the crystalline silicon PV modules. Yet, thermal application is applied for the modules that do not contain silicones. Hence, this application would not be very convenient for Turkey. Fundamentally, crystalline silicon PV modules are structured in layers, both upper and bottom layers are covered with silicon-based surfaces and inner layers are charged thanks to additive materials and the aluminium strapped part. In both sides, silver is a perfect touch point to collect and transmit the electrons. Cynthia EL Latunussa et al. explained the panel module contents by quantity ratios and it was shown by Table 1 (GVR, 2017; Latunussa et al., 2016).

As regarded in Table 1, the amount of silver, copper and aluminium are quite low and thought to be insignificant. However, in the large panel applications they create an economic impact on recycling and waste management.

Besides, Table 1 shows the most convenient materials existence in crystalline silicone PV modules, however, PV modules also include lead and cadmium in low amounts, which should be considered very carefully as hazardous wastes for environment and employees (D'Adamo et al., 2017; Xu et al., 2018b).

PV module unit capacity. Regarding the real scale applications of PV modules and product information gathered from the

Table 2. Different PV module brands, PV module unit powers, total PV module numbers and total installed power capacity information for different real-scale applications of solar power plant.

Capacity (KWp)	Module number	Unit (KWp module^{-1})	Module brand	Application	References
1000	4600	0.217	-	Turkey, Kayseri	Oktik, 2012
18,500	74106	0.250	Yingli Solar YL250P-29p	Turkey, Konya	TeknoRaySolar, 2017a
12,000	44445	0.270	-	Turkey, Konya	TeknoRaySolar, 2017b
10,800	44056	0.245	Astro Energy 265wp	Turkey, Aydın	TeknoRaySolar, 2017c
8400	31112	0.270	-	Turkey, Konya	TeknoEnerji, 2017a
6600	24445	0.270	Yingli Solar YL250P-29P	Turkey, Burdur	TeknoEnerji, 2017b
1000	4000	0.250	Yingli Solar YL255P-29b	Turkey, Adıyaman	TeknoRaySolar, 2017d
6317	24288	0.260	Trina Solar PD05-60	Turkey, Kayseri	TeknoRaySolar, 2017e
7410	27962	0.265	Trina Solar 265wp	Turkey, Elazıg	TeknoRaySolar, 2017f
3145	11868	0.265	Astro Energy 265wp	Turkey, Adana	TeknoRaySolar, 2017g
3552	13662	0.260	Astro Energy 260wp	Turkey, Nevsehir	TeknoRaySolar, 2017h
254,000	940741	0.270	JA Solar	Brasil	TeknoRaySolar, 2017i
0.220	1	0.220	Centro Solar	Commercial PV Module	CentroSolar, 2017
0.240	1	0.240	Eclipsal	Commercial PV Module	SolarDesignTool-Eclipsall, 2017
0.220	1	0.220	JA Solar	Commercial PV Module	JaSolar, 2017
0.255	1	0.255	Sun Tech	Commercial PV Module	SuntechPower, 2017

real-scale applications of installed solar power plants in Turkey, the average unit power capacity of a standard module is calculated from each real-scale application and shown in Table 2.

As a consequence of these results, the average module unit capacity (module per capacity) is computed. The average module unit capacity is computed as 0.252 KW, which basically means for each panel module unit, produced electricity power is 0.252 KWH.

Installed solar power capacity of Turkey. With respect to the data taken from the Ministry of Energy and Natural Resources of Turkey, at the end of 2016, Turkey's total installed capacity is counted as 832.5 MW for solar power (Republic of Turkey Ministry of Energy and Natural Resources, 2017b). The major part of the solar panels installation were installed in the market after 2015 (Sönmez, 2017), since installed capacity was 15 MW until 2013 (Oktik, 2012).

Installation of PV module number in Turkey. Determining the total PV module number is the key point to make sufficient assumptions of the potential of materials that can be recycled and to calculate the economic impact for the future:

$$\begin{aligned}&\textit{Total module number}\\&= \textit{total installed solar power capacity}\ (kW)\\&x\ \left(\textit{installed capacity per module}\ (kW)\right)^{-1} \textit{Equation } 1\end{aligned} \tag{1}$$

Since, Turkey's total installed solar power capacity (832.5 MW) was known and installed capacity per module (0.252 kW) was computed, both data are used to approach the total module number that was installed in the country using equation (1). Equation (1) was derivate to determine the total PV module number from available and proper information of total installed solar power capacity and installed capacity per module.

Average lifetime to recycle the PV modules. For the lifetime of a PV module on its own particular content, features and silicon density (Jungbluth, 2005), according to the studies, average usage life of a PV module is between 20 to 30 years (Corcelli et al., 2018; Domínguez and Geyer, 2017; Sherwani et al., 2010). With respect to this range, the average lifetime of a module is assumed to be 25 years. As a result, the first bulk recycling process of the panels will start in between 2040 and 2050 for Turkey. While assuming the first recycling time, the longer usage of panels or early recycling owing to the higher efficiency replacements are neglected. In this study, the new technology developments and higher efficiency PV module replacements are ignored.

Average weights of a PV module. In order to analyse the accurate value of the recycled materials, a brand–model–weight relation table is given in Table 3. Most commonly used brands in Turkish market are selected and depending on models, weights of the modules differ. According to this information, the average weight of a PV module is assumed as 20.75 kg per PV module.

Results and discussion

The environmental and economic impacts of the recycled materials are inevitably important for every product type, especially glass and metal, including wastes such as PV modules. The installation of PV modules has risen enormously in Turkey after 2015 owing to being a renewable energy source for rising energy need.

Thanks to the composition of PV modules, their wastes would be highly valuable if they go to the process of recycling. The average lifetime of PV modules is between 20 to 30 years, which means they will end their usage life and will be replaced with higher performed versions somewhere between 2040 and 2050. Plus, reusing these recycled compounds for reproducing the PV

Table 3. Weights of PV modules for different brands and models.

PV module brand	Model	Weight (kg)	References
Astroenergy	CHSM6610P	18.4	(AstroEnergy, 2017)
Astroenergy	CHSM6610M	19	(AstroEnergy, 2017)
Astroenergy	CHSM6612M	25.8	(AstroEnergy, 2017)
Jasolar	Jam6K	23	(JaSolar, 2017)
Jasolar	JAP6KDG	23	(JaSolar, 2017)
Jasolar	JAP6	23	(JaSolar, 2017)
Trina Solar	TSM-320PD14	22.5	(TrinaSolar, 2017)
Trina Solar	TSM-PD05	18.6	(TrinaSolar, 2017)
Yingli Solar	YGE 48	17	(YingliSolar, 2017)
Yingli Solar	Panda 60	21	(YingliSolar, 2017)
Yingli Solar	Panda 48	17	(YingliSolar, 2017)

modules would decrease the production costs of the material and support to diminish the carbon footprint.

In this approach, the basic and fundamental contents of PV modules are focused in order to be use as a secondary material after recycling, which is given in Table 1. The most recent total installed solar power capacity was approached as 832.5 MW and the average module unit capacity was determined as 0.252 KW from the real case applications' information in Table 2. In relation with the installed capacity per module and total installed solar power capacity equation (1) helped to reach to the total module number as 3.3 million modules in the country.

Economic values of recycled materials

It is known that the raw material abundance and their price fluctuations are always a tough challenge to conduct an efficient production. This is why, secondary materials of PV modules would create an economic benefit for producers on the costs side. By recovery of crystalline silicone PV modules main ingredients, almost 90% of the first raw material investment cost can be regained (D'Adamo et al., 2017).

The expected end of lives of the PV modules in 20–30 years and these modules contain a high amount of copper, aluminium, silver and glass wastes. The 2030 forecasts by the World Bank for copper, aluminium and silver prices are 7000 USD t^{-1}, 2200 USD t^{-1} and 514.47 USD kg^{-1}, respectively (IBRD, 2017). While prices of aluminium and copper have increased, silver has diminished in the forecasts. In these circumstances, the prices of copper, aluminium and silver are assumed averagely as 7500 USD t^{-1}, 2350 USD t^{-1} and 495.18 USD kg^{-1} between 2040 and 2050. In this respect, the economic income from the PV wastes is shown in Table 4 indicating waste PV module metals (silver, aluminium and copper), weights, their unit prices and expected economic values for a single module.

From Table 4, total economic value of recycled metals for a single module is calculated as 14.66 USD (8.78 USD + 0.26 USD + 0.17 USD + 5.45 USD).

Until now, the average metal recovery yield could reached 94% and there are few sites to do this recovery, mainly in the US, the European Union (EU) and in some parts of Asia (Domínguez and Geyer, 2017). Today, Turkey's total module number is calculated as 3.3 million and since there is not a regulation related to the PV recycle, it is assumed 60% to 70% of these modules will be recycled. The remaining 30% to 40% of the modules are assumed as non-recycled or already de-installed before their end of life. In this respect, 65% was selected as the recycle ratio of PV modules for the following calculations.

In order to evaluate the economic value of the recycled metals of the modules at the end of the lifetime equation (2) is implemented:

$$\begin{aligned}&\textit{Modules recycled metals' economic value}\\&\textit{at the end of the lifetime} = \textit{country total module}\\&\textit{number x assumed recycle ratio x average metal}\\&\textit{recovery yield x total economic value of}\\&\textit{recycled metals for a single module}\end{aligned} \qquad (2)$$

From equation (2) the single module recycled metals' economic value is roughly 30 million USD (3.3M × 60% × 94% × 14.66 USD).

As a result, overall savings of the three metals recycling at the end of the lifetime of PV modules would bring 30 to 35 million USD cash and 30,000 t of reusable glass wastes in 2040–2050. Hereby, there are two very important ways to evaluate these recycled materials. First, this process is a great cost benefit in terms of reusing them to invest in reproducing new generation PV modules. Second, metal excavations and glass fabrication supplement the main resource need of the production process of PV module, which cause huge energy consumption and GHG release so that it increases the level of the carbon in the atmosphere and induces climate change in the long-run.

Discussion on economic benefits of recycling

Despite being a middle-eastern country, Turkey is far more different than its neighbours. The country has invested its main resources and manpower to develop its economic power to reach well-civilised country levels since its foundation. Especially, the European Union (EU) accession process has endorsed and improved the efforts of the country's investments on economic

Table 4. Expected economic values for aluminium, copper and silver and waste glass weight content of a waste PV module.

Component name of waste PV modules	Weight percentages (%)	Weights of materials for a single PV module (kg)	Expected unit prices of materials in 2040–2050 (USD kg^{-1})	Total economic values (USD) of recycled materials for a single PV module in 2040–2050
Glass	70	14.53	-	-
Aluminium (for frame)	18	3.74	2.35	8.78
Aluminium (for conductor)	0.53	0.11	2.35	0.26
Copper	0.11	0.02	7.5	0.17
Silver	0.053	0.01	495.2	5.45

platforms and cash generator solutions. This is why Turkey invests in technology and renewable energy even more intensely than before as a mandatory face of the civilisation and future development expectation (Acaroğlu and Baykul, 2018; Salihoglu et al., 2017; Satir et al., 2016; Yorucu and Mehmet, 2018). This investment strategy is not only targeted by Turkey, but also the main objective of EU countries (Honrubia-Escribano et al., 2018; Malandrino et al., 2017). Considering this objective, the EU has not predicted well for the future of these investments as a cash generator and so has not posed a legal boundary for recycling (Malandrino et al., 2017). However, only with the PV module waste estimations of Turkey, the economic value of the main three metals would generate up to 35 million USD income and many million tonnes of glass waste.

The result of estimations and calculations of this manuscript clearly show that PV module wastes include high profit margins. A careful consideration with the collaboration of governments and private equity holders would create better solutions for both parties. Turkey is one of the very important raw-material and semi-finished goods suppliers for European producers and these wastes are great resources for reusing in semi-finished goods to reduce the costs of production. In this respect, the government's support for the private equity holders is a great source in terms of embracing and enhancing to understand their responsibility in terms of recycling and supporting the sustainable future for providing resources for new products. Governments holding the power of policy maker position first need to promote private equity holders who build and/or benefit from the PV modules to dispose by laws and rules to learn the responsibility and gaining money over this action. In addition, legal and governmental boundaries for companies would increase the attention on waste minimisation and recycling strategies, so that they can try to improve their process for reusing or re-gaining their wastes to decrease their costs and obey the policies.

On the other side, this responsibility of knowledge and awareness can be acquired and raised by education, which also returns to country level platforms. This is why, by implementing more sustainable future-related topics to the curriculum of educational, institutions could help producers and people to change their habits and demands on the wastes and waste management issues.

Regaining the metals to use in new production lines is a way for cost reduction, which directly affects the prices and so encourages the country's competitiveness power. Being an EU resource-supplier country, decreased prices would be a great advantage to lower the expenses for production to compete with other resource suppliers in the market and later to dominate the market as a powerful resource supplier. In short, they all generate a cash inflow to the country, empower the development and become a powerful candidate for access to the EU.

Discussion on environmental benefits of recycling

On the other side of the economic perspective, renewable energy resources are demanded to replace the fossil-based energy production owing to their lower carbon emissions. However, the production of the content of these renewable energy resources consumes a huge amount of energy and emits carbon and GHGs, which have been underestimated while selecting and using (Krueger, 2010). In order to reduce environmental effects of production processes, raw material saving and waste minimisation are important factors (De Wild-Scholten, 2013; Luo et al., 2018). Commonly, environmental effects of processes are measured by the life cycle assessment. Recently, there have been many publications related to life cycles assessment of the PV modules (Jungbluth, 2005; Latunussa et al., 2016; Luo et al., 2018; Srinivasan & Kottam, 2018). Liang Xu reports that PV module production includes many steps, such as material mining, semi raw material production, solar cell production, assembling PV module, transporting, installing and end-of-life recycling. They indicated that especially silicon ore mining, industrial silicon smelting and solar grade silicon purification have a relatively higher environmental impact in terms of toxic pollutants production, wastewater creation and high energy consumption (Xu et al., 2018a). This is why recycling PV modules is highly effective to prevent the adverse environmental effects that are coming from raw material production steps. For 1 kW PV module production, it is estimated to release 80,113 kg of CO_2 for subsidising the raw material (Domínguez and Geyer, 2017). However, compared with fossil-based coal burning systems, for the same amount of electricity power generation, the PV modules production phase emits 3.3% less (Srinivasan and Kottam, 2018).

In this manuscript, at the end-life of PV modules, the expected waste amount is 3.3 million modules, equal to 832.5 MW solar power panels. Only 65% of this PV module power is assumed to be recycled, which would be 540 MW. As previously mentioned, the major part of the CO_2 emission of the panel production comes from raw materials. Hence, if these metals are regained and reused for panel productions or other applications, from the recycled 540 MW PV modules, 43 millions of tonnes of CO_2 will be saved. On the one hand, recycling the wastes of PV modules brings waste minimisation and raw material saving, but on the other hand it is a great source of carbon release to the atmosphere and so decreases the countries carbon footprint. Today, this release can be observed at a country level, yet, in the years that recycling will be taking place, it is going to be much more important than today because of climate change and increasing levels of industries and population (Luo et al., 2018; Srinivasan and Kottam, 2018).

Conclusion

This article represents a discussion on the economic and environmental importance of PV module wastes and the need of disposal for renewable energy resources at the end of their lifetimes. They are renewable in terms of their energy production, but not well managed afterwards to value them and to reuse them. The major installation of the PV modules had started in 2015; in this sense PV modules are expected to finalise their usage life during 2040–2050 in Turkey. During that period, the total ready-for-disposal solar power capacity is expected to be 832.5 MW, which is roughly 3.3 million PV modules. In this research, four main contents are focused in PV module wastes: copper, aluminium, silver and glass. If the module wastes are well managed to recycle and reuse, it is shown that up to 35 million USD cash from metals and 30,000 t of glass would be regained from recycling the capacity of 65% and with the assumption of metal recycle yield as 94%. Moreover, PV module units manufacturing steps are high energy consuming and carbon-out processes that contains material mining, semi raw material manufacturing and solar cell production. In order to decrease the negative effects on the environment of PV modules production, reusing mine metals is very promising. In the previous studies it was estimated that 80,113 kg of CO_2 per 1 kW PV module production is released to supply raw materials. Again, if 65% of the 832.5 MW solar power system is recycled and the processed metal wastes are reused, 43 million tonnes CO_2 will not be released to atmosphere.

This research has aimed to address two objectives of the PV modules recycling: economic and environmental benefits. First, the economic gains of recycling is very crucial for a country like Turkey. Because Turkey is a candidate country of the EU, it is being expected to adjust its economic, environmental and civil infrastructure to become a developed and powerful country. Plus, being one of the main suppliers of the EU for raw material and semi-finished goods, low-priced products would affect positively the producers to switch their suppliers. Thanks to the recycled metals and glasses, Turkish producers can minimise their costs and so prices for supplying their goods to the European market and in the long-run empower the country's competition power and enhance development.

Lastly, the environmental awareness and pressure on countries to decrease their carbon footprints have increased tremendously. The environmental vision of PV module manufacturing has been underestimated. However, massive constructions and increased energy need has caused undeniable carbon release, especially the main release comes from raw material production. If recycled materials are reused for PV module productions, carbon emission can be lowered and so climate change effects can be shaded.

Recently, the EU imposed a directive to cover PV panels as electronic devices for collecting and disposing at the end of their lives, yet the Turkish government is still quite slow to follow-up. However, it is very important to understand the wastes of PV module contents, economic and environmental contributions. Even if the regulations are to be imposed, the other important leg of this case, the responsibility knowledge of producers, should also be well-supported by education. In this sense, countries should assign their educative institiutions to develop new curriculums for supporting public concious on sustainable knowledge. This article is a forward-looking study for the renewable energy resources future and value after its end of life. That is why, it is expected to be an influencer for rule makers.

Highlights

- Recent investments and instalments of solar power plants are increasing tremendously.
- The metal recovery ratio reached up to 94% for PV module.
- The economic value of the wastes can reach up to 35 million USD from metal recovery.
- By reusing glass and reducing mining processes 43 million tonnes of CO_2 will be saved.

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Disclaimer

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