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PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

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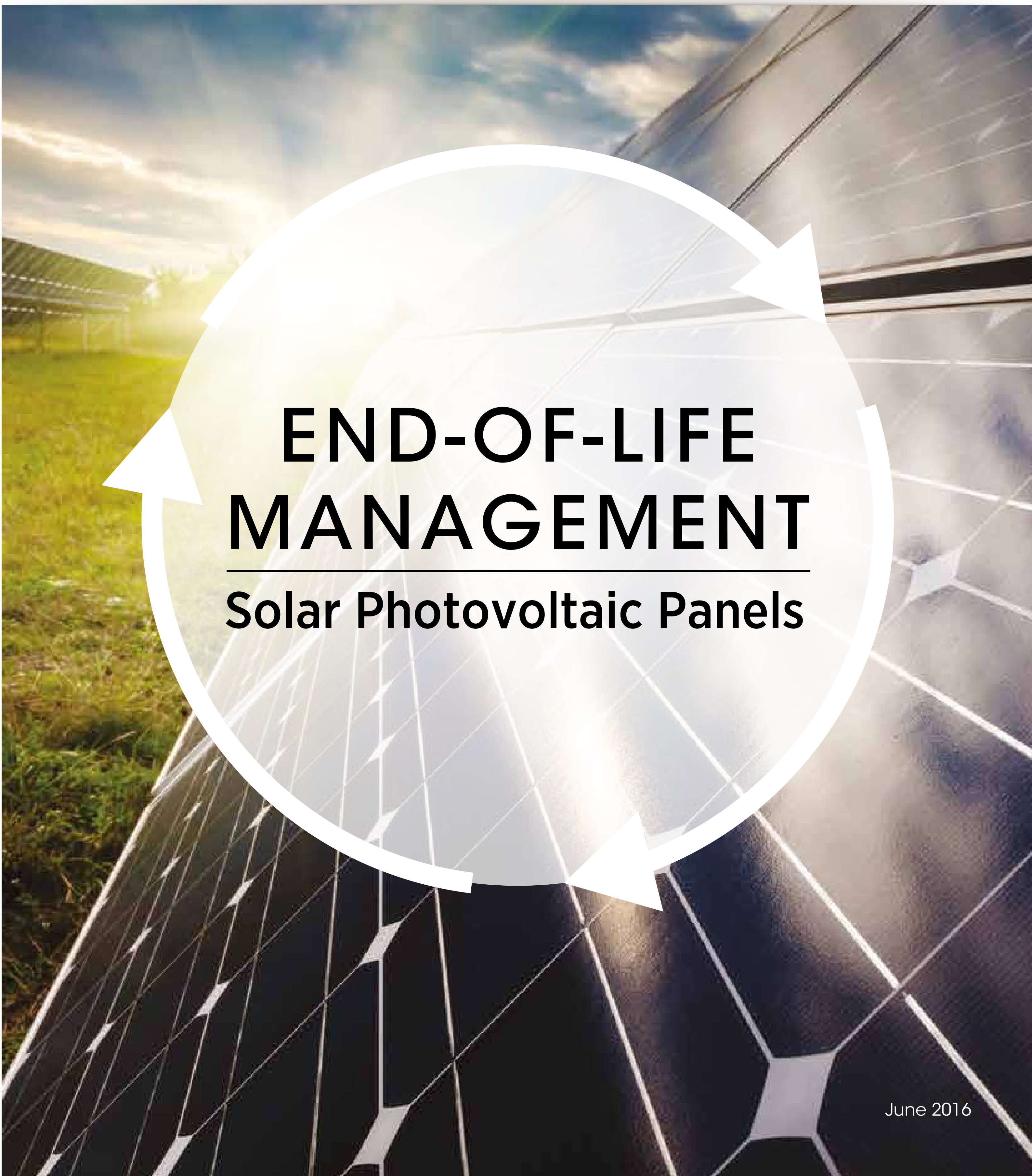

END-OF-LIFE MANAGEMENT

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.

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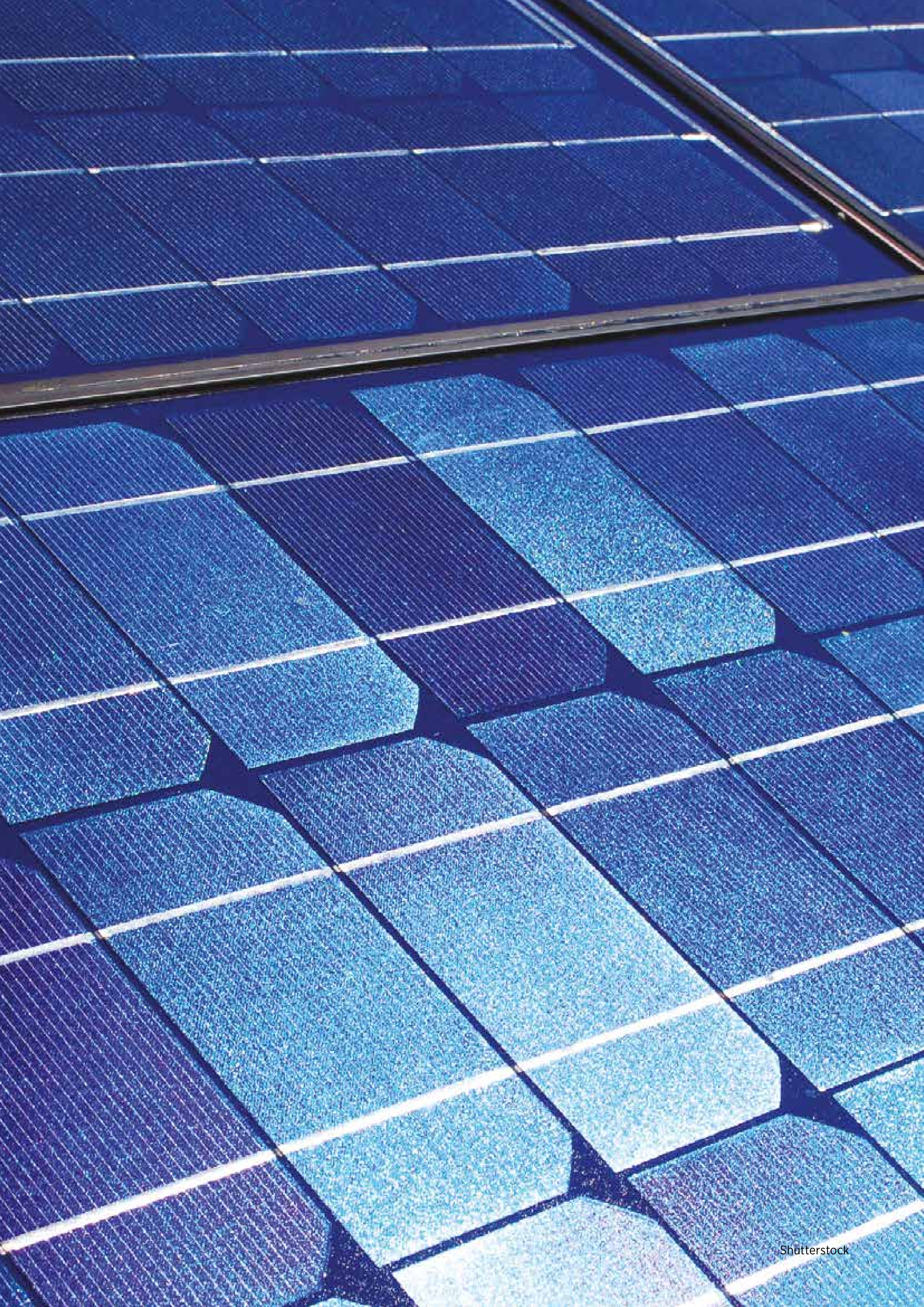

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GLOSSARY

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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FIGURES

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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

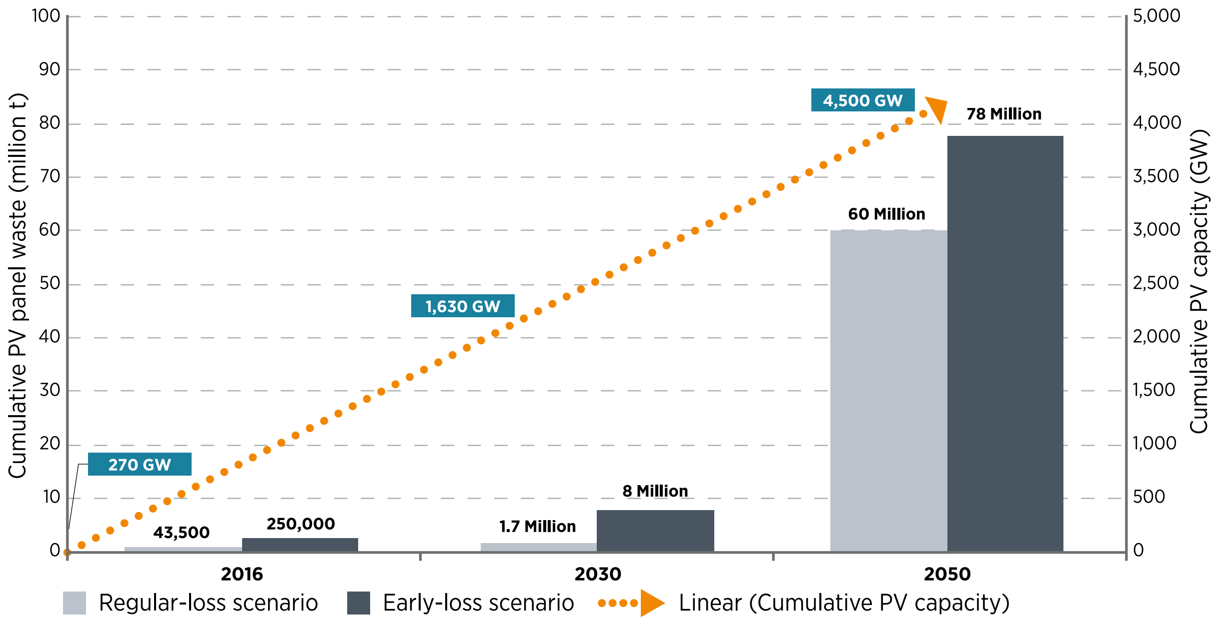
The world's total annual electrical and electronic waste (e-waste) reached a record of 41.8 million metric tonnes in 2014. Annual global PV panel waste was 1,000 times less in the same year. Yet by 2050, the PV panel waste added annually could exceed 10% of the record global e-waste added in 2014.

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.

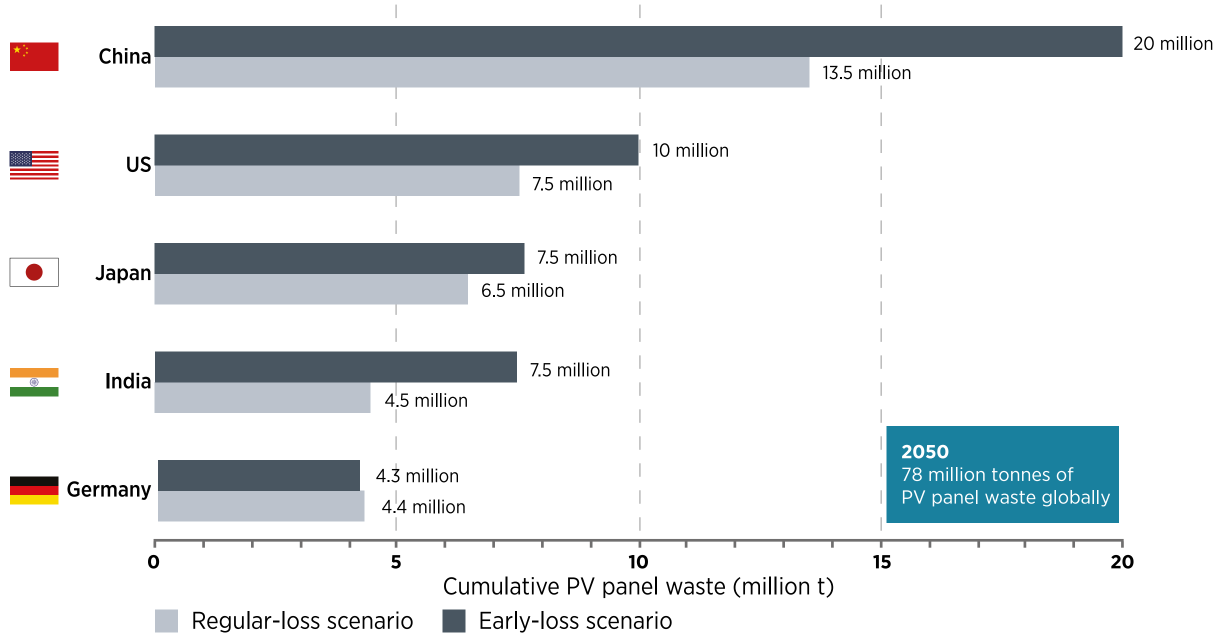
- Regular-loss: Assumes a 30-year lifetime for solar panels, with no early attrition
- Early-loss: Takes account of "infant", "mid-life" and "wear-out" failures before the 30-year lifespan

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

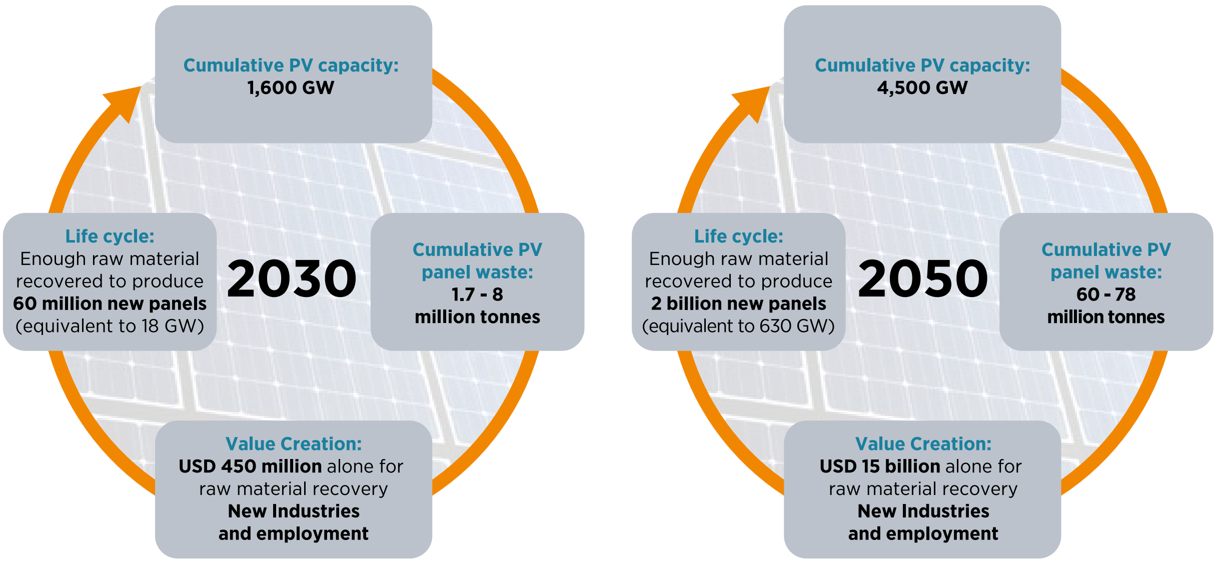


At present, only the European Union (EU) has adopted PV-specific waste regulations. Most countries around the world classify PV panels as general or industrial waste. In limited cases, such as in Japan or the US, general waste regulations may include panel testing for hazardous material content as well 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**

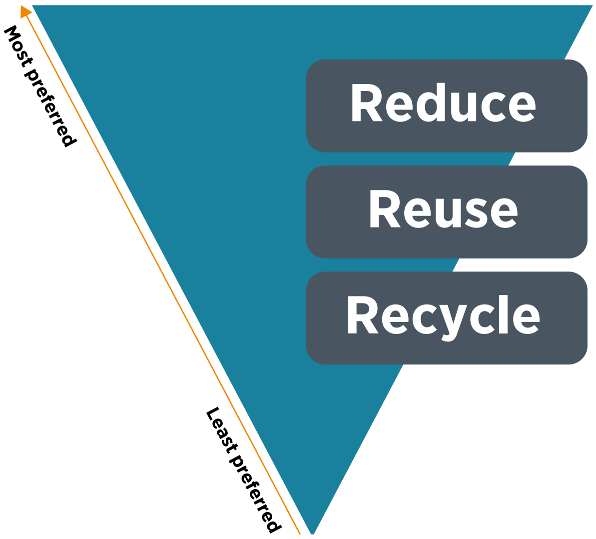
As research and development (R&D) and technological advances continue with a maturing industry, the composition of panels is expected to require less raw material. Today, two-thirds of globally manufactured PV panels are crystalline silicon (c-Si). These are typically composed of more than 90% glass, 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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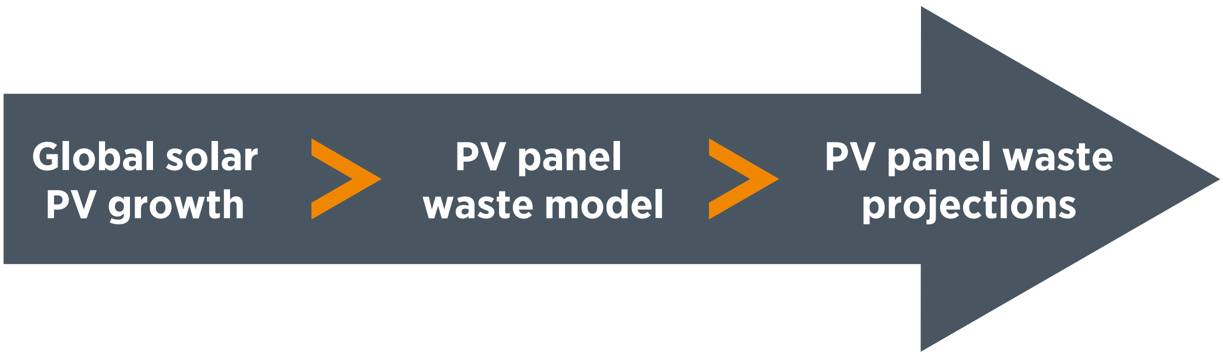
SOLAR PV PANEL WASTE PROJECTIONS

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).

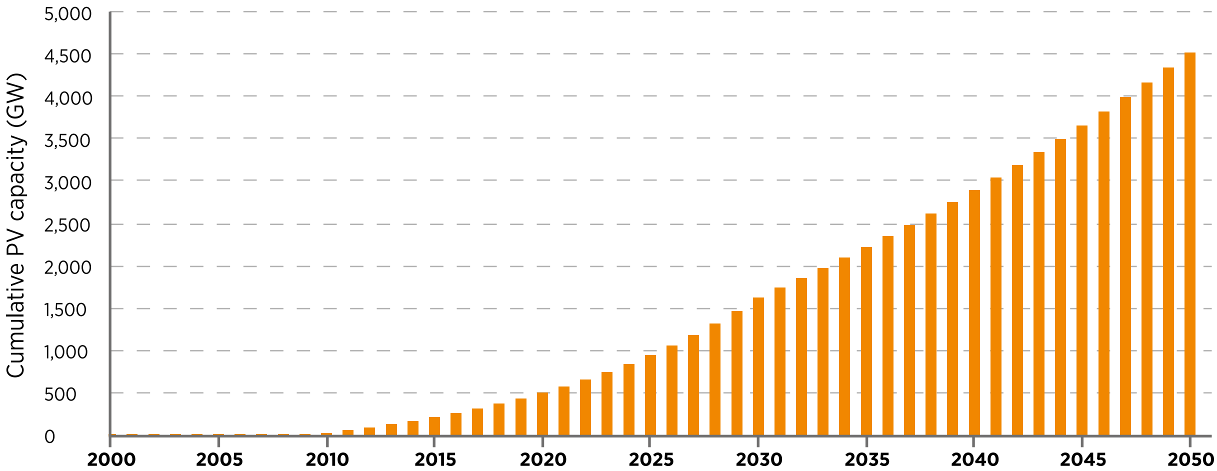
Box 2 An overview of the IEA's PV Technology Roadmap to 2050

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 CO2 in 2030 and USD 152/t CO2 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)

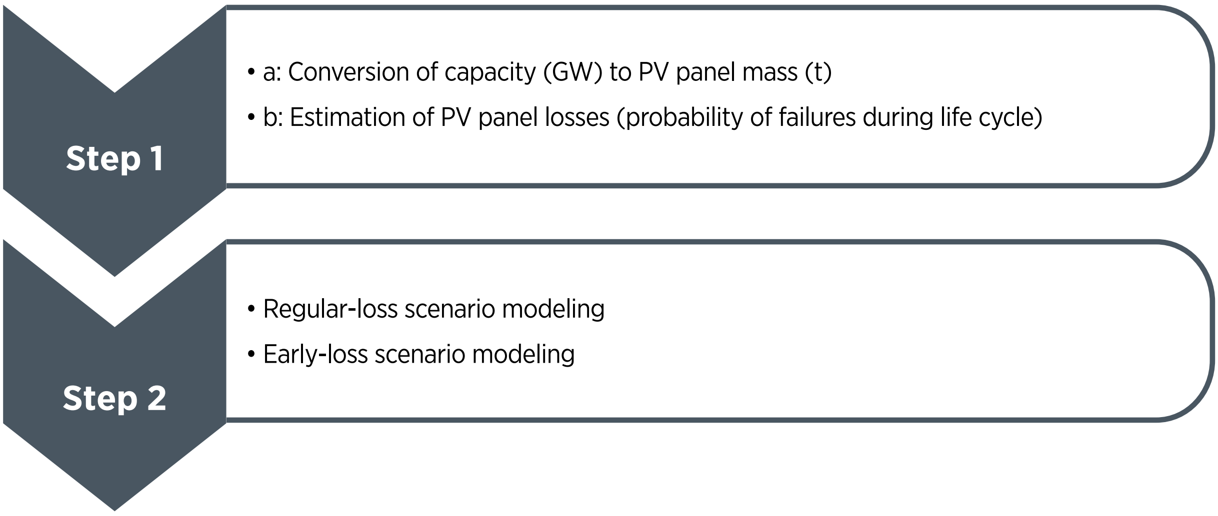
Year	2015	2020	2025	2030	2035	2040	2045	2050
Cumulative installed PV capacity (GW)	222	511	954	1,632	2,225	2,895	3,654	4,512

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.

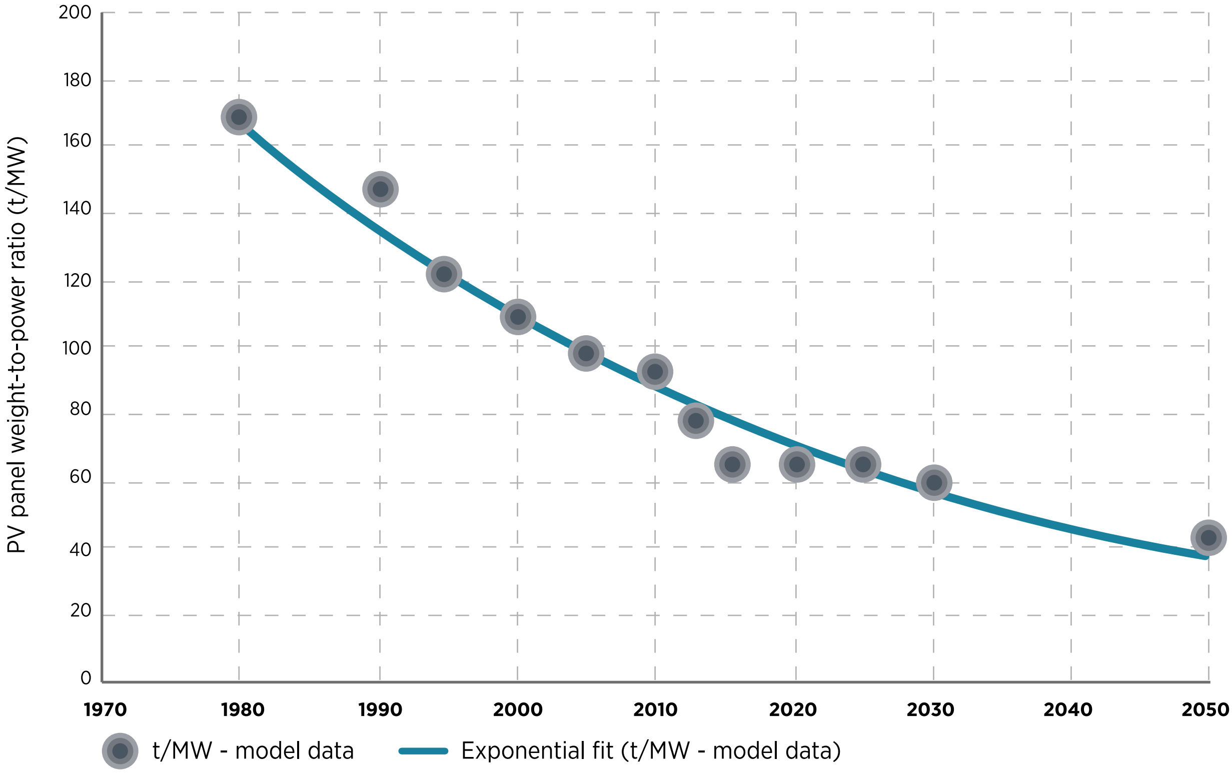
5. Note that 'volume' is used interchangeably in this report with the more accurate metric 'mass' despite the incongruence of units.

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).

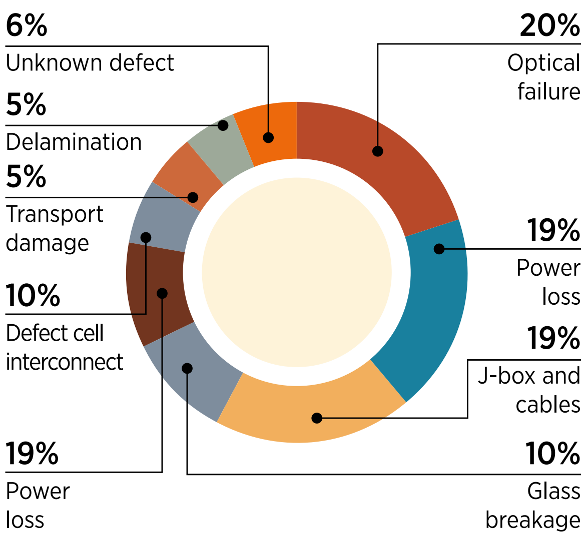
The potential origin of failures for rooftop and ground-mounted PV panels was analysed independently from PV technology and application field to estimate the probability of PV panels becoming waste before reaching their estimated end-of-life targets. The three main panel failure phases detected are shown 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

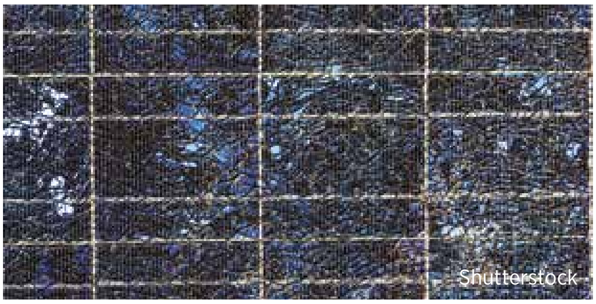
Empirical data on causes and frequency of failures during each of the phases defined above were obtained from different literature (IEA-PVPS, 2014a; Padlewski, 2014; Vodermayer, 2013 and DeGraaff, 2011). Independent of those phases, Figure 5 provides an overview of the main causes of PV panel failure.

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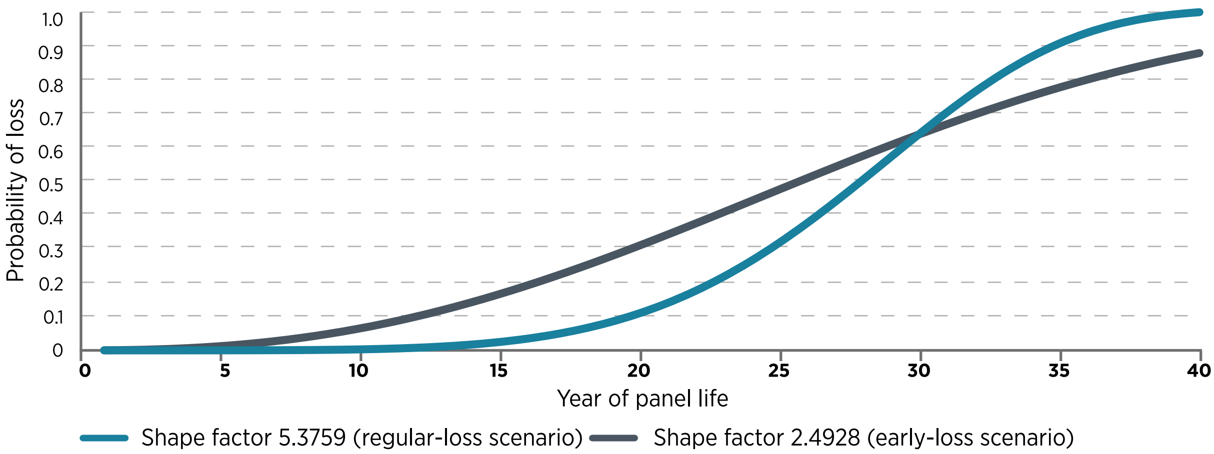
Figure 6 Example of Weibull curve with two different shape factors from Table 5



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

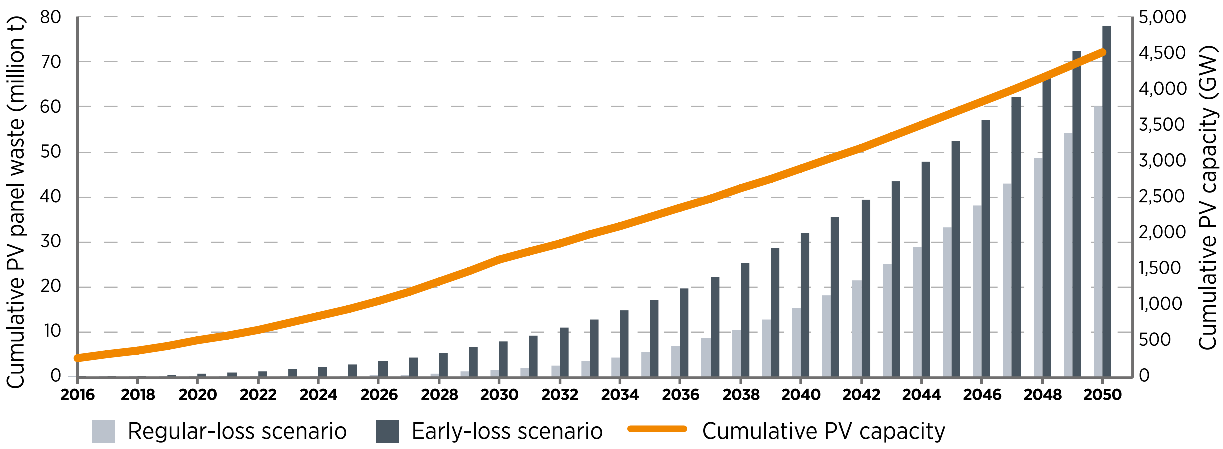
Total annual e-waste in the world today accounts for 41.8 million t (Baldé, 2015). By comparison, projected annual PV panel waste will account for no more than 250,000 t by the end of 2016 according to the early-loss scenario modelled in this report. This represents only 0.6% of total e-waste today but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

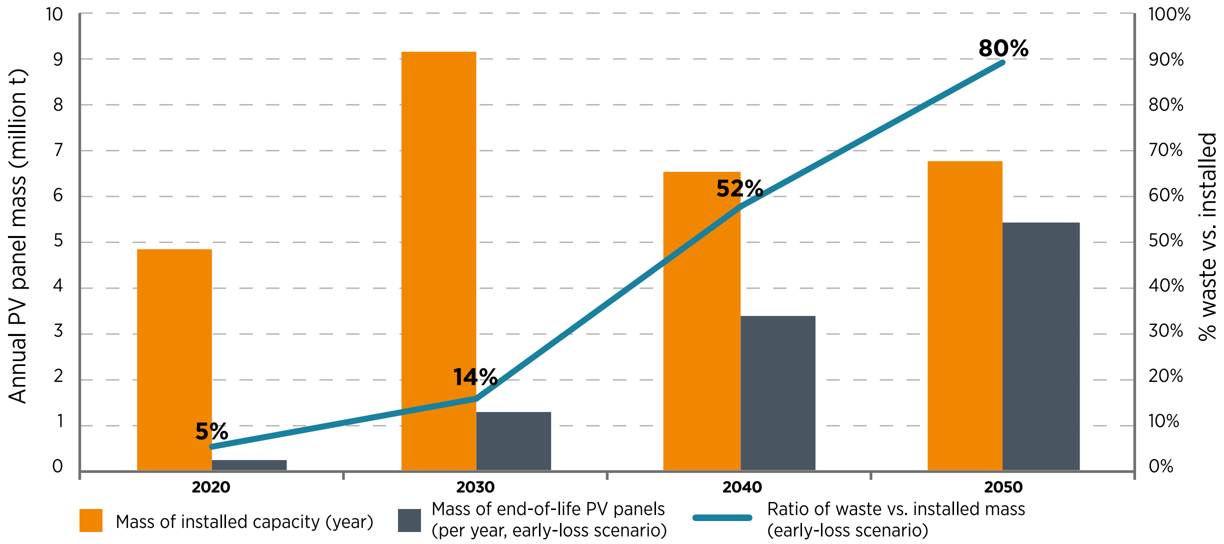
Figure 7 Estimated cumulative global waste volumes (million t) of end-of-life PV panels

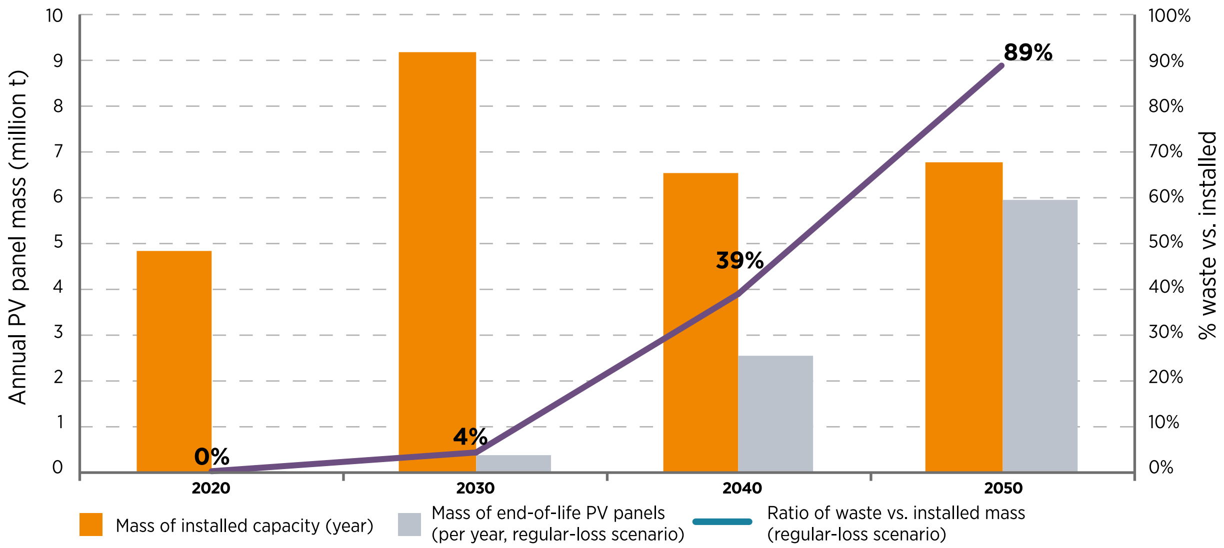


Annual PV panel waste up to 2050 is modelled in Figure 8 by illustrating the evolution of PV panel end-of-life and new PV panel installations as a ratio of the two estimates. This ratio starts out low at 5% at the end of 2020, for instance (i.e. in the early-loss scenario, annual waste of 220,000 t compared 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 and 1.5 million t in waste by the same year. Japan and India follow, with projections of between 200,000 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.

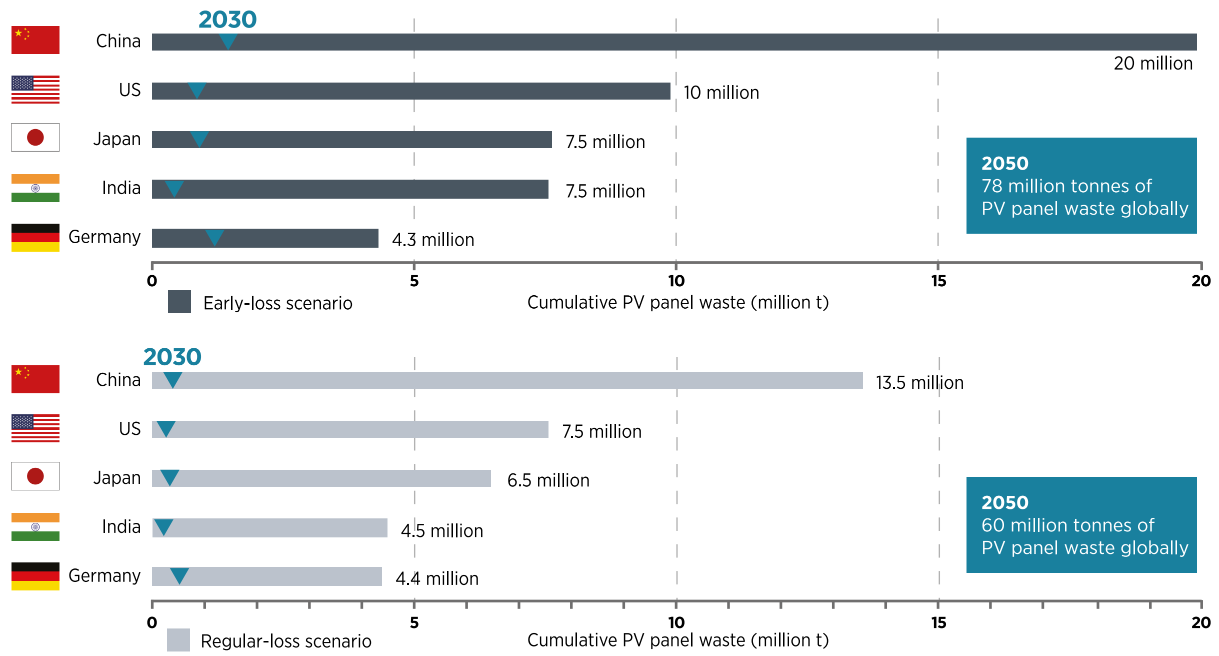
By 2030 Africa and Latin America are predicted to also see expanding PV-waste volumes. South Africa (8,500-80,000 t by 2030) and Brazil (2,500-8,500 t by 2030) will be regional leaders in this respect. Other significant PV-waste markets by 2030 will include the Republic of Korea with cumulative waste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

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

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. 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**

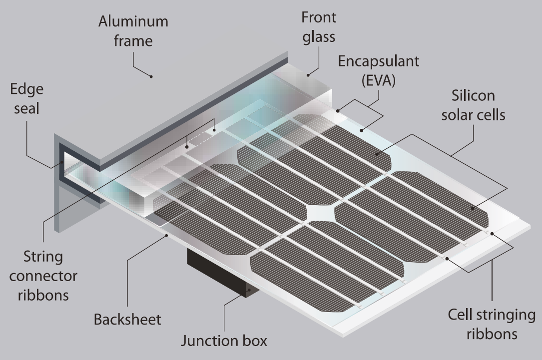
IRENA/IEA-PVPS estimates, 2016[9]

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).

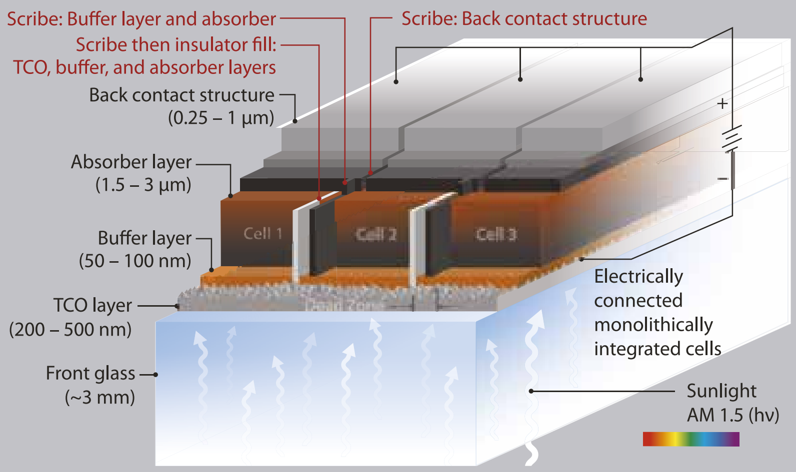
PV CYCLE

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).

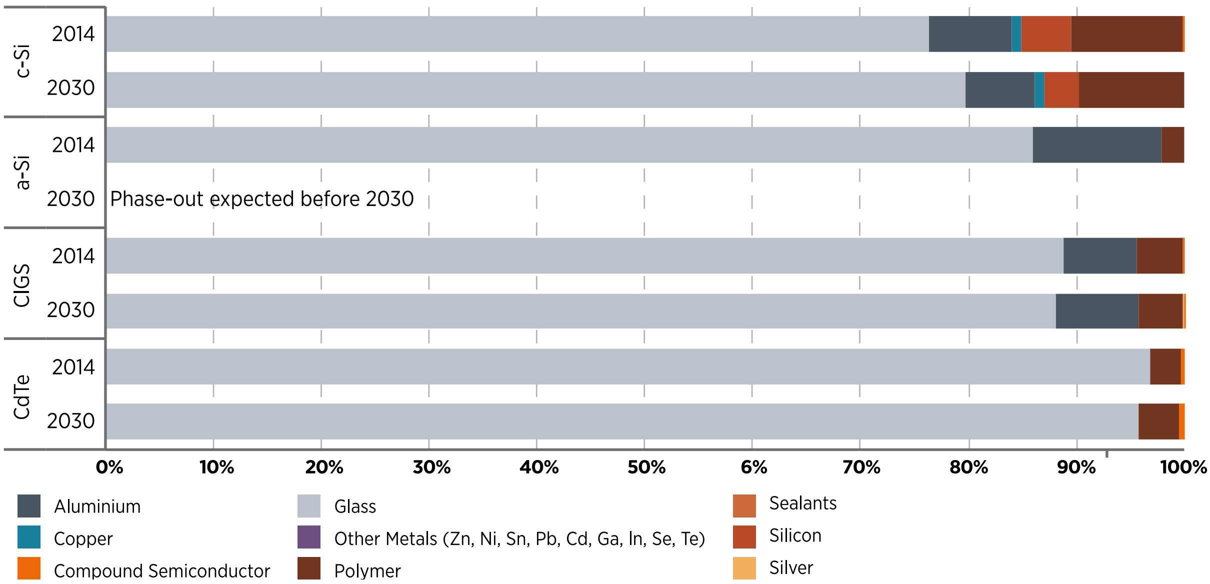
Furthermore, CIGS panels contain cell absorbers made of 'chalcopyrite,' a crystalline structure, with the general formula Cu(In,Ga)(S,Se)2. Most frequently, a mixed crystal compound copper indium diselenide with various additions of gallium (either copper indium selenide or CIGS) is used in the manufacturing 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).

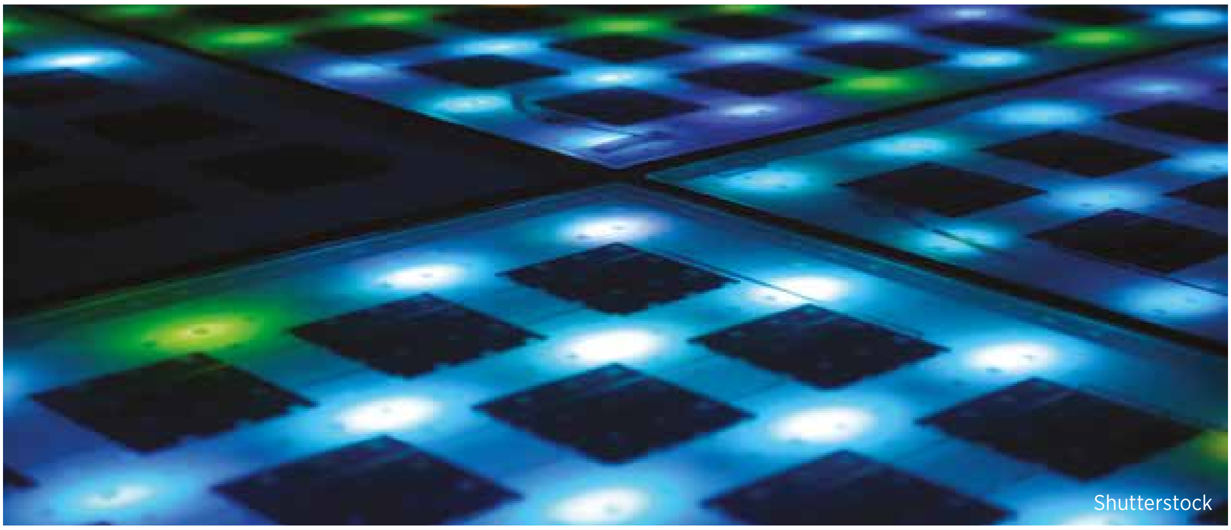
Hence, the waste management and classification for PV panels is regulated in the EU by the WEEE Directive in addition to other related waste legislation (e.g. Waste Framework Directive 2008/98/EC). This comprehensive legal framework also ensures that potential environmental and human health risks associated 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)



Shutterstock

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

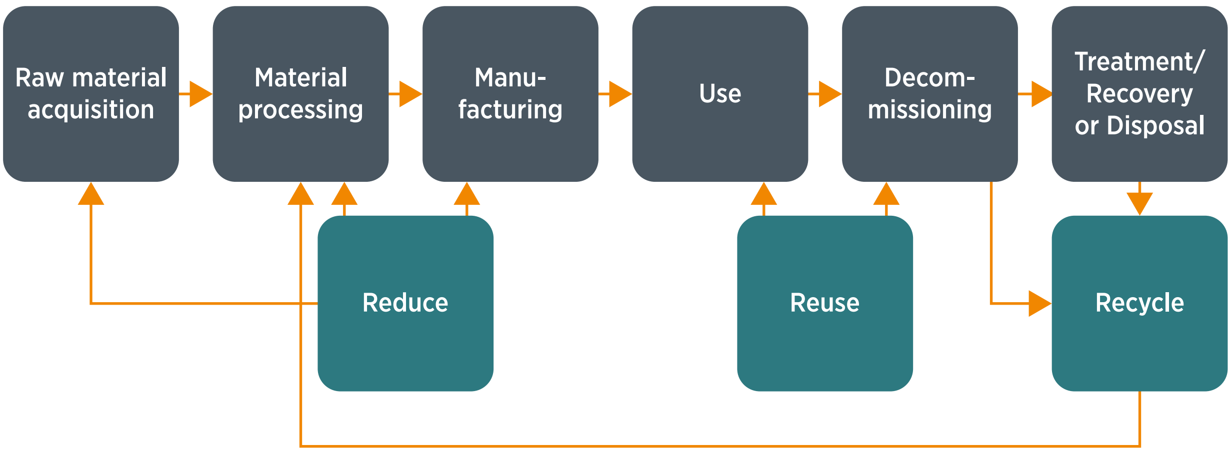
All waste management approaches follow the life cycle stages of a given product.

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.

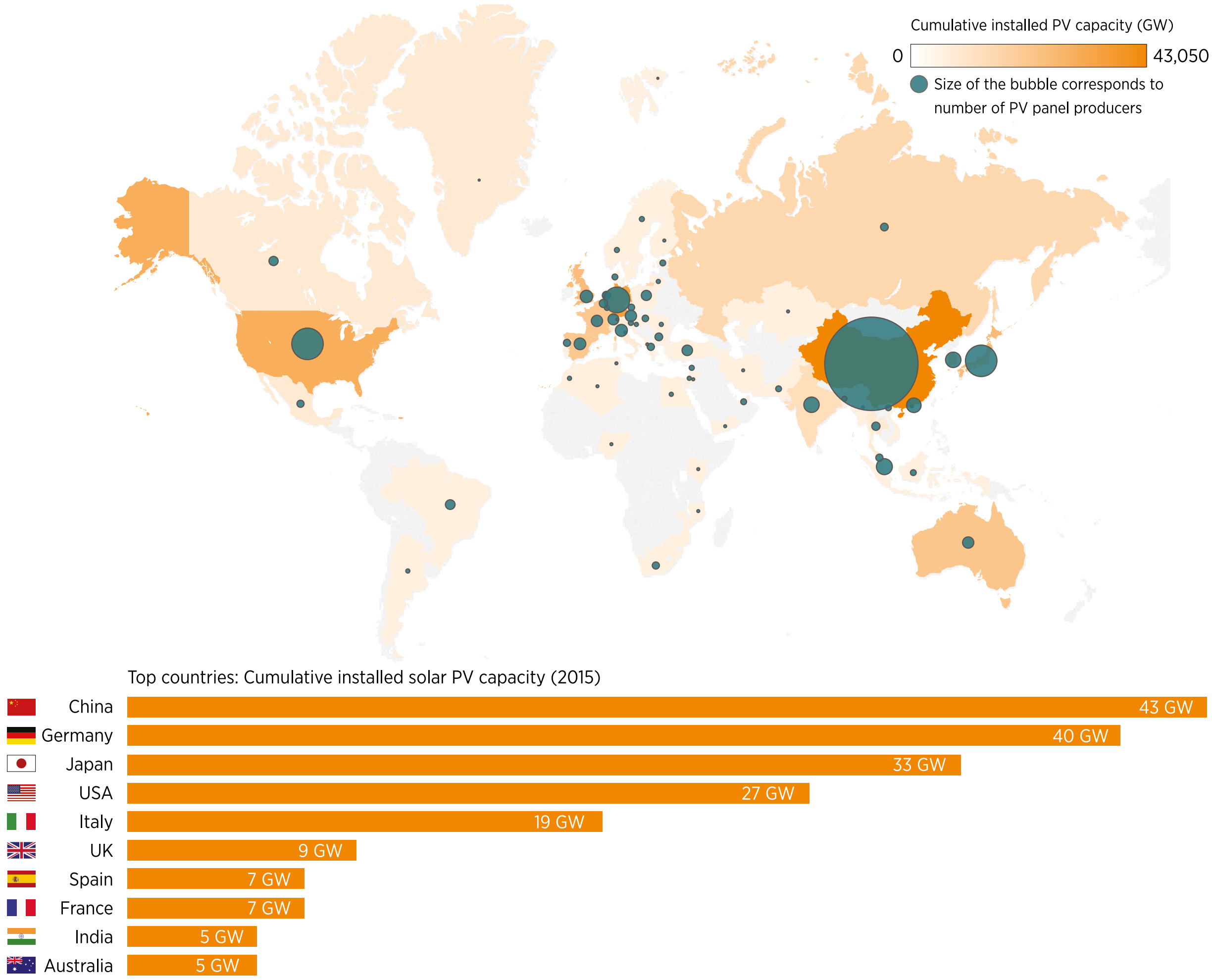
4.2. REGULATORY APPROACH: EUROPEAN UNION

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

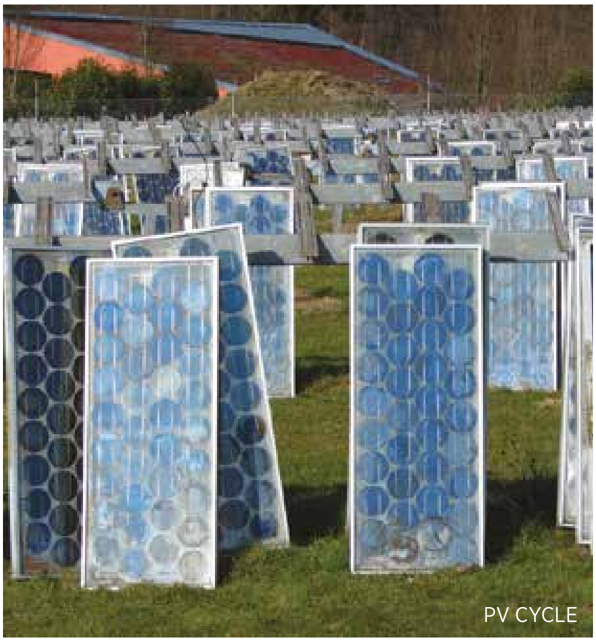
Varying requirements for end-of-life PV panels under the WEEE Directive have included classifying the waste stream as 'waste from private households' in France and the option to classify the waste as 'waste from other users than private households' in the UK. These differing definitions have implications 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

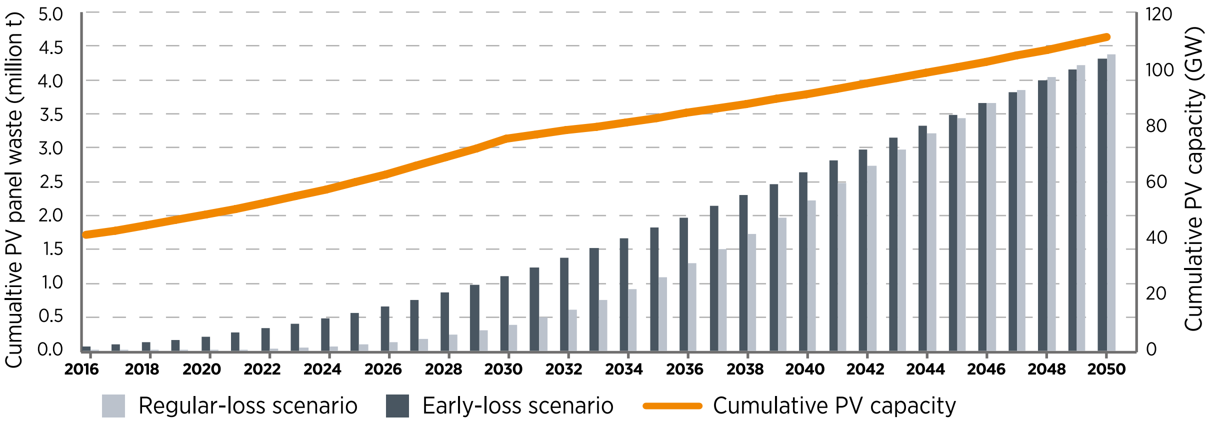
PV market and waste projection

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 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 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)

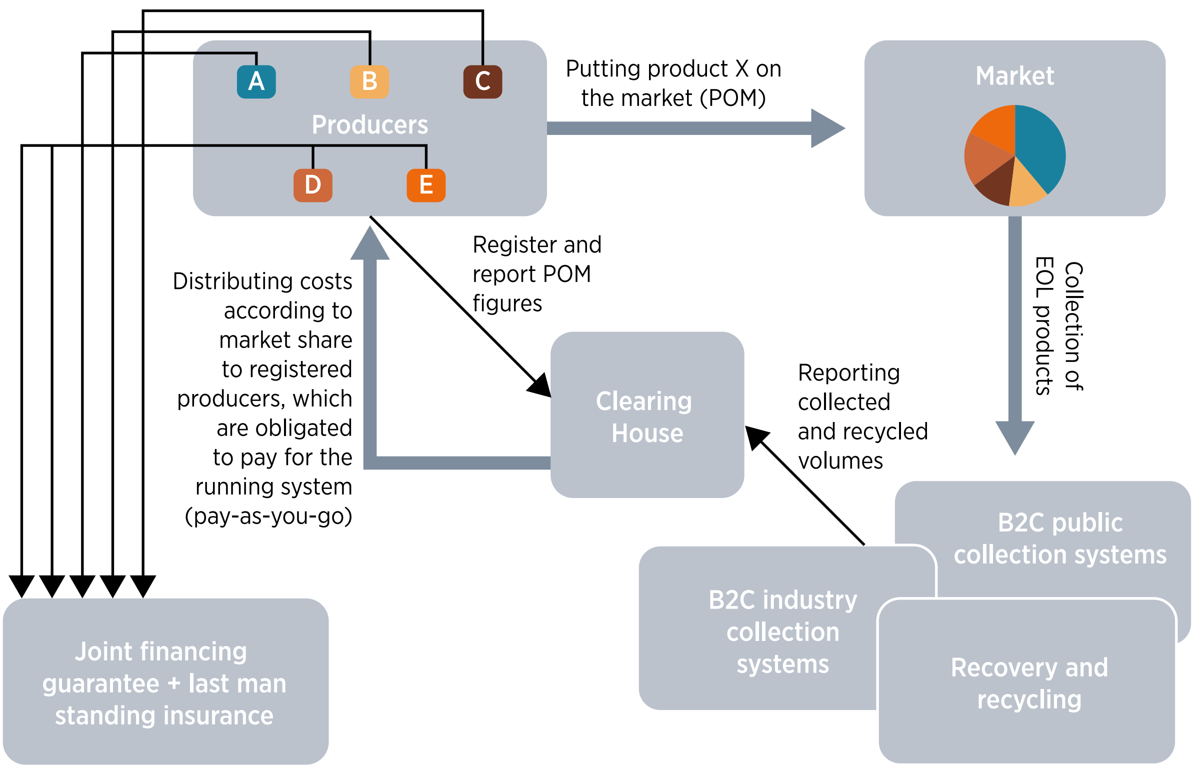
end-of-life obligations. This ensures producers are taking care of end-of-life management of PV panels sold to private households (e.g. residential rooftop systems) when placing products on the market. The approach is the result of previous experience of accredited producer compliance schemes that follow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

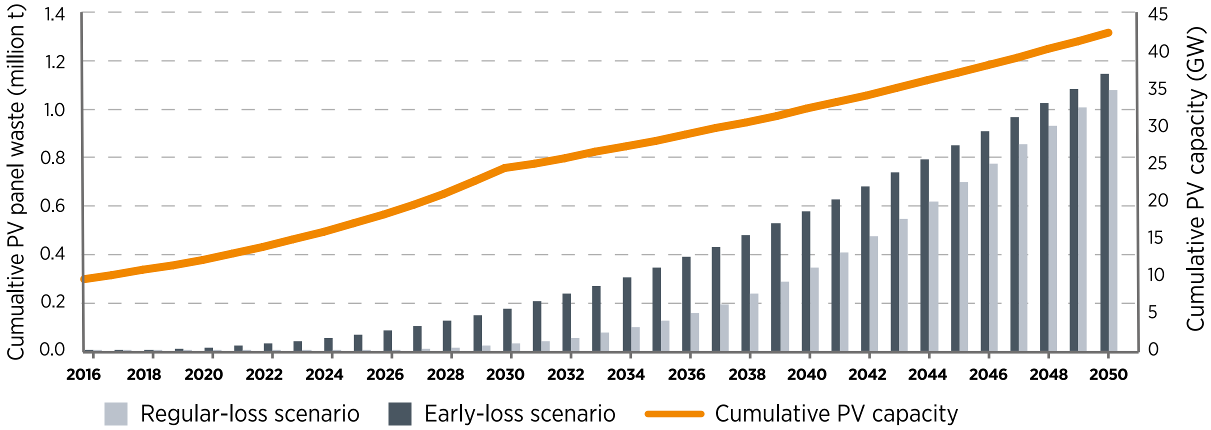
5.2 UK: YOUNG MARKET WITH EU-DIRECTED, PV-SPECIFIC WASTE REGULATIONS

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.

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

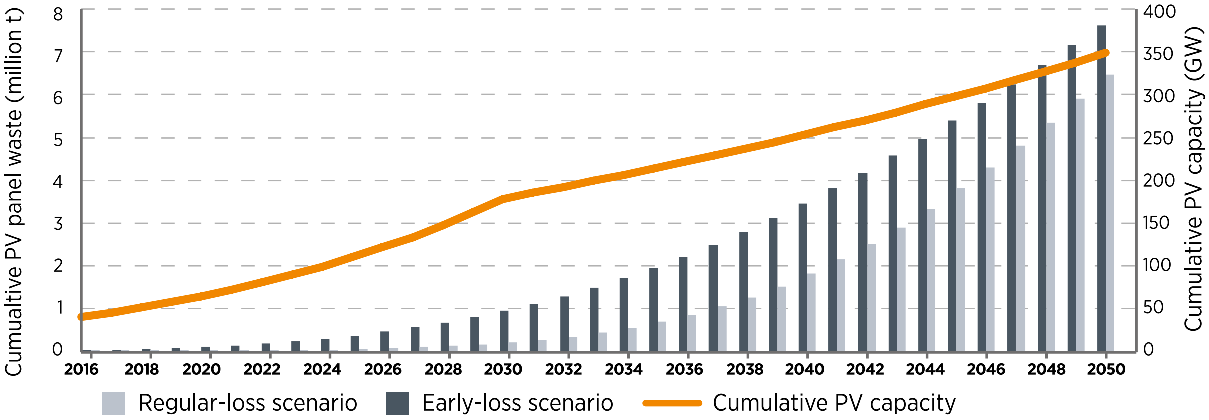
Japan has been a PV pioneer, contributing substantial R&D for decades and home to several of the world's leading manufacturers (e.g. Sharp, Kyocera and Panasonic). Although the country's own PV market was relatively small to start with, a feed-in-tariff introduced in July 2012 has stimulated rapid expansion. 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.

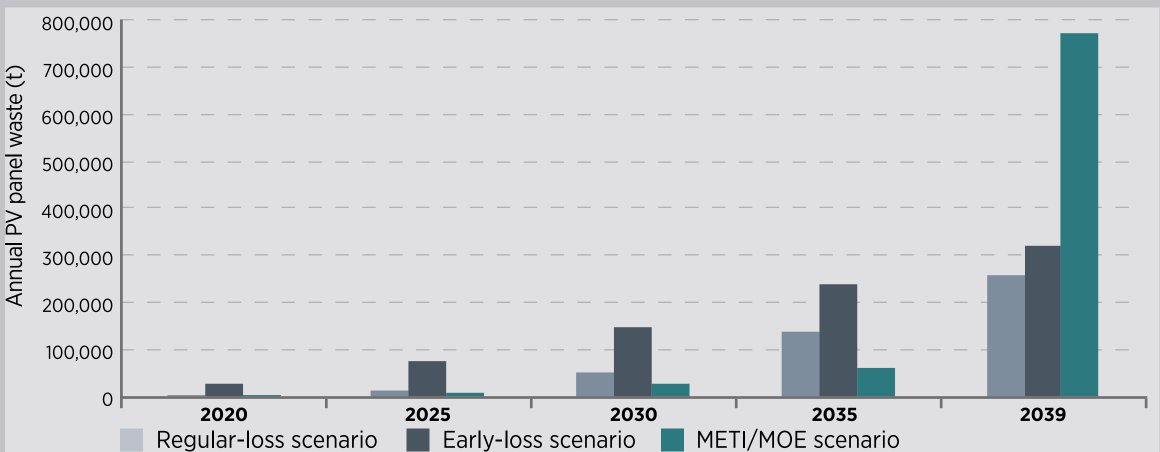
Figure 16 End-of-life PV panel waste volumes for Japan to 2050



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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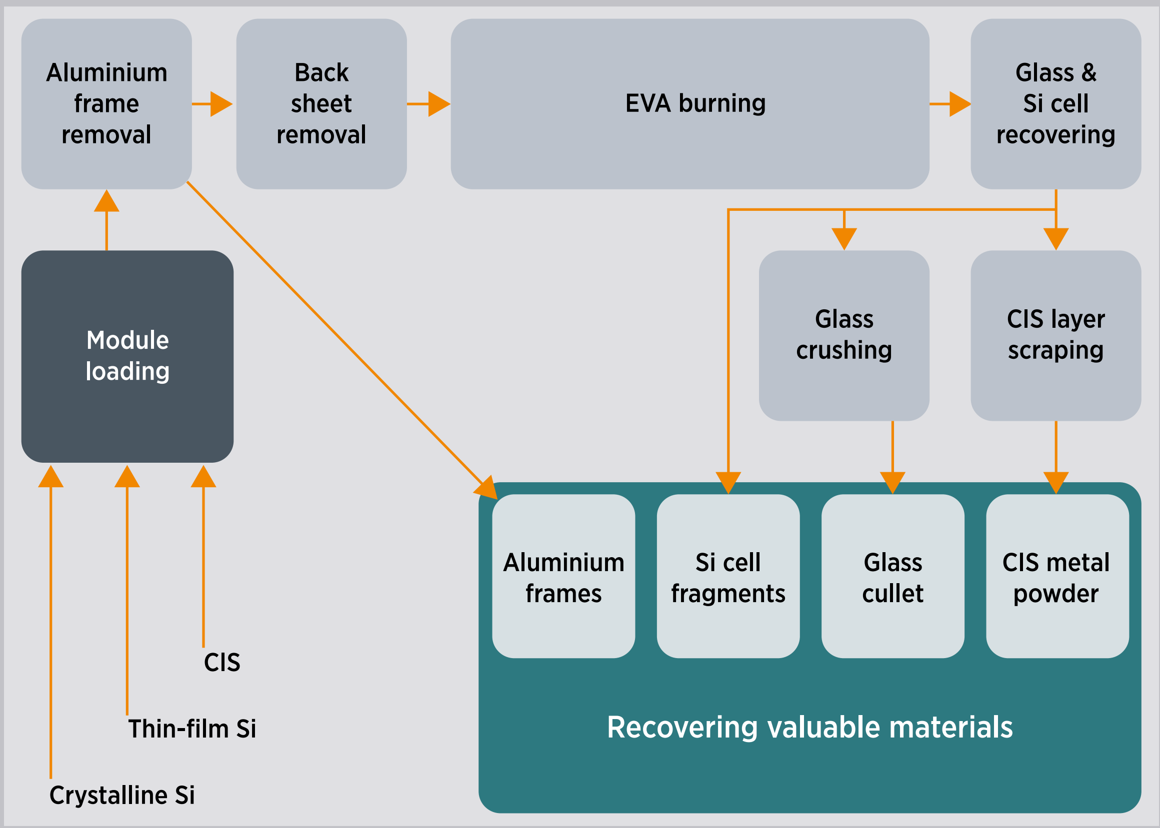
Box 15 R&D on PV panel recycling in Japan

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

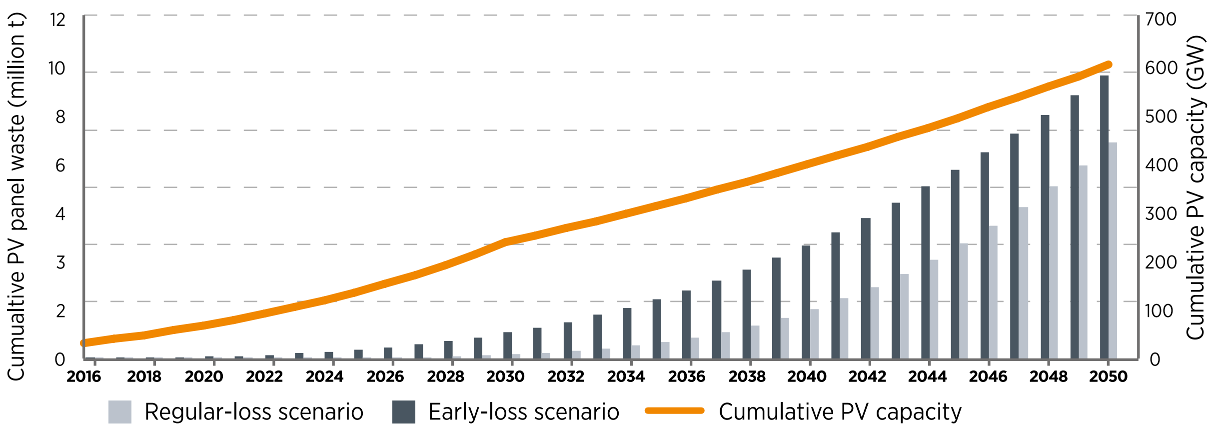
Since the mid-2000s, the US PV market has been growing rapidly, and cumulative installed capacity reached over 25 GW by the end of 2015 (IRENA, 2016b). With 7.2 GW new PV capacity installed in 2015 alone, the US presents today the fourth largest PV market in the world after China, Germany and Japan (IRENA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

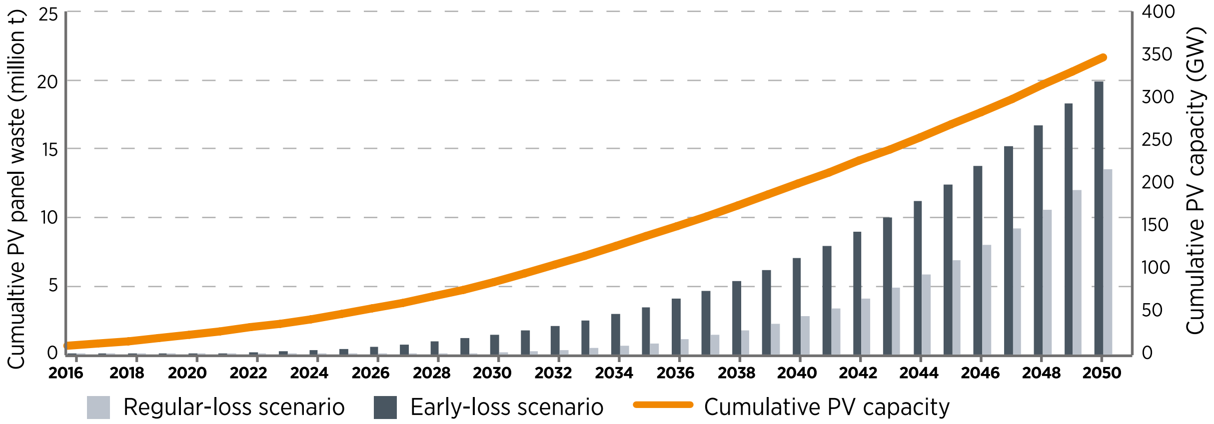
5.5 CHINA: LEADING MARKET WITHOUT PV-SPECIFIC WASTE REGULATIONS

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 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

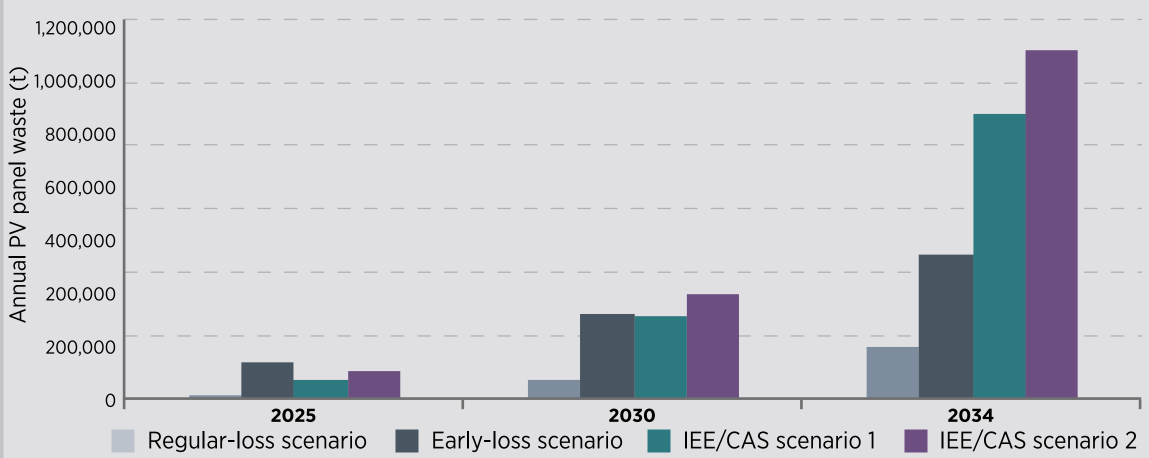


Because of China's rapidly developing PV industry, PV panel recycling is receiving more attention from the government and PV producers. China has therefore developed its own national PV panel waste projections outlined in Box 18.

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 61,250-87,000 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 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

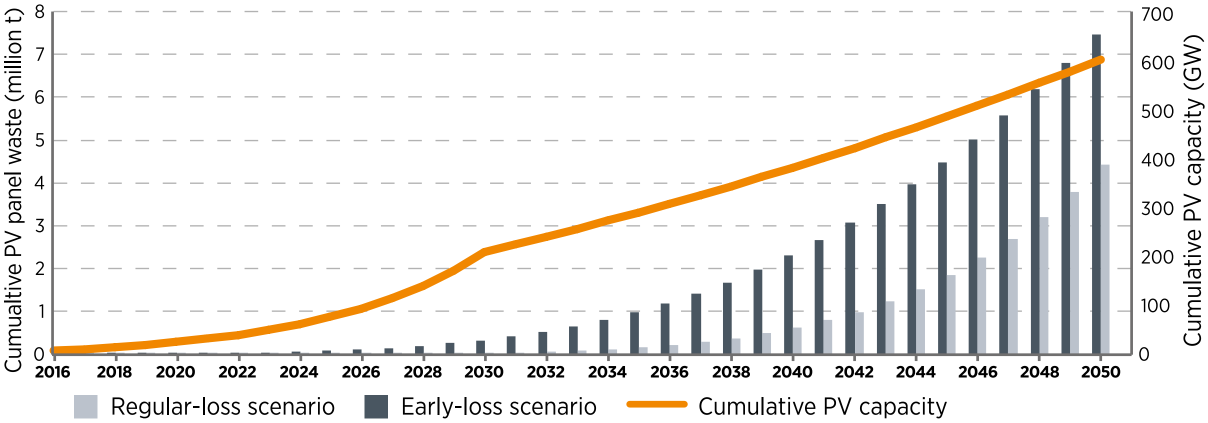
PV market and waste projection

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
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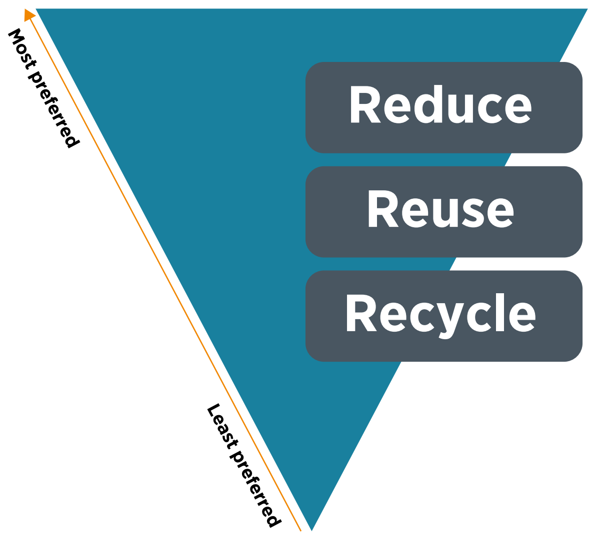
VALUE CREATION FROM END-OF-LIFE PV PANELS

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.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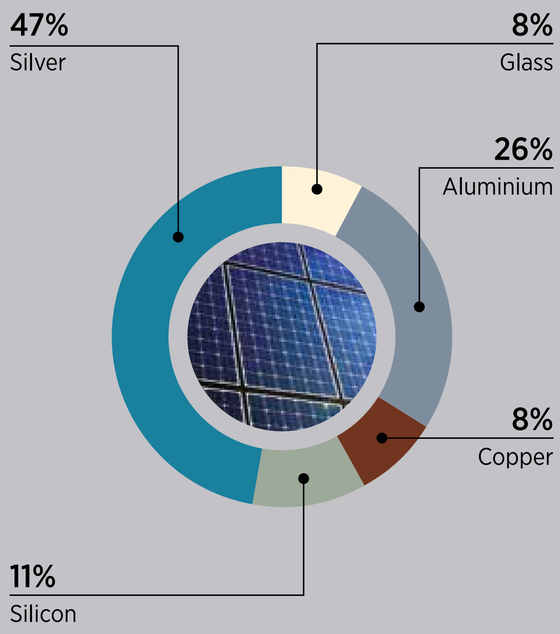
Box 22 Silver components

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.

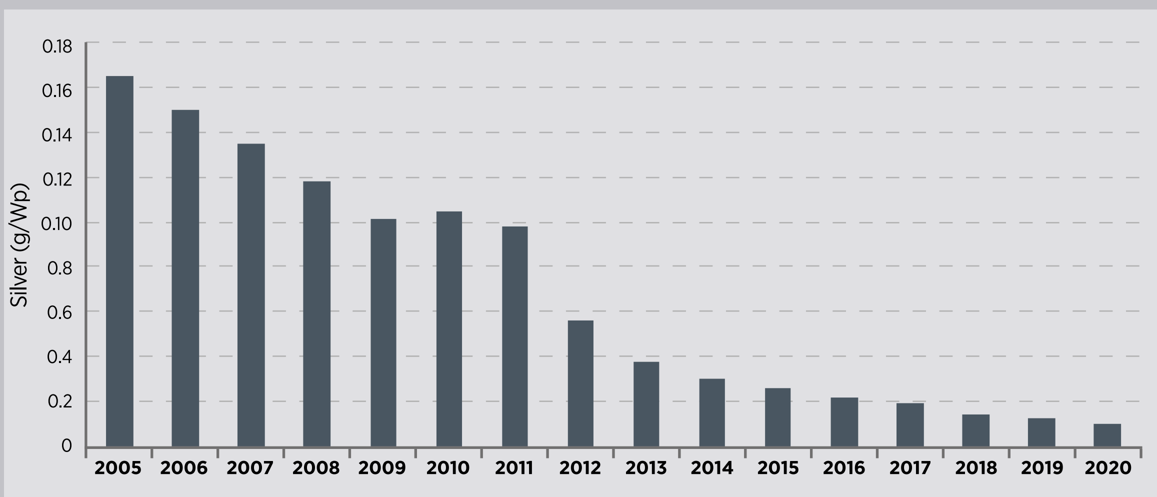
Figure 24 Relative material value (%) of a c-Si PV panel



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:

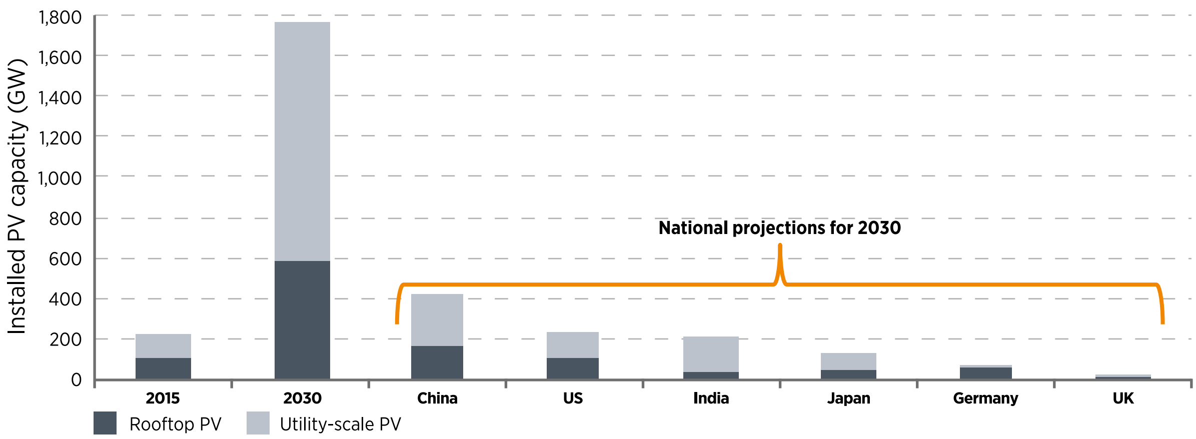
- Utility scale (> 100 kilowatts – kW)
- Home single-panel system (< 500 W), small rooftop (< 5 kW) and large rooftop system (> 5 kW)

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.

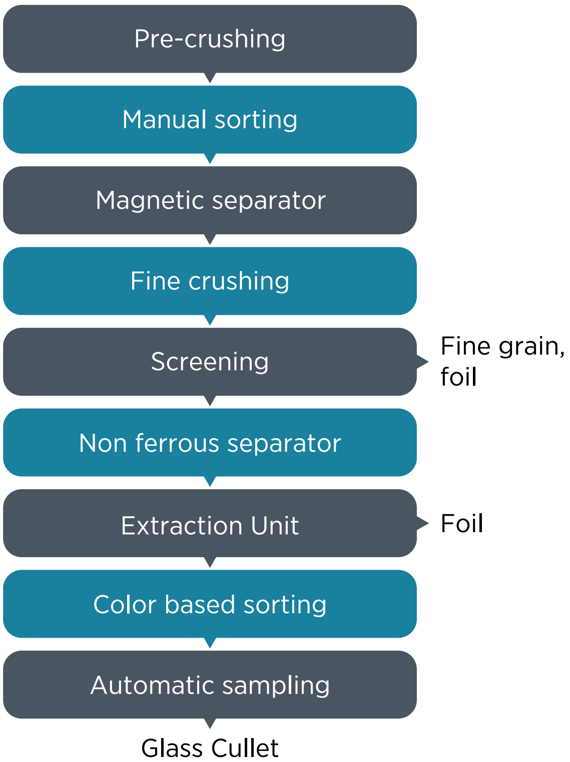
Recycling crystalline silicon PV panels

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.

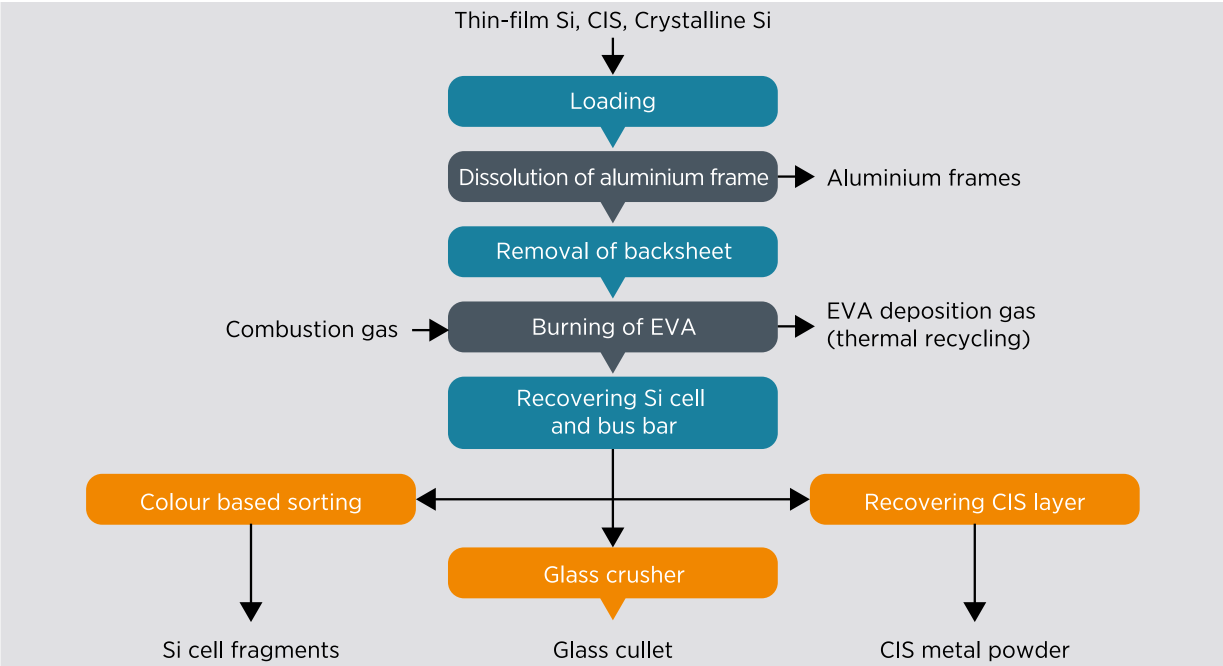
Figure 27 Process for laminated glass recycling



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.

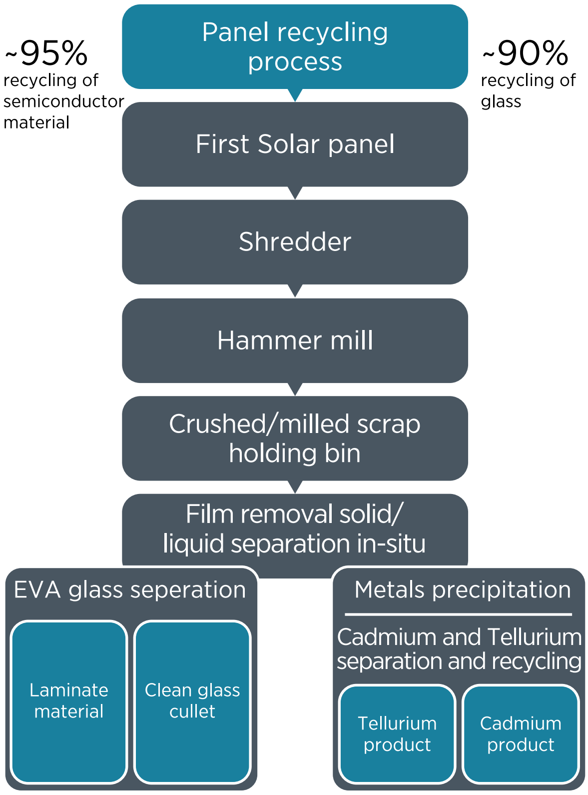
Recovering small amounts of valuable (e.g. silver, copper), scarce (e.g. indium, tellurium), or most hazardous materials (e.g. cadmium, lead, selenium) as components might require additional and more advanced processes. These are found predominantly in the glass and encapsulant (polymer) fractions. For 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:

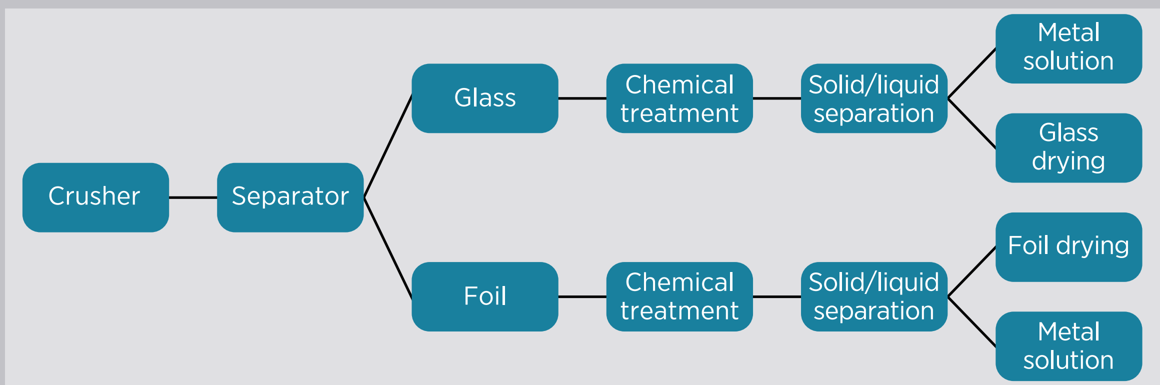
1. Panels are shredded and crushed in a hammer mill to particles of about 5 millimeters to break the lamination bond. The dust is then collected in an aspiration system equipped with a high-efficiency particulate air filter.

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).

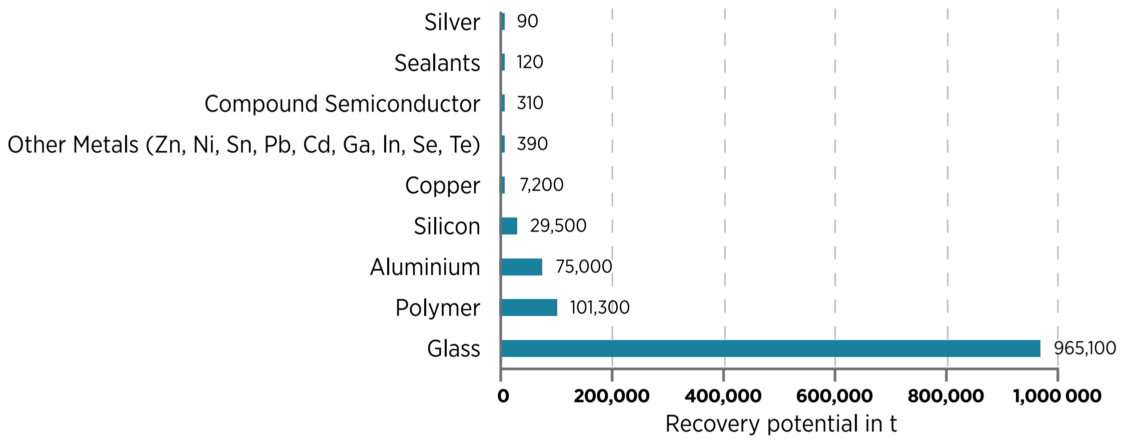
Value creation from unlocking raw materials is estimated below. The following assumptions are used:

- 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 (e.g. c-Si, CdTE, CIGS) 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.

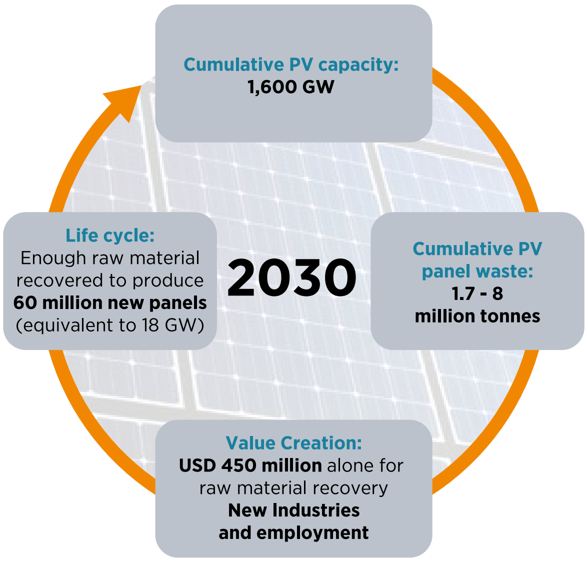
19. The value creation in different segments of the solar value chain has been studied in IRENA's publications "The Socio-economic Benefits of Solar and Wind" (2014) and "Renewable Energy Benefits: Leveraging Local Industries" (2016 forthcoming).

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.

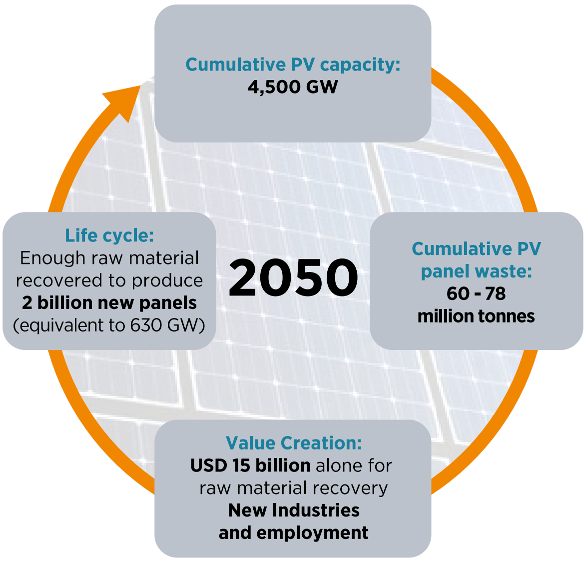
Table 13 World production of mineral commodities used in PV panels, 2015

	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

R&D Organisations

- Public and private institutions
- Producers

Repair/Reuse services industry

- Producers
- Independent service 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

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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