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Circular Solar

The Opportunities and Challenges for Increased Circularity in the Solar PV Industry

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While every effort has been made to faithfully reflect and build on the inputs provided, this paper does not necessarily reflect the views of these companies or the interviewees.

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Executive Summary

This report looks at the challenges, opportunities and pathways to an improved circular economy for solar photovoltaic (PV) panels in the EU. For the purposes of this analysis, circular economy is defined as "a system which maintains the value of products, materials and resources in the economy for as long as possible, and minimises the generation of waste [...and...] where products are reused, repaired, remanufactured or recycled."

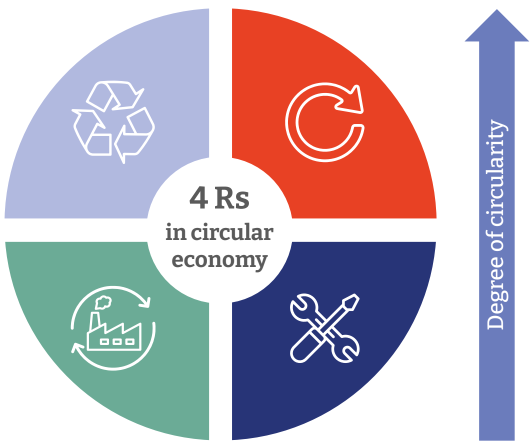
Solar PV is one of the most widely deployed and cost-effective technologies for renewable electricity generation, featuring heavily in national and global net zero strategies and pathways for the energy sector transformation. In the past two decades, the adoption of solar PVs has grown by around 25 per cent per year, driven by a virtuous cycle of improved efficiency and declining costs. Following the agreement at COP28 in Dubai to triple renewables globally by 2030, the solar boom is expected to expand further. Despite advancements in alternative solar cell technologies, most of this growth will stem from silicon-based PVs, driven by their technological maturity and market dominance.

Developing circular economy solutions for solar PVs is essential to avoid causing an environmental crisis by addressing the climate crisis. Transitioning from the largely linear solar PV value chain to a more circular model can reduce import dependency, waste, and emissions from raw material extraction and manufacturing, delivering benefits for the environment, climate, economies and society. Circular economy strategies such as extending the lifespan of solar PVs and maximising material recovery through recycling can significantly lower resource consumption, pollution, environmental harm and emissions – especially when powered by sustainable energy. Although circular economy strategies for solar PVs have attracted growing interest in recent years, these have largely failed to achieve economies of scale, with many promising new operations existing in the margins of the industry.

Investing now in the development and scaling up of circular economy technologies and strategies presents an important economic opportunity for the EU. As the number of damaged and decommissioned solar PVs grows, so do the business opportunities for repair, refurbishing and recycling operators to develop economies of scale and enhance the financial viability of their operations. The global economic opportunity associated with the circular economy and the value of recovered raw materials from solar PVs is expected to increase radically over the next 10–35 years. A broad range of companies across the solar PV value chain can benefit from these emerging opportunities by investing in new designs, technologies and business models.

Policy and governance are crucial drivers of the business transition to a circular economy. The EU has strong circular economy ambitions backed by an extensive set of directives and regulations, some of which are yet to be implemented fully. However, measuring progress towards these targets is difficult in the absence of detailed and comprehensive data on the location, age and status of each solar PV deployed in each EU Member State.

Figure 1: Circular economy



Reuse a product in good condition for the same purpose for which it was conceived.

Repair a defective product so it can be used for its original function.

Remanufacture a product using parts of discarded products in a new product with the same function.

Recycle materials from waste products and reprocess these into new ones, whether for original or other purposes.

Developing circular solutions is challenging in a context where linear models, behaviours and infrastructure prevail. This research identifies and discusses four key factors that impede the upscaling of circular economy strategies in the solar PV industry. These include:

1. **Weak market formation on the supply and demand side.** Demand for circular services and recycled materials remains low, hindered by cheap new PV imports, inconsistent waste volumes, and a lack of incentives for circular consumer practices among households and businesses.

2. **Technological challenges.** Solar PVs have been designed to maximise efficiency rather than repairability and recyclability. The layered design of silicon-based solar PVs inhibits cost-effective, high-purity material recovery, while limited standardisation of component design and material data complicates repair. Limited profitability from resale of recovered materials requires recyclers to charge for their services, discouraging demand.

3. **Ineffective policy frameworks.** Current frameworks and directives fail to provide targeted, long-term incentives and clear waste management responsibilities.

4. **Lack of contextual accelerants and enablers.** Insufficient resource mobilisation deters investment in circular business models, while logistical challenges – such as dispersed waste volumes and inadequate infrastructure – exacerbate costs and inefficiencies.

Overcoming these barriers requires holistic solutions, including better collaboration, data-sharing, targeted policy support and scaled infrastructure, to unlock the economic and environmental benefits of circularity in the PV industry.

This report emphasises the need for collaboration between businesses and policymakers to foster demand, incentivise innovation and implement cohesive policies. Co-ordinated actions – such as establishing effective end-of-life strategies, advancing technology readiness and leveraging policy support – will be essential in creating a robust circular economy framework that sustains the growth and sustainability of the solar PV sector. Our five recommendations for businesses and policymakers to address the circular economy challenge in the PV value chains are shown in the infographic below.

Figure 2: Recommendations for businesses and policymakers

Recommendations for businesses

1. **Strengthen collaboration** across the value chain to encourage circularity in product design and improve recycling efficiency and material recovery.
2. **Leverage digital technologies** to enable panel tracking, predictive maintenance and improved resource recovery.
3. **Create demand** for second-life products and materials by forming buyer coalitions and promoting shared standards.
4. **Encourage and adopt circular business models** by using recycled materials, components and second-life PVs, and expanding operations into repair, refurbishment and advanced recycling.
5. **Increase investment** in workforce training and research and development (R&D) through pilot projects to drive innovation in design, repair, recycling and sustainable materials.

Recommendations for policymakers

1. **Develop a dedicated circular economy package for PVs**, focusing on actions that facilitate circular design, second-life strategies and high-value material recovery.
2. **Align small-scale takeback systems with regionally distributed recycling infrastructure** to enable economies of scale to develop for PV panel takeback, tracking and logistics.
3. **Channel public sector funds to support circular innovation and commercialisation**, focusing on scalable projects for reuse, repair and high-value recycling.
4. **Create demand for second-life PVs, recycling and recycled materials** by establishing reliable quality standards for second-life PVs and implementing public awareness campaigns to promote circularity.
5. **Develop mechanisms to foster international collaboration** despite geopolitical sensitivities.

List of abbreviations

AI	Artificial intelligence
B2C	Business-to-customer
C2C	Cradle to Cradle
CdTe	Cadmium telluride
CEAP	Circular Economy Action Plan
CIGS	Copper indium gallium selenide
CO2	Carbon dioxide
CRM	Critical raw materials
DG ENV	European Commission Directorate-General for Environment
DSSC	Dye-sensitised solar cells
EOL	End-of-life
EPR	Extended producer responsibility
ESG	Environmental, social and governance
GHG	Greenhouse gas
IoT	Internet of Things
OPV	Organic photovoltaic
PV	Photovoltaic
R&D	Research and development
SG	Solar grade
TIS	Technological innovation system
TRL	Technology readiness level
VAT	Value Added Tax
WEEE	Waste from Electrical and Electronic Equipment (WEEE)

1. Introduction

The purpose of this report is to explore and examine the opportunities and challenges to improving circularity in the solar photovoltaic (PV) value chain. This is a topic that has recently begun to attract growing attention from policymakers and stakeholders across the solar PV industry, but progress remains slow. Many emerging operations providing circular solutions are struggling to achieve financial viability and scale-up.

The circular economy can help to address multiple challenges that contribute to the climate crisis. It will reduce demand for raw material extraction and fossil fuels that are needed in their manufacture, as well as waste volumes and the associated risk of land and groundwater pollution. By reducing import dependency, waste, and emissions from raw material extraction and manufacturing processes, the circular economy can deliver benefits for the environment, climate, economies, and people's wellbeing.

The EU defines circular economy as "a system which maintains the value of products, materials and resources in the economy for as long as possible, and minimises the generation of waste. This means a system where products are reused, repaired, remanufactured or recycled."[1] Due to the first letter of each activity, these actions are widely referred to as 'Rs', and can be ranked on the degree of circularity, with 'higher R' strategies enabling materials in the product chain to retain their value for longer. Reuse constitutes the highest-level R among the four, and recycling the lowest. Although the Rs themselves refer primarily to activities that focus on the end-of-life of a product, these Rs will necessitate extensive changes across the product value chains, including design, to preserve value and materials.

The transition to a more circular economy is one important part of the broader sustainability transformation. The EU, the UK and the US – alongside several other countries and private sector companies around the world – have pledged to reduce their greenhouse gas (GHG) emissions to net zero by 2050. This means that they are committed to cutting their GHG emissions to a level equivalent to carbon dioxide (CO_2) removal from the atmosphere, achieving a net zero balance. To realise this goal, countries will need to invest heavily in economy-wide decarbonisation and improved energy efficiency and material efficiency, as well as circular economy strategies that keep products and materials in circulation for longer periods of time.

This report brings together two strands of the net zero transition challenge that are closely intertwined but rarely discussed in conjunction with each other: circular economy and the energy sector transformation. There is a growing need to ensure that measures to reduce GHG emissions through increased deployment of renewable electricity technologies do not create new problems. For example, environmental degradation and damage from mining activities for critical raw materials (CRMs) for renewable electricity technologies[2] or large quantities of waste from decommissioned low carbon technologies, which have shorter lifespans than fossil fuel technologies such as coal and gas power plants.

To keep the scope of the report manageable while providing concrete examples of opportunities and challenges, this report focuses on one specific renewable energy technology: solar panels (often referred to as solar PV), and the need to create more circular value chains for this technology. Solar PV is one of the most widely deployed and cost-effective technologies for renewable electricity generation, featuring heavily in national and global net zero strategies and pathways for the energy sector transformation.[3] The adoption of PV panels has accelerated much faster than expected just two decades ago: between 2010 and 2020, the installed capacity grew by an average of 25 per cent per year. Due to increased uptake, which enabled the solar PV markets to benefit from economies of scale, the cost fell by 15 per cent each year.[4]

Considering the worldwide surge in solar PV deployment since 2010 and expected future growth in the deployment of the technology,[5] waste from solar PVs is becoming a challenge that cannot be ignored. With an average solar PV lifetime of 25–30 years, the amount of material contained in damaged and decommissioned solar PVs globally is projected to increase exponentially between 2021 and 2030, reaching more than 200 Mt by 2050.[6] If the current trends in disposal continue unchanged, most of this solar PV waste will end up in landfills or uses that reduce the value of the materials, such as cement production.[7]

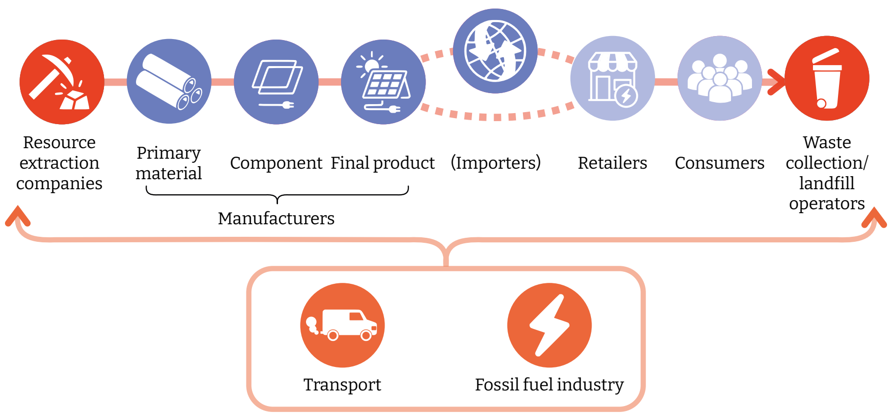
Like many other industries, the solar PV industry currently operates largely under a linear 'take–make–use–dispose' model, whereby natural resources are extracted, panels are manufactured, commercialised, deployed, and then mostly disposed of in landfills, where soil and groundwater contamination can occur. This is depicted in Figure 1.

Circular economy strategies could help countries to mitigate the environmental impact of the growing numbers of damaged and decommissioned solar PVs. Addressing sustainability questions across the whole value chain now, before waste volumes become unmanageable, is essential to maximise the environmental and economic benefits of the solar energy boom and to minimise its potential adverse impacts on the planet.

The incoming surge of solar waste also presents multiple opportunities for stakeholders across the PV value chain. These opportunities range from the development of circular product design to new business models centred around reuse, repair, remanufacturing/resale, and recycling. In recent years, circular economy strategies for solar PVs have attracted growing interest, as stakeholders across the solar PV industry have become increasingly aware of the importance of improving the industry's sustainability and resilience. Despite this growing attention, circular economy strategies for solar PV have largely failed to achieve economies of scale, with many promising new operations existing in the margins of the industry, unable to grow their market share.

Given this context, the primary aim of this report is to promote greater circularity within the PV industry. We make the **societal and environmental case** for circularity for PVs: without circularity, we will end up with high levels of solar PV waste, which poses a risk to environmental and human health and wellbeing.

Figure 1: Linear value chain for solar PVs



We also make the **business case** for enhanced circularity for PVs: companies can generate revenue from investing in new designs, technologies and business models in this field. While the initial markets may be primarily in the EU and the UK, where the policy frameworks to incentivise a circular economy transition are more developed, these will grow as the challenges of disposing of large volumes of solar PVs become global. However, we acknowledge that developing circular solutions in a context where linear models, behaviours and infrastructure prevail is not easy, and many barriers to upscaling emerging circular economy solutions continue to hinder progress.

The report starts with a background chapter that highlights why we need to transition from a linear value chain to a more circular one, and the environmental, economic and social benefits this could deliver. Chapter 3 provides an overview of the different solar PV technologies and an assessment of the comparative advantages and disadvantages of different solar cell materials, focusing on factors that influence their environmental footprint of recyclability. Chapter 4 looks at how circular the solar PV value chain is currently, focusing on silicon-based solar PVs as the market-leading technology. This chapter gives an overview of the basic structure and composition of a solar panel, second-life strategies designed to extend the lifespan of solar PVs through repair, refurbishment and reuse, and different recycling strategies that are being developed to reduce the amount of solar PV waste ending up in landfills. The last section of Chapter 4 includes a brief description of the EU's circular economy policies that are relevant to the solar PV industry.

Chapter 5 draws on qualitative research, exploring what a truly circular and sustainable solar PV value chain could look like. It maps out the key stakeholders who could play an active role in enhancing circularity within the PV industry, and illustrates how stakeholders could create and capture value through circular economy strategies. Chapter 6 identifies and discusses the key barriers to enhanced circularity, while Chapter 7 puts forward suggestions for how policy could foster greater circularity in the PV industry. Chapter 8 concludes by providing actionable recommendations for businesses and policymakers to accelerate the adoption of circular economy strategies in the solar PV industry.

This report is the final output of a collaborative, multi-disciplinary research project by the University of Cambridge Institute for Sustainability Leadership (CISL), IfM Engage at the University of Cambridge, and E.ON Group Innovation GmbH. This year-long project, running throughout 2024, was funded by E.ON Group Innovation GmbH. It combined a background literature review with detailed technological analysis, insights from industry experts and policy analysis. More detailed descriptions of the methods and analytical frameworks used in this study (relating to different sections of the report) are available in Annex 1 (technological analysis) and on request (qualitative analysis).

Although much of the content is applicable to solar PV value chains globally, this report focuses primarily on the EU context. It does not include assessment of the circular economy solutions for solar PV batteries, PV industry reshoring or trade policies to protect the EU's solar PV industry.

2. Why do we need more circularity in the PV industry?

This chapter presents the rationale for increased circularity in the PV sector, examining its necessity and the potential benefits. Solar PV waste is projected to grow rapidly as countries expand solar deployment to achieve decarbonisation goals and renewable energy targets. However, it is important to ensure that efforts to address climate change do not end up causing environmental damage that can also be harmful to the environment and human health. With effective oversight and management, a shift towards greater circularity in the PV value chain can deliver substantial environmental, economic and social benefits.

The 'solar surge' and growth in solar PV waste

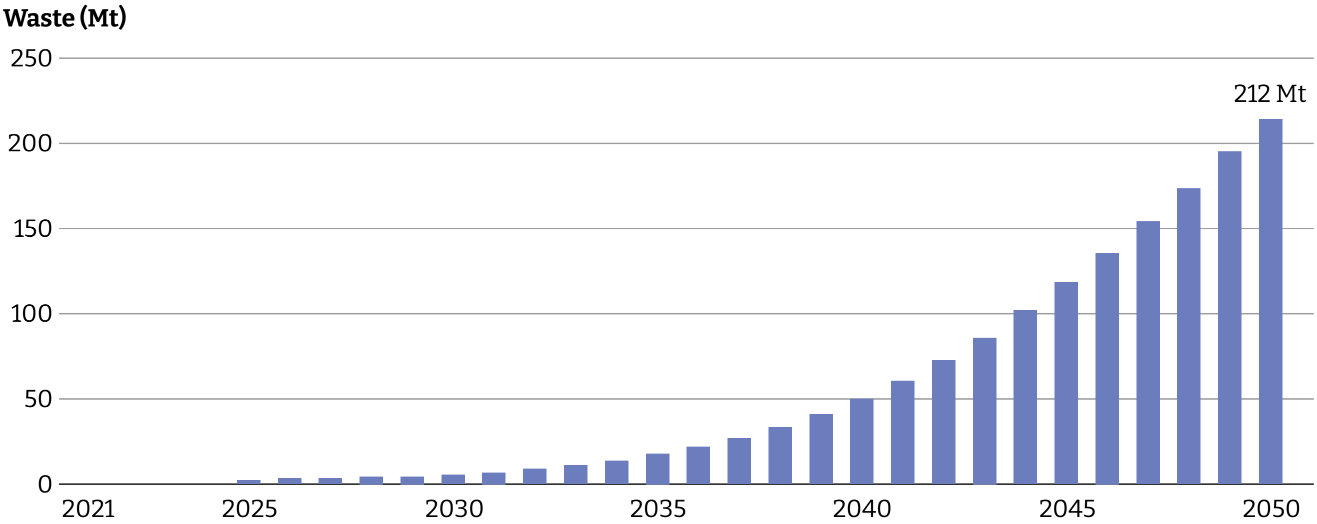
Solar PVs currently contribute nearly 4.5 per cent of the world's electricity generation.[8] This capacity is continuing to grow: assuming continuation of the current trend, the world will install 593 GW of solar panels in 2024. That is 29 per cent more than were installed in the previous year, maintaining strong growth even after an estimated 87 per cent surge in 2023.[9] In 2023, solar PVs accounted for three-quarters of renewable capacity additions worldwide,[10] surpassing all other renewable technologies, including wind and hydropower, for the first time in history.[11]

By 2050, the world's installed solar PV capacity is expected to surpass 4.6 TW.[12] China leads this transition, boasting a cumulative solar installed capacity of 710 TW as of June 2024, following investments totalling US$50 billion since 2011.[13] Other countries experiencing rapid growth in solar power include the United States (total: 200 GW), Japan (total: 90 GW) and India (total: 89.4 GW). In Europe, 2023 marked another record-breaking year for solar PV, with 55.9 GW installed across the 27 Member States, representing a 40 per cent increase from 2022. Germany led this growth, adding 14.1 GW and bringing its cumulative installed capacity to 82 GW.[14]

Considering the worldwide surge in PV deployment since 2010 and an average solar PV lifetime of 25–30 years, the amount of material embedded in damaged and decommissioned solar panels is growing rapidly and will likely follow a pattern that is similar to the installation boom. As shown in Figure 2, waste from cumulative solar PV projects globally is expected to increase from 0.2 Mt in 2021 to 4 Mt in 2030, around 50 Mt in 2040 and more than 200 Mt by 2050.[15] In 2030, countries with the largest amounts of solar PV waste are expected to include Germany (400,000 tonnes), China (200,000 tonnes) and Japan (200,000 tonnes).[16]

From 2030 onwards, the amount of solar PV waste is estimated to rise from around 4–14 per cent of total generation capacity in 2030 to over 80 per cent by 2050.[18] If current trends in the disposal of decommissioned solar PVs continue unchanged, the vast majority of this solar PV waste will end up in landfills, albeit not necessarily within the EU.[19] In jurisdictions such as the EU where landfilling is prohibited and recycling targets are in place, it is not unusual for decommissioned solar PVs to be exported to emerging economies where rules regarding landfilling, incineration and reselling for second-life use or low-value recycling are absent, less stringent, or not properly enforced.[20] Despite these policies and

Figure 2: Waste projection for solar waste



Source: IRENA, 2022, p326[17]

frameworks, measuring progress towards achieving these targets is difficult in the absence of detailed and comprehensive data on the location, age and status of each solar PV deployed in each EU Member State.

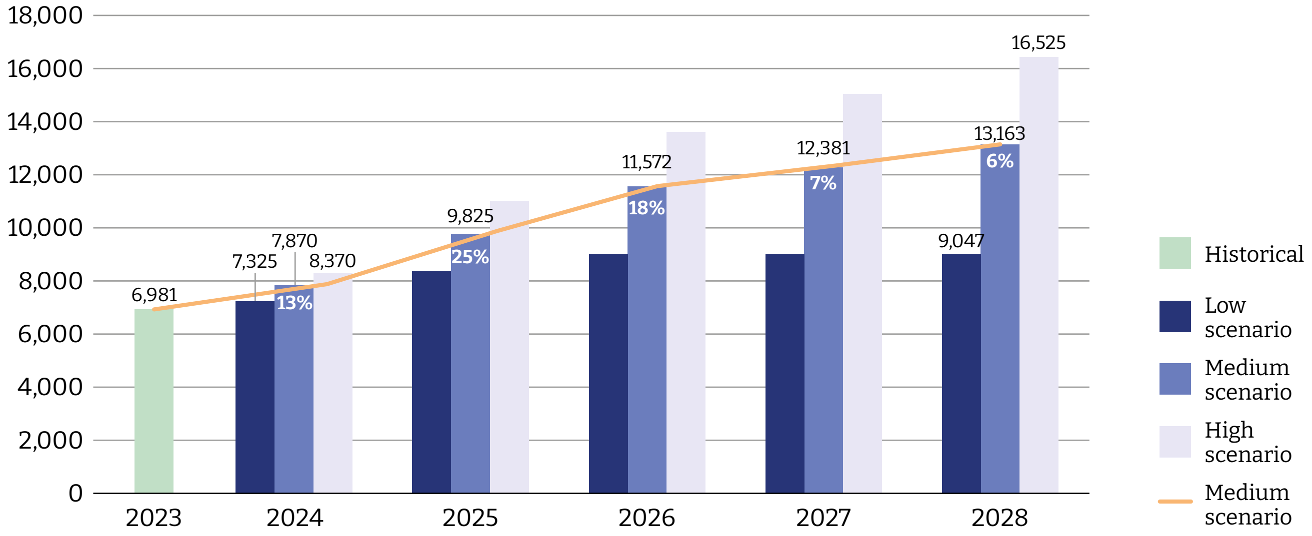
The benefits of implementing circular economy strategies

Large-scale deployment of more circular economy strategies for solar PVs can deliver various environmental, economic and social benefits, and reduce the demand for the manufacture of energy-intensive materials, such as glass, aluminium and silicon.[21] From the **environmental perspective**, reduced risk of pollution and positive ecological externalities are key drivers to be leveraged in circular economy strategies in the solar PV value chain. These include reductions in GHG emissions, landfill use and the risk of hazardous waste materials ending up in nature, either through landfills or illegal disposal.[22]

A study by the European Commission Directorate-General for Environment (DG ENV) estimated that the pre-treatment and recycling of solar panels could reduce the end-of-life (EOL) environmental impact of a PV by a factor of six.[23] Another study suggests that around 1.2 tonnes of CO_2 equivalent emissions can be saved by the recycling of one tonne of silicon-based PV modules.[24] A reduction in environmental and climate damage associated with manufacturing and landfilling of solar PVs, including raw material mining and manufacturing, can also have substantial benefits to environmental, human and animal health through reduced risk of pollution and GHG emissions that contribute to climate change.[25]

There are also considerable **economic** benefits to be gained from developing circular economy strategies for the solar PV value chain, within Europe and globally. As the number of damaged and decommissioned solar panels grows, so do the opportunities for repair, refurbishing and recycling operators to develop economies of scale and enhance the financial viability of their operations: the value of recovered raw materials from solar panels globally is expected to increase radically over the next 10–35 years. Estimated scale of the economic opportunity is also expected to be considerable, with global estimates ranging from US$450 million to US$2.7 billion in 2030,[26] and US$15 billion to US$80 billion by 2050,[27] depending on the forecasting methodology used. The European solar panel recycling market is expected to grow by over 20 per cent per annum from an initial value of US$41.027 million in 2020 to reach a market size of US$128.583 million in 2026.[28]

Figure 3: EU-27 Solar decommissioning and recycling jobs scenarios 2024-2028

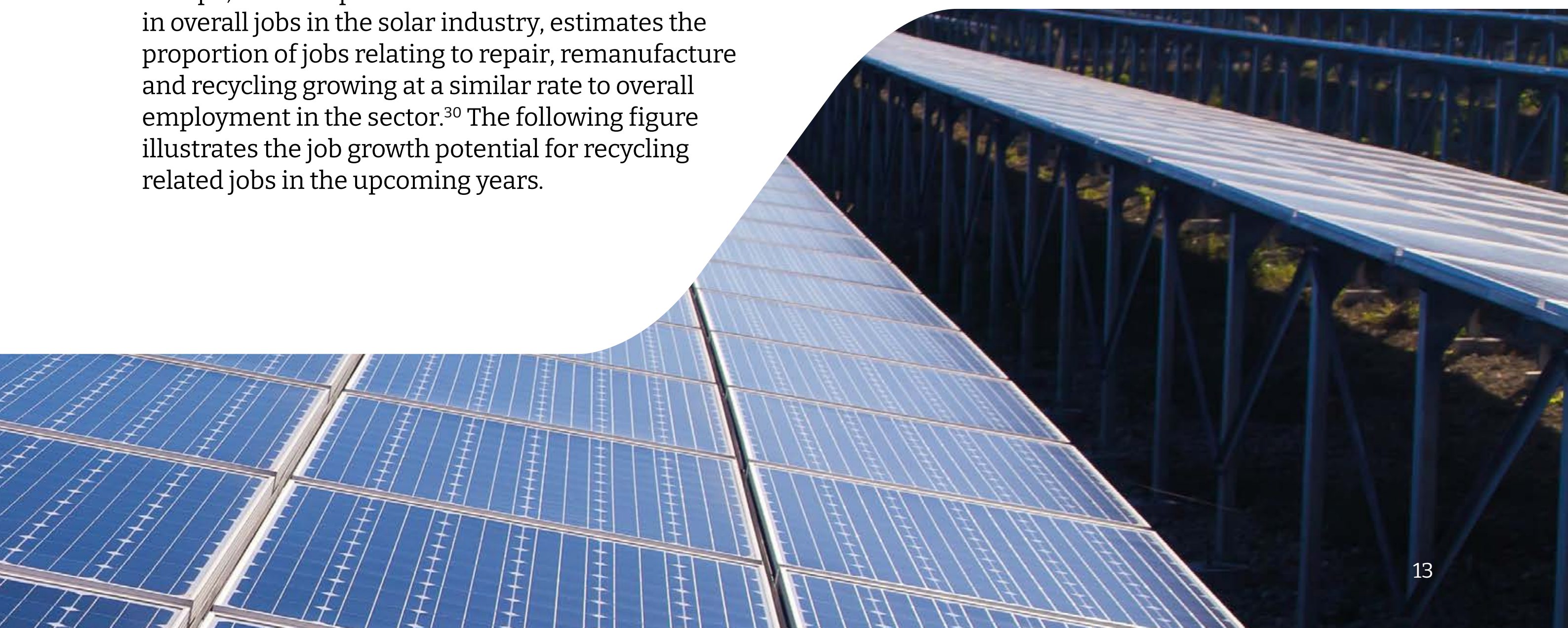


Source: SolarPower Europe (2024), p33[31]

The potential economic benefits could be leveraged through **technological innovation**, such as improved efficiency in design and manufacturing (which improves profitability through reduced use of materials and energy), as well as innovation in circular economy strategies, such as recycling, reuse, remanufacture and repair/refurbishing. The EU can play a role in scaling up circular economy industries by expanding funding and support mechanisms. Initiatives such as those under the European Investment Bank, Horizon Europe and EIT Raw Materials Innovation Hub Central & West are already paving the way.[29] A more detailed list of completed and ongoing projects under Horizon 2020 in the EU is included in Annex 2.

Circular economy strategies can also have **social** benefits, such as the creation of new jobs. SolarPower Europe, which expects to see a substantial increase in overall jobs in the solar industry, estimates the proportion of jobs relating to repair, remanufacture and recycling growing at a similar rate to overall employment in the sector.[30] The following figure illustrates the job growth potential for recycling related jobs in the upcoming years.

In the long run, investing in developing local circular economy strategies for solar PVs could foster innovation, strengthen the EU's energy security, support sustainable growth and offer geopolitical advantages by reducing import dependencies. By recycling high-value materials like silicon, silver and certain rare earth elements – classified as critical raw materials (CRMs)[32] in the EU due to their importance in low carbon technologies – the EU could improve its domestic supply. Enhanced CRM recovery from technologies such as solar PVs would help the EU mitigate the risks associated with supply chain disruptions and price volatility, especially given its limited or non-existent domestic sources for these materials. This factor has been widely acknowledged in the EU context and highlighted as one of the key objectives of the 2023 European Critical Raw Materials Act.[33]



3. Solar cell technologies

There is a significant amount of innovation happening in PV technology. This chapter starts with a brief explanation on solar cells and how their material composition impacts a solar PV's environmental footprint. It then introduces key solar PV technologies, comparing emerging technologies against the current market leader, the crystalline silicon cell. The comparative analysis focuses on factors that affect PV recyclability and its environmental footprint throughout its life cycle.

What are solar cells?

Solar cells convert light into electrical energy through the photovoltaic effect, whereby light exposure releases electrons.[34] Solar cells are the core component of a solar PV, even though they make up only a small fraction of its total weight and size.

Different solar technologies can be categorised according to the materials used in solar cells, such as silicon-based cells, wafer-based semiconductor compounds (eg, cadmium telluride or CdTe and copper indium gallium selenide or CIGS), and new emerging materials, such as organic, dye-sensitised solar cells (DSSC) and perovskite-inspired PV materials[35] (see Annex 1 for a graphical illustration of different solar cell technologies).

Multiple connected *solar cells* form the core of a solar module (often referred to as solar PV), generating its electrical output.[36] A typical solar PV panel consists of several layers: a layer of solar cells, encapsulants to insulate and protect the cells, glass layers for protection, a backsheet for further insulation and shield against environmental and electrical damage, a frame for support, and a junction box to connect to external circuits.[37] Depending on which materials the cells are composed of, this basic structure may vary in terms of the layers and components surrounding the actual solar cell.[38]

How the composition of the solar cell matters for circularity

The material composition of solar cells affects the structure of the solar module, the length of its life span, the potential for various failures, and the difficulty of repair and refurbishment. The solar cell's composition also has implications for recycling, reusability of components and, consequently, the environmental footprint of the PV panel throughout its life cycle. For example, certain materials used in solar cells can be more easily purified and reused than others, while some materials (such as cadmium in CdTe cells and lead (used in perovskite and in the solder of crystalline silicon solar PV cells) are toxic, pose environmental hazards and complicate recycling processes.

Different solar cell technologies vary widely in terms of technological and commercial maturity. Some recent technological advances, for instance in perovskite PVs, enable new functionalities – such as flexibility, low weight and transparency – opening up opportunities for new applications for PV in building integrated PVs or agriphotovoltaics. However, these advancements will also increase the demand for rare materials like cadmium and tellurium, whose mining is resource-intensive and environmentally harmful. Therefore, recovering these materials will become crucial to reduce reliance on raw material extraction.

Comparison of different types of solar cell technologies

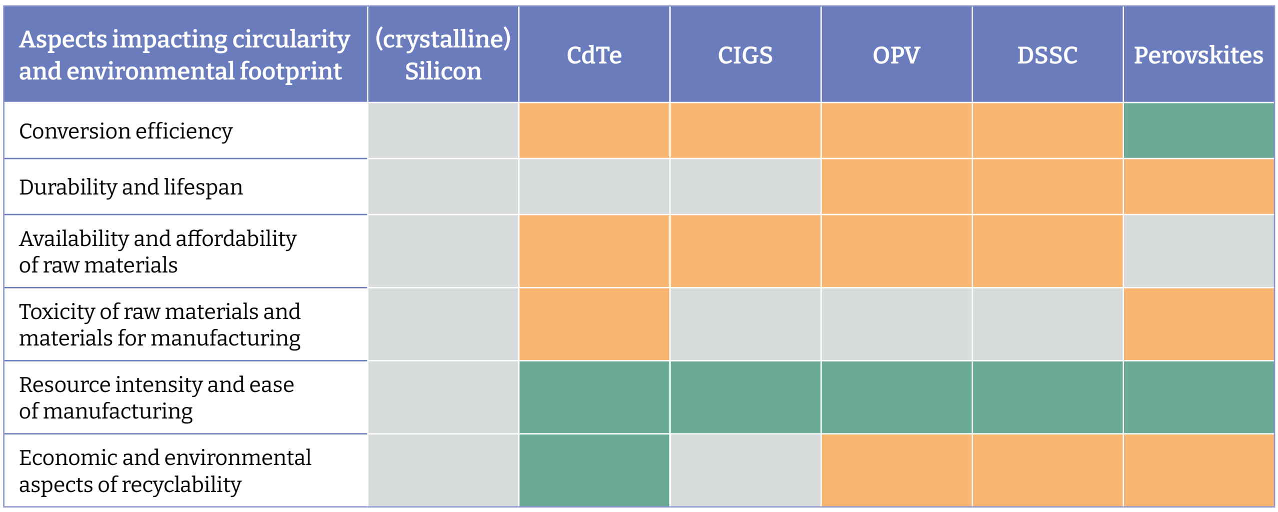
While crystalline silicon PV dominates the current market, advancements in alternative solar cell materials are progressing. These 'next generation' solar cells, which enable new applications, are expected to gain market share and eventually contribute to a new wave of solar waste. For the analysis in this section, we have selected the most advanced and commercially mature new technologies to compare against crystalline silicon-based PV to explore the potential implications of different solar cell technologies on circularity and whole life cycle environmental impact. The evaluated technologies include cadmium telluride cells (CdTe), copper indium gallium selenide (CIGS), (OPV), dye-sensitised solar cells (DSSC) and perovskites and perovskites-inspired solar cells (in the following as 'perovskites').

The analysis identified six factors that have direct and indirect impact on circularity and environmental footprint across the PV's full life cycle. These include:

- **Conversion efficiency:** Higher-efficiency solar cells produce more electricity per square metre over a given period. This means that the same energy output can be achieved using fewer panels or a smaller surface area, reducing material use as well as the environmental impact associated with their manufacture, deployment and disposal.
- **Durability and lifespan:** Durability of a solar cell refers to its ability to withstand physical, chemical and environmental degradation without a significant drop in efficiency. Higher durability leads to a longer **lifespan**, reducing demand for new materials as each panel lasts longer.
- **Availability and affordability of raw materials:** The economic viability and circularity potential of solar PVs are significantly influenced by the availability, geographic distribution and accessibility of the materials required for the cells and the manufacture of the PVs. Limited material availability tends to raise manufacturing costs and could hinder large-scale deployment of the technology, even if it has desirable physical properties, such as high conversion efficiency and high durability. Theoretically, the high cost and scarcity of certain materials could incentivise their recovery and reuse – however (as discussed in Chapter 6), the low concentrations of these materials in solar PVs have so far prevented recovery services from reaching economies of scale. Also, the mining of rare and scarce materials is often associated with serious environmental problems and pollution, especially in the Global South.
- **Toxicity of raw materials and materials for manufacturing:** Use of toxic and hazardous materials in the solar cells, solar PV components and production processes pose risks to the environment and human health if not properly managed at end-of-life. However, these materials play a key role in enabling higher efficiency and new physical properties of the cells, or are needed during the manufacturing process. To minimise the risks posed by toxic substances, strict handling and disposal methods are needed in repair, refurbishment and recycling at end-of-life.
- **Resource intensity and ease of manufacturing:** The amount of energy and other resources, including raw materials and water, required to manufacture the solar PV determines its overall environmental footprint. The physical design of a solar PV, in turn, is influenced by the choice of solar cell technologies, as some require more complex or more energy-intensive manufacturing processes.
- **Economic and environmental aspects of recyclability:** The potential for recycling and recovering materials from solar cells and other PV components depends on several factors. These include the technology readiness level (TRL) of the recycling equipment, the energy and resource demands of the processes, the quality of materials that can be technically recovered, and the market demand for the recovered materials. These issues are discussed in more detail in Chapter 6.

The key findings are summarised in the figure below.

Figure 4: Comparative analysis of solar cell technologies



Note: in the colour coding, grey denotes performance of the baseline technology (crystalline silicon PV) or performance comparable to it; orange indicates performance lower than the baseline technology; green indicates performance better than the baseline technology.

Crystalline silicon solar cells achieve in-field **efficiency** of 20–25 per cent,[40] comparable to other technologies, except perovskite solar cells, which have reached efficiencies of up to 35 per cent in laboratory conditions.[41] In terms of **durability**, silicon cells again outperform all other technologies, with an average **lifespan** of around 25 years,[42] which new technological advancements could extend to 30–35 years.[43] However, alternative technologies such as CdTe and CIGS are catching up with silicon cells,[44] with growing interest potentially leading to further improvement in the coming decades. The advances in durability and efficiency, utilising material improvements and innovative design approaches,[45] could significantly reduce the waste volumes from 'next generation' PVs.

In terms of **availability and affordability of raw materials**, silicon compares favourably against alternative technologies due to its reduced reliance on scarce or high-value metals. CdTe, CIGS and DSSC require metals such as tellurium,[46] platinum,[47] indium and gallium, and OPV can require expensive catalysts, polymers and solvents. Scarce and high-value metals such as silver are, however, also used in various components of all solar PV technologies, including silicon-based technologies and perovskites. Their recovery at a sufficient purity is technically complex and recycling solutions are still under development (see Chapter 4). However, as many of these materials are in high demand for the net zero transition, their recovery may become increasingly appealing to address import dependencies (as implied by the EU's Critical Raw Materials Act).

Solar PV cells and components often contain **toxic materials**, creating a widespread challenge for the responsible disposal of all solar technologies. While this issue is common to all PV technologies, the types and quantities of hazardous substances differ. For example, perovskites have higher concentrations of heavy metals such as lead, while CdTe cells contain cadmium and tellurium.[48] Manufacturing processes may also involve solvents that pose toxicity risks to humans, animals and plants.[49] However, accurately estimating the quantities of toxic materials needed for large-scale production of emerging technologies remains challenging until these technologies achieve a certain level of maturity.

The **resource intensity and complexity of manufacturing** associated with solar cell production can be very high. Purifying silicon to produce solar grade (SG) cells consumes between 50 and 75 kWh of energy per kg.[50] This is significantly higher than the energy needed to produce other PV technologies.[51] Although the in-field energy payback time for the other technologies* is currently longer due to their lower efficiencies,[52] this may change over time as 'new generation' technologies mature. For example, with economies of scale, thin-film PV technologies could have the advantage of potential low-cost and low-material production, which would improve their energy payback period.[53]

Analysis of **recyclability** of different solar PV technologies considered both **economic and environmental aspects**. These vary substantially among the different technologies for many reasons, including technology readiness levels, material composition and design. For silicon-based PVs, recycling technologies are the most advanced, although there remains room for significant improvement, especially in enhancing processes to recover materials of high purity using scalable and cost-effective approaches.[54] Currently, commercial-scale recycling of silicon-based solar PVs primarily relies on mechanical processes, resulting in significant loss of material value during the recycling operation. However, if global demand for recovered materials such as high-purity silicon, silver and copper grows, this could stimulate investment in research and development (R&D) into the technologies needed to recover these materials at higher purity levels.[55]

The limited availability and high environmental impact of cadmium and tellurium (eg, pollution caused in manufacturing processes) increase the need to reuse and reprocess CdTe-based solar panels. Some of these recycling technologies are already being developed and commercially piloted.[56] For other emerging solar PV technologies, progress on recycling processes lags further behind. CIGS, DSSC and perovskites all contain toxic materials, as well as rare and critical materials. While the presence of these materials increases the need for material recovery and recycling, it also makes these processes more complex. Although material recovery has been demonstrated in lab conditions, significant challenges remain, highlighting the need for further R&D[57,58] and putting alternative solar cell technologies at a disadvantage compared to silicon-based cells.

This comparative analysis demonstrates that silicon-based PVs currently perform better than alternative technologies for each criterion apart from resource intensity and ease of manufacturing. It is highly likely that silicon-based PVs will continue to perform better than the others for the foreseeable future due to the combined positive feedback loops of *technological maturity and market dominance*. Given this projection, the discussion in the rest of this report focuses on silicon-based solar PVs.

*For example CIGS and OPV have shorter energy payback times in laboratory conditions.

4. How circular is the solar PV value chain currently?

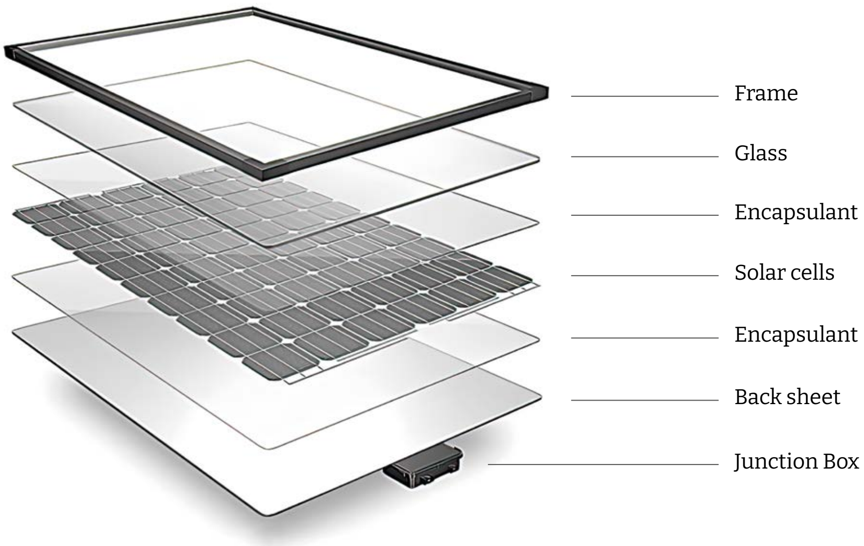
This chapter provides a broad overview of the current PV ecosystem and the policy framework that has been implemented to improve circularity in it. It begins with a short overview of the structure of a typical silicon-based solar panel, which accounted for over 97 per cent of global PV production in 2022.[59] It then provides an overview of different circular economy strategies that are being or have been developed for silicon-based solar PVs, including various second-life strategies (reuse/resell, repair/refurbish and remanufacture) and recycling methods. The chapter concludes with an overview of the key EU policies to incentivise circularity in the solar PV value chain.

The purpose of this chapter is to help the report to contextualise where and why certain barriers to circularity exist along the value chain (Chapter 6) and how enhanced policy levers for circularity could be deployed (Chapter 7) to address these challenges. However, it is pertinent to note that while there are detailed statistics for solar deployment across the EU and projections of expected waste volumes, official data on established waste streams and deployment of circular strategies is scarce.

Silicon-based solar PVs

Silicon-based technologies currently dominate the global market, having benefitted from factors that ensure high price competitiveness, such as synergies with the semiconductor supply chain in the provision of silicon, technological advancements, economies of scale and China's leadership in the sector, resulting in high price competitiveness.[60] Therefore, creating circular economy strategies to address the waste challenges specific to this technology (see Figure 5) is a priority.

Figure 5: Basic structure of a monocrystalline silicon solar PV



Source: Kant et. al (2016) p.148

Typical silicon solar cell-based PVs consist of up to 70 per cent glass, 18 per cent aluminium (which is used primarily for the frame), and other materials, including those used in the solar cells.[61] The valuable materials present in trace amounts of less than 1 per cent play a significant role in the cells' and the PV's functionality. These include silver (up to 0.05 per cent), copper (approximately 1 per cent), tin and lead (less than 0.1 per cent).[62] The different layers of a solar PV are held together using adhesive sealant, which is applied as thin layers around the solar cells. This sealant secures the cells to the glass sheet and the backfilm, which consists of various plastics.[63] Materials such as copper, lead and plastics are also used in the junction box and electrical connections.

Silicon-based solar PVs were designed to address the need for technologies that can be deployed easily and quickly, at various scales (by households, businesses and utility companies), to reduce demand for fossil fuels in power generation. R&D focused on increasing their efficiencies.[64] Second-life and end-of-life solutions were not the key concern guiding this process, meaning that most contemporary solar PVs have not been designed to maximise the reusability, repairability, or recyclability of the panels, their components or the materials embedded in them. This has hindered the development, economic viability and scaling of circular economy strategies for solar PVs, as will be discussed in more detail in Chapter 6.

However, some circular economy strategies have already been developed (or are being developed) to mitigate the risks that growing amounts of solar waste could cause for the planet. These strategies include the so-called higher R strategies as well as different recycling methods.

Circular economy strategies for silicon-based solar PVs – higher R strategies

Higher R circular economy strategies (repair, reuse, remanufacturing) can be deployed at various points in the solar PV value chain. For the purpose of this report, these strategies are grouped together as '**second-life solutions**', to distinguish them from recycling, which entails the destruction of the solar PV, making it an **end-of-life strategy**.

Repair restores the functionality of defective PV modules without significant structural changes.[65] Common repairs include replacing damaged connectors, rewiring, and repairing cracked frames or glass. This method is particularly useful for addressing minor defects and ensuring continued power generation without necessitating complete replacement. Repairing extends the life cycle of PV modules and minimises the need for new material inputs.

Refurbishment of a solar PV involves a more extensive reconditioning process than repair. It typically includes inspecting, testing and replacing worn-out components to restore PV modules to a near-original state.[66] After repair or refurbishment, PV modules can be **resold** in secondary markets. This strategy is particularly viable for older modules that are still functional but have decreased efficiency. Reselling promotes the **reuse** of PV modules in less-demanding applications such as off-grid systems, as backup power solutions, or for educational use. Currently, refurbished PV modules from the EU are often sold to less developed countries, where cost considerations override the desire for the latest technology. Reselling, whether within Europe or internationally, can reduce the premature disposal of functional modules, while also enabling broader adoption of solar technology. However, resales abroad risk improper disposal of solar PVs once they are no longer repairable, particularly in countries with lax or poorly enforced disposal regulations.

Remanufacturing is a more comprehensive process than repair or refurbishment.[67] During a remanufacturing process, the PV modules are disassembled, cleaned and reassembled using a mixture of used and new components. Defective or outdated parts are replaced, and the entire system is restored to meet or even exceed the original performance standards. Due to the reuse of old components that are undamaged or have been repaired, remanufactured PV modules can provide comparable performance to new ones at a lower cost to the environment. This process is ideal to maximise the material value from solar PV modules that cannot be repaired or refurbished.

Second-life strategies lower the environmental footprint of individual PVs by reducing emissions associated with new production and the need for recycling, which can be energy intensive, result in greater loss of value, and may release harmful substances (see next section). As mentioned in Chapter 2, second-life strategies for PV modules could also stimulate economic activity, create jobs, and make solar energy more accessible and affordable. However, despite their potential benefits and recent technological developments in this field, these strategies are less widely deployed than recycling, which also lags behind the EU target of 80–85 per cent. The new entrants offering second-life PV solutions – such as Rinovasol, Solreed, SecondSol and 2ndlifesolar (see the case study below for an example) – continue to face barriers that hinder market growth and, consequently, the financial viability of these operations. These barriers are discussed in more detail in Chapter 6.

Case study 1: 2ndlifesolar

2ndlifesolar processes used PV modules to harness the potential economic and environmental benefits from giving them a second life. Their service portfolio includes collecting, preparation for reuse, recycling and disposing of PV systems and solar modules. Once tested, the PV modules can serve as replacements for defective modules in an otherwise functional large-scale PV system, as balcony-mounted power systems, or can be assembled to form new PV systems. 2ndlifesolar serves primarily large solar park owners who manage extensive ground-mounted solar installations and often face performance losses due to damaged panels, but also provides services to household consumers. The company has three dedicated testing facilities in Germany where panels undergo rigorous tests such as power output assessments, insulation strength evaluations and electroluminescence scans. Panels passing these tests are refurbished, reclassified and resold, providing solar parks with cost-effective, sustainable replacements. Panels that do not meet the quality standards are sent to certified recyclers.

To ensure efficiency and lower costs, the company has partnered with MBJ for advanced testing equipment. It also collaborates with local recycling companies across different regions. This decentralised approach minimises the cost and environmental impacts of transport. Currently, revenue is generated mainly through recycling services, with reselling refurbished panels and other services accounting for the rest. This is despite their overall focus on second-life rather than end-of-life solutions (as espoused in their motto “reuse before recycling, and recycling before disposal”).

The main barriers identified by the company to achieving higher resale volumes include cheap PV imports, which reduce cost competitiveness and eat into their profit margins, lack of insurers and certification for second-hand panels, and lack of a supportive policy framework for second-life solutions. The unregulated export of panels also remains an issue for 2ndlifesolar, with better regulations and monitoring needed to address this challenge.

Despite these challenges, 2ndlifesolar remains optimistic about its future prospects, especially as PV deployment and decommissioned panels are projected to continue to accelerate. The company’s growth plan includes expanding their services into European markets, and exploring new revenue streams through backward integration across the value chain. The company is also pushing for improvements in solar panel recycling processes to address high costs and material losses in traditional recycling methods.

Collaborations are underway within an EU Horizon project with recycling companies, such as ROSI Solar and LuxChemtech, to develop innovative technologies that recover valuable materials like silicon and silver. 2ndlifesolar is also actively involved in EU-funded projects like QUASAR, which promotes recycling innovation and regulatory alignment across European markets.

Circular economy strategies for silicon-based solar PVs – recycling

Silicon-based solar PVs can be recycled through mechanical, chemical, thermal, or combined methods, with the value of recovered materials largely determined by the method used. However, the layered design and use of sealants create significant technological challenges. Separating the layers is complex, hindering the effective recovery of critical materials such as silver, intact glass sheets and high-purity silicon cells.[68] The reduced purity and quality of currently recovered materials limit their usability in high-value applications, adversely affecting the economic viability of recycling operations.[69]

In Europe, the recycling method that has been most comprehensively demonstrated[70] and is already commercially available[71] is **mechanical recycling**, which involves shredding and crushing processes, recovering primarily glass and aluminium at reduced quality and purity. It begins with the disassembly of the PV module, separating the aluminium frame, junction box and copper cables. The PV modules (consisting primarily of glass) are then shredded, in processes adapted from flat glass recycling.[72] The recovered glass cullet is typically used for foam glass applications rather than flat glass or container glass products, which have more stringent quality requirements[73] and greater economic value.

Mechanical recycling can achieve the EU targets for PV panels of over 85 per cent recovery and over 80 per cent preparation for reuse and recycling.[74] Although some of the most widely used mechanical recycling methods lead to lower purity and quality of recovered materials, ongoing research in this area is showing positive results in recovering raw materials at higher levels of purity and quality. However, many of these high-value recycling methods[75] are still at pilot or prototype stages.[76,77]

Other high-value recycling methods currently under development employ thermal, chemical and advanced mechanical methods (or a combination of these) to:

- Remove the adhesive sealants from the laminated part of the structure,[78] resulting in the separation of glass from solar cells in unbroken, intact states.
- Recover metals from the silicon cells,[79] primarily high-value silver. Lead is sometimes also removed from solar waste to reduce hazardous environmental impact.[80] Higher purity silicon can also be recovered and used in applications like lithium-ion batteries[81] or even new PV cells.[82]

The following case study illustrates a company trying to further develop its mechanical recycling methods to improve the long-term financial viability of its business model.

Case study 2: Reiling

Technologically, advancements in mechanical recycling methods are improving the recovery rates of valuable materials such as glass, silicon and silver, but challenges persist, particularly in extracting high-purity silicon for reuse. Reiling, a German recycling company, has responded to these challenges by developing a dedicated PV recycling facility and investing in R&D to optimise material recovery rates. Collaborating with research institutions like Fraunhofer, Reiling aims to recover up to 100 per cent of PV materials, focusing on innovations in silicon recovery – a critical step towards circularity. The company has already made great strides in improving the recovery of high-quality glass such that it can now be used in high-quality, optimally sophisticated glass production (and need not be used as substitute material in buildings and construction), effectively closing the loop on that.

But despite their significant investment in technological development, barriers to circularity in PV recycling remain a cause for concern for them. These include the export of obsolete modules to countries with lenient recycling regulations, undercutting local recyclers and hindering domestic recycling efforts. Additionally, the variety of PV module designs and the diversity of materials complicates the recycling process, as different materials and configurations require unique processing methods.

Further, despite progress on the technological front, policy and market gaps remain. Stronger regulations are needed to curb exports of PV waste, while government support could ease the financial burden on last owners and foster recycling infrastructure. Though there is a viable market for recycled glass and aluminium, developing robust markets for silicon and other materials is ongoing, with clients primarily motivated by both cost-effectiveness and environmental benefits like CO_2 reduction. Reiling's expansion plans, including new facilities in regions with dense PV installations, aim to reduce transportation costs and enhance recycling capacity. However, the family-owned company acknowledges that the sector's future depends on balancing sustainability with economic feasibility, highlighting the ongoing need for affordable, advanced recycling technologies and supportive policies.

Chemical recycling methods are favoured for their ability to recover silver, other metals and high-purity silicon[83] without significant damage to it. Chemical recycling typically employs organic solvents (eg, toluene and trichloroethylene), sometimes in combination with ultrasound irradiation to accelerate the process.[84,85] Silver and other metals including copper can also be recovered using leaching agents such as nitric acid or hydrochloric acid, followed by a precipitation to recover the dissolved metals from the leachate and further purification to recover the final metal products.

While chemical methods can achieve high-value recycling, they present significant challenges in terms of the toxicity of chemicals used and the risks to human health and the environment,[86] if not managed properly. The complexity of the process can also diminish its financial viability, especially for silicon-based PV modules, which have a relatively low content of high-value materials, compared to thin-film PVs.

Thermal methods are favoured for removing adhesive sealants due to their ability to fully eliminate encapsulants,[87] while preserving the integrity of components such as glass and silicon cells. Pyrolysis is a particularly effective variant of thermal recycling. It involves thermochemical decomposition at high temperatures of around 500°C in an oxygen-free environment, breaking down organic elements into gases and liquids, leaving inorganic components such as metals, glass and the silicon cell largely intact.[88] The resulting glass and metals can then be sent for further recycling, while silicon cells can undergo an additional step of chemical etching for conversion into silicon wafers for new PV modules.[89] Some variants of pyrolysis methods can also be deployed to recover materials from the backsheet for recycling.

While thermal methods offer benefits like recovering intact, high-value materials, enabling closed-loop recycling, and avoiding the use of potentially hazardous and costly chemicals,[90] they are energy-intensive and may produce GHG emissions (depending on the energy source). Furthermore, the high temperatures can cause minor degradation of the silicon cells.

Because of the low content of high-value materials, the profitability of all recycling operations for silicon-based PVs is heavily reliant on large processing volumes within a geographically concentrated area.

Estimates vary as to the throughput necessary for recycling plants to achieve economic sustainability for silicon-based solar PVs, with one study suggesting 20,000 tonnes per year[91] and industry practitioners citing 10,000 tonnes.[92] In regions or markets where such volumes are not available, the establishment and operation of recycling facilities may not be economically feasible or may rely heavily on transporting panels for long distances (which may compromise the environmental benefits of recycling, unless using low carbon transport). To overcome these challenges, experimental studies have been carried out to explore the feasibility of using crushed solar PVs in their entirety to replace sand (fine aggregates) in concrete production. Although this approach has potential in the sense that it reduces landfilling of solar PVs and enables them to be used to replace another depleting natural resource (sand),[93] it is less desirable than higher R strategies or more sophisticated recycling methods discussed above, which allow more of the material value and value-added components to be retained in use for longer.

Current EU policies to incentivise greater circularity in the solar PV industry

Policy and governance are crucial drivers of the business transition to a circular economy, and the EU has strong circular economy ambitions backed by an extensive set of directives and regulations, although some of these are yet to be implemented fully. Since the first EU Circular Economy Action Plan (CEAP) was published in 2015,[94] the EU has adopted several important circularity initiatives, including the second CEAP adopted in 2020.[95] The definition for circular economy informing the CEAP is the same as the definition we are using for this study.

The 2020 CEAP laid out a comprehensive and ambitious policy agenda, covering 35 EU-level measures and legal acts.[96] It prioritises seven key product value chains that are considered central to the implementation of the circular economy because of their high use of resources and potential for circularity.[97] One of these seven product value chains is electronics and information technology, a category which has included PV panels since 2014.[98]

The CEAP goes beyond the R strategies that focus on the end-of-life treatment of products, seeking to also address factors that would make these strategies easier to implement in practice. As such, the CEAP emphasises circular economy as a concept that addresses the full life cycle of a product, including the stages 'before use' (to incentivise designs that enable more second-life solutions and recycling), 'during use' (eg, maintenance and repair) and 'after use' (second-life solutions and recycling).[99] A set of cross-sectoral initiatives rolled out under the CEAP – which have been adopted or are nearing adoption – include various initiatives. Those that are most relevant for the solar PV industry include:

- The **Waste from Electrical and Electronic Equipment (WEEE)** Directive, which stipulates that producers are responsible for the proper collection and disposal of EEE waste. Since 2019, Member States have been required to ensure that 85 per cent of the solar PV panels should be recovered and 80 per cent prepared for reuse and recycled.[100] The WEEE Directive also makes it mandatory for the producers to finance and establish 'takeback and recycling' schemes for solar inverters and panels.
- The principle of **extended producer responsibility (EPR)**, which means that the party that places a product on the European market is also responsible for organising its collection, treatment and financing once it becomes waste. Therefore, in addition to guaranteeing the quality and safety of the products placed on the European market, producers must also provide for the environmentally sound management of waste from products and packaging.[101] This has been applied in the EU since 2012.
- The **Ecodesign for Sustainable Products Regulation** to ensure products sold in the EU are more sustainable by design[102] (noting that up to 80 per cent of a product's environmental impacts are determined at the design stage).[103] Although this regulation is not yet enforced, it could have a substantial impact on the EU solar PV market in the future, depending on how it will be implemented and applied to imports.
- The **Common Rules Promoting the Repair of Goods** to improve repairability and consumers' ability to have broken products repaired rather than replaced.[104]
- **Digital Product Passports**, which are intended to support circular business models by providing access to relevant data on embodied emissions.[105] This tool, once operational and enforced, could radically improve information flows and transparency, as well as the markets for second-life solar PVs and components.

The purpose of these directives and regulations is to enhance both supply and demand for more circular products and materials, encourage investments in improved product design, waste collection and recycling infrastructures, and enable more circular business models.

5. How to improve circularity in the solar PV value chain?

This chapter maps out how stakeholders across the solar PV value chain can enhance the adoption and scaling up of circular economy strategies, and how external stakeholders influence the conditions within which this transition will take place. It starts by presenting a visual illustration of what a truly circular and sustainable value chain for solar PVs could look like, before moving on to more detailed analysis of how different stakeholders stand to benefit the most from enhanced circularity.

Idealised model for a circular value chain for solar PVs

A truly circular value chain would be a system where the value of the solar PV and the materials embedded in it is extended and preserved for as long as is technologically and economically feasible. Once a solar PV can no longer be repaired, the panel would be disassembled, the components that can be reused would be taken out, quality tested and redeployed, and the different materials in parts that are not reusable would be decontaminated and recycled, ideally into the same value chains (for example, glass would be recycled back into glass manufacturing).

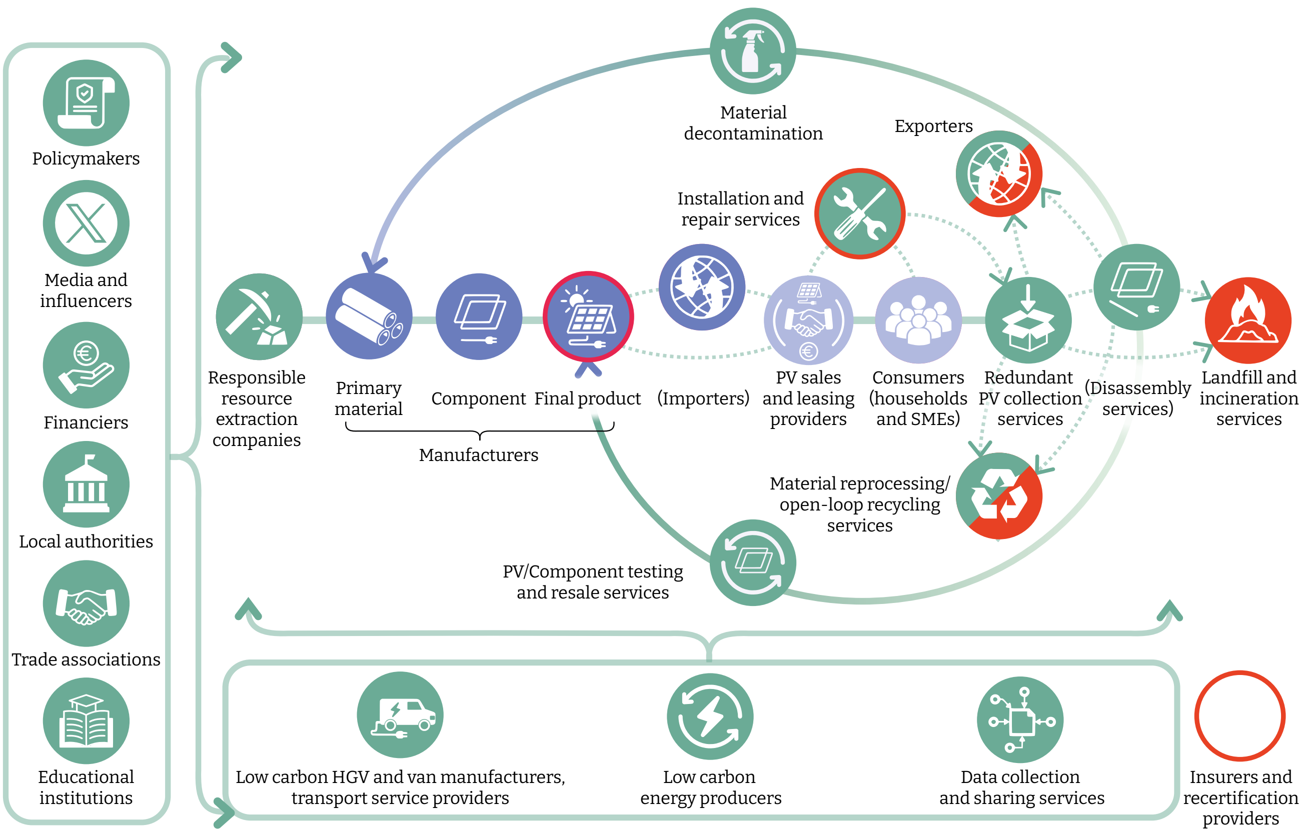
A transition to a more circular value chain will be an incremental process but, to be successful, it needs to be systematic. This means involving all stakeholders and stages of a product or service's life cycle, from raw material sourcing to initial design and production, distribution, use, and end-of-life management. It may also be necessary to engage solar PV manufacturers abroad and solar PV importers.

End-to-end value chain analysis[106] – which captures all stakeholders and stages of PV manufacturing, use and disposal – is a helpful tool to illustrate how value can be created, delivered and captured by different stakeholders across the value chain. It can be used to highlight where new operations need to emerge, and to explore how stakeholders across the value chain could change their operations to become more circular, and to enable greater circularity downstream, or across the economy more generally. For example, a solar PV manufacturer may be able to facilitate greater circularity across the economy by using (and gradually scaling up their use of) materials or components that have some recycled content, thus creating demand for recycled materials such as glass and aluminium and improving the financial viability of recycling operations. However, they can also influence the solar PV value chain more specifically, for example through adopting product designs that make it easier for downstream stakeholders to repair, refurbish, remanufacture and recycle them.

Figure 6 (below) gives an idealised depiction of what a truly circular PV and sustainable value chain would look like and how it could work. It shows the different stakeholders across the value chain (horizontal line and related loops), as well as the stakeholders whose input feeds into the operations and performance of the solar PV value chain (boxes on the left and the bottom of the graph). Some of the stakeholder categories in Figure 6, particularly those on the right focusing on second-life and recycling-related activities (such as repair, material decontamination and disassembly) will need to grow substantially for the EU to meet its circular economy objectives in the PV industry. These stakeholders will play a crucial role in facilitating the development of services focusing on the four Rs discussed in this report. However, their ability to emerge and grow depends on enabling activities, such as data collection, data sharing and insurance products to meet the needs of companies operating in a more circular value chain. As will be discussed in Chapter 6, substantial barriers exist to accelerated action in this area.

Services that would enable not just a more circular but also a more overall sustainable value chain for solar PVs (such as low carbon transport, renewable energy and responsible resource extraction), are also included in Figure 6 to illustrate some of the interlinkages between the solar PV industry and the broader low carbon transition.

Figure 6: Idealised model for a circular and sustainable solar PV value chain



Naturally, the shift to a more circular value chain will not happen overnight. Instead, circularity will be enhanced incrementally as existing stakeholders change their practices and new stakeholders emerge, especially around second-life strategies, recycling, and services that enable and facilitate the growth of these circular economy strategies.

How can companies create value through circular economy activities?

Successful transition to a more circular economy hinges on how stakeholders across the solar PV value chain leverage measures and create value from the transition. The most obvious growth opportunities are found among the stakeholders towards the right side of Figure 6 (above) and the loops emerging from the end-of-life options that replace landfilling and exporting of decommissioned PVs, including new business models that could unlock new revenue streams from second-life and recycling operations. These opportunities could be available to existing stakeholders who expand their operations into circular economy activities, as well as new entrants. However, existing stakeholders may also find other ways to benefit from improved circularity.

Research has identified common patterns in approaches to value creation from circular economy principles.[107] Most approaches fall into one (or more) of the following categories:

- **Slowed-down resource loops** can be achieved through activities that improve resource efficiency, extend the life span and improve the durability of products. These activities reduce resource demand, as fewer products need to be manufactured to meet the same needs. Examples of activities that slow down resource loops include using environmentally friendly manufacturing processes and durable designs, business models that enable consumers to pay for the use of a product instead of purchasing it (good as a service), and second-life strategies such as reuse, repair, refurbishment and remanufacturing.
- **Open resource loops** enable some of the value of resources to be preserved through the recycling of a product or the materials embedded in it, but with some value being potentially lost due to loss of purity or quality (for example, contaminated materials being recycled into manufacturing other materials, such as glass being used as aggregate for cement manufacturing instead of glass manufacturing).

- **Closed resource loops** preserve the value of the resources during the recycling process better than open resource loops. Closed resource loops can involve components of a decommissioned solar PV being used in the manufacture of new solar PVs without material recycling (reuse), or the embedded materials being decontaminated and reused as material inputs into the same value chains (for example, recovered silicon is of sufficient purity to be used again in PV manufacturing, and recovered flat glass is sufficiently well decontaminated to be used to manufacture more flat glass).
- **Generation of new value through digital technologies and data** to improve the circulation of resources and the ability of stakeholders across the PV value chain to adopt circular economy principles.

These categories can be used to map how existing and new stakeholders can benefit from the circular economy across the PV value chain.

Material manufacturers

Manufacturers of materials such as glass and aluminium that are used in PVs can draw value from recycled materials from closed resource loops. First, they may be able to save on material input costs or energy costs once recycled material is available at a comparable or lower cost than virgin raw materials. Second, they can use recycled material in their manufacturing process to boost their environmental, social and governance (ESG) rating and to reduce their direct and indirect emissions.* Third, they may be able to use their higher recycled material content as a unique selling point to appeal to environmentally conscientious consumers, including downstream companies seeking to reduce their embedded emissions.[108] In progressive policy conditions, for example where public sector procurement places certain requirements on recycled content, these companies may benefit from such incentives.

Manufacturers of PV cells, panels and components

Greater resource efficiency can reduce the resource and material input costs for manufacturers, increasing profit margins. Although activities that slow down the resource loops (such as repair and refurbishment) go against the basic business model of solar cell and panel manufacturers, these companies can benefit from forming partnerships and becoming trusted suppliers and collaborators on second-life and recycling services and solutions with retailers/utilities that offer third-party ownership models for solar panels.

Component manufacturers will also be able to generate value through increasing sales of replacement parts. In the future, standardisation of solar module components will ideally simplify the replacement of components, securing a steady market demand and enabling economies of scale to develop faster than is currently the case.

Solar PV manufacturers that develop new designs that facilitate the deployment of second-life strategies and make it easier for the PVs to be recycled may benefit from growing market shares as demand for more circular products grows.†

*Indirect emissions can be reduced primarily when use of recycled material enables production at lower temperatures that can be achieved using electric technologies (as opposed to fossil fuels).

† SoliTek offers solar panels that are designed and manufactured in Europe, reducing dependency on Chinese imports, and offers sustainable, zero CO_2 emission solar panels certified with Cradle to Cradle (C2C) Gold.

Solar PV retailers/utility companies that own solar PVs

These companies can unlock new market opportunities by adopting circular economy principles in their business models for solar panels. By investing in circular economy strategies for their solar assets – such as repair, refurbishment and recycling – they can reduce the overall costs of solar energy production by expanding the lifetime of their assets. Offering third-party ownership models like leasing, where panels are regularly maintained and upgraded, will also allow them to generate new revenue streams through provision of products as a service.

By ensuring a circular supply chain through collaboration with sustainable and local manufacturers, and recovery and reuse of damaged panels or their components, solar PV retailers and utility companies can secure more stable and resilient supply chains. These practices can also enable them to reduce their indirect emissions upstream and downstream in the value chain, and enhance loyalty and brand value among customers who value sustainability and environmental responsibility.

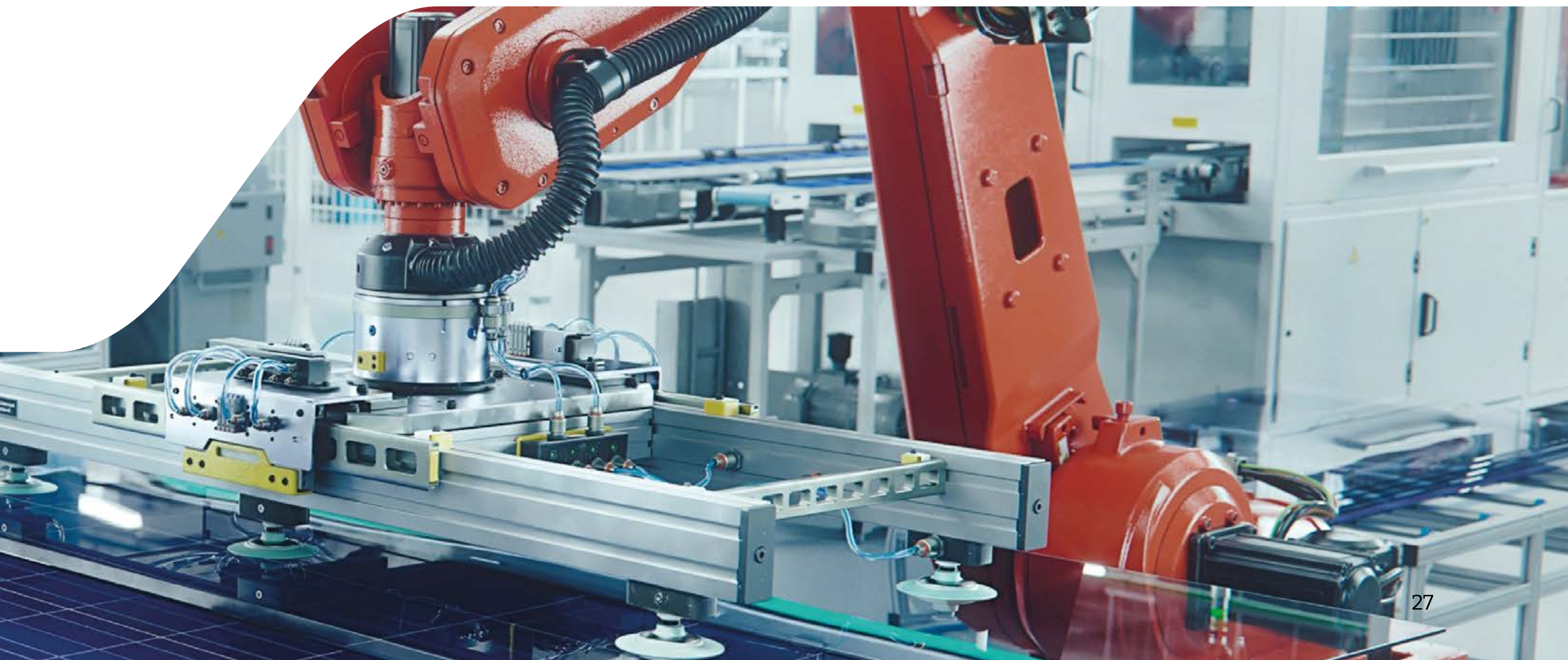
Offering takeback and buyback programmes for old panels, repairing, refurbishing, remanufacturing and reselling them can allow solar PV retailers and utility companies to create secondary revenue streams. Alternatively, they can donate these panels to charity, contributing to the social aspects of sustainability.

Users/Consumers (households and businesses)

Third-party ownership models, whereby users lease solar PVs from a provider/owner, are an example of a practice that provides the good (solar PV) as a service, without requiring outright purchase. This model has been successfully trialled by Berlin-based Enpal.[109] In these cases, users benefit by not needing to provide the capital for the initial investment. In many cases, they also benefit from 'all-inclusive' packages that comprise repair and maintenance services.[¶]

However, the pricing models can vary – for example, a fixed fee paid in regular instalments over a fixed period of time may be higher than the cost of the solar PV if purchased outright, enabling the companies that provide these services also to benefit. Incentivising durable and circular construction, repair and refurbishment of solar panels will contribute to a longer lifespan and, consequently, improved performance over the entire life cycle of the solar panel. For the owners of these panels, this means a better return on investment and lower environmental footprint as the panels last longer, while the customers (in the case of leasing services) benefit from predictive maintenance that retailers, utility companies and repair and refurbishment service providers can develop using digital tools and data analytics.

¶ Palmetto offers convenience through inclusive pricing, end-to-end services, long-term maintenance and support, and a 25-year warranty (https://palmetto.com/).



Repair Services

The need for more repair and refurbishment services (done more comprehensively) induces a new specialised industry segment that will tailor its business models to the service demand. Successful examples include 2ndlifesolar, SecondSol and Rinovasol. By positioning themselves within a circular economy landscape, these businesses may be able to access potential incentives, partnerships and innovation opportunities, ultimately improving their competitive advantage. Integrating digital and data-based solutions into their operations will further streamline and standardise their processes, for example through the use of detailed information on material compositions and components, enabling faster and accurate repairs and more closed-loop recycling.

In addition to repair, new business models can also emerge around the reuse of panels that have reduced efficiency but still produce enough power for some purposes. An interesting example of this would be SunCrafter, a Berlin-based startup that has developed a way to transform discarded solar panels into charging stations for festivals, power supplies for off-grid areas, and even into a sustainable charging solution for electric scooters.[110] For applications such as these, data about deployment and decommissioning would help business models to emerge and flourish.

Collection services

The landscape of collection services is currently very fragmented, particularly in the business-to-customer (B2C) solar panel market. The majority of recycling and waste management companies are not achieving sufficient volumes to establish profitable business models for second-life PV or recycling, even if they work with some utility companies with substantial solar PV assets. Additionally, the cost of transporting PV modules from a collection point to a processing facility increases the difficulty of establishing profitable business models.[111]

Increased demand for circular economy-related services could result in new market demand for collection, aggregation and logistics services.[112] Policy incentives for circularity will drive the demand for such services. The logistics companies will also benefit from new digital platforms that organise the information on potential sources of the upstream supply (ie, solar panels that are likely to be decommissioned within a certain time period), as well as their downstream customers (ie, businesses providing second-life and end-of-life services).

The following case study provides some insight into how collection and takeback services can play a role in the value chain.

Case study 3: PV Cycle

PV Cycle was initially established as a voluntary takeback system for end-of-life PV panels, operating as a non-profit organisation. Its primary focus was to enable the sustainable disposal and recycling of solar panels. With the inclusion of PV panels under the EU's WEEE Directive, which requires extended producer responsibility, PV Cycle transitioned into a WEEE Producer Responsibility Organization (WEEE-PRO). This shift resulted in the creation of country-specific organisations, each tailored to national legal frameworks. While some of these organisations remain non-profit, others function as accredited compliance schemes, certification organisations or semi-commercial entities.

PV Cycle provides services for the collection and recycling of PV panels, as well as batteries, packaging and other WEEE appliances, with operations adapting to diverse legal contexts. Its work aligns with regulatory mandates, helping producers meet their obligations under the WEEE Directive and equivalent frameworks. In addition to its compliance-focused activities, PV Cycle supports circularity by helping in recovery of valuable materials such as glass, silicon and metals. The organisation also participates in various R&D projects, contributing to innovation in recycling technologies and sustainable waste management practices. While it started its operations in countries in the EU-28 as well as the European Free Trade Association, PV Cycle has expanded its activities internationally, reflecting the growing global demand for environmentally responsible solutions in the solar energy sector.

Organisations like PV Cycle can play a key role in managing the full life cycle of PV panels and other electronic waste. Its focus on sustainability, compliance and innovation addresses critical challenges in the ecosystem. By offering tailored services and participating in recycling initiatives, it provides essential infrastructure that can support a more sustainable approach to waste management.

Recycling and Waste Management services

Improvements in resource efficiency and improved recycling throughout the value chain will reduce waste volumes, thus reducing demand for landfilling. However, companies operating in the waste management sector can benefit from third-party ownership models introduced by retailers/utilities by entering contracts to secure large volumes of decommissioned solar PVs. The steady supply of decommissioned PVs will enable recycling and waste management companies to establish new revenue streams by recovering recyclable materials and selling them to companies inside and outside the solar PV value chain that need these materials (see case study below). There will also be growing demand for training and specialised programmes for solar panel recycling, which may be readily provided by companies already working in this area.

Digital and Data Service Providers

As will be discussed in the next chapter of this report, more data on the material compositions of the solar PVs, availability and durability of spare parts, and available collection services is needed for the transformation towards a circular PV value chain.

New digital solutions will benefit various actors in the value chain, driving and enabling collaboration and adoption of circular economy strategies and the provision and consumption of recycled materials from disassembled PVs. While some information that could compromise the competitiveness of specific actors will need to be available only on a 'need-to-know' basis, other data can be made available as open-source. This includes information such as a map of industries that have a high demand for different materials that can be recovered from solar panels, virtual marketplaces for second-life panels,[113] and platforms that connect service experts specialising in maintenance, testing, cleaning, repairs, integration and retrofitting of solar systems with customers. There will also be a need for the software and algorithms to implement and to host and operate such platforms, enabling the creation of a new specialised market segment.

Case study 4: ROSI Solar

Founded in 2017 in Grenoble, France, ROSI Solar operates in high-value solar panel recycling, working with European initiatives and strategic partners such as Soren, the organisation responsible for handling end-of-life solar panels takeback in France. In June 2023, ROSI opened its first dedicated recycling plant in the French Alps, initially processing 3,000 tonnes of solar panels annually, with potential scalability to 10,000 tonnes per year in response to market demand.

ROSI's recycling approach focuses on high-purity material recovery through a three-step process that includes pyrolysis to remove polymers, mechanical sorting, and chemical separation of silicon and silver. This method allows ROSI to recover valuable materials like aluminium, glass, copper, silicon and silver, providing secondary raw materials to the market. The semi-automated process requires limited manual intervention, balancing operational efficiency with economic viability amid market fluctuations. ROSI's revenue model combines fixed income from an eco-tax paid by photovoltaic producers in France and income from selling recovered materials, including silicon, copper and silver.

Enablers of ROSI's operations include a rising number of decommissioned solar PVs, increasing demand for recycled materials bolstered by regulations, and partnerships with eco-organisations that manage logistics.

Barriers include regulatory frameworks that favour traditional shredding over advanced recycling methods (as they do not specify the purity of materials to be recovered), variable waste volumes influenced by external factors, and the capital-intensive requirements of expanding to new markets. The market for secondary materials remains unestablished and is susceptible to price fluctuations and competition from cheaper virgin materials and imports. However, ROSI's focus on high-purity material recovery, as well as mitigating environmental impacts (such as through heat recovery from their thermal processes and calculating emissions savings through their optimised recycling methods), positions it among companies aiming to enhance circularity in the solar recycling sector.

6. What is hindering circularity in the solar PV industry?

This chapter focuses on barriers that impede the development and scaling up of circular economy strategies in the solar PV value chain. The ecosystem is currently in flux, with fledgling stakeholders and a need for new entrants and service providers. Technological readiness is lacking, and market formation remains immature. The emergent policy framework is misaligned with practical realities. Resource mobilisation is ineffective, and enabling infrastructure is largely absent. To promote greater circularity, these barriers must be addressed holistically. This starts with ensuring that demand for circular economy services is sufficient to make their provision and upscaling financially viable.

The analysis to map the barriers and potential policy solutions uses qualitative research (interviews and focus groups) in combination with adapted version of the **technological innovation systems (TIS) approach**.[114] The TIS framework is particularly useful in analysing and accelerating innovations in sustainable technologies, such as renewable energy, electric vehicles, and circular economy practices. By examining the structure and dynamics of innovation systems, it helps explain why certain technologies succeed or fail and offers insights into designing interventions that support systemic change.[115]

Weak demand and sluggish market formation

The demand for circular economy services in the PV industry, such as second-life strategies and recycling, has been slow to develop. Experts and stakeholders identify the low-cost availability of new solar PV imports, mainly from China, as a major barrier to second-life strategies, making it challenging for companies specialising in repair, refurbishment and resale of used PVs to compete on cost grounds. While second-life PVs can match new ones in quality, low resale volumes have limited available data on performance and longevity, reducing consumer confidence. This hesitancy, combined with a lack of awareness, prevents businesses that specialise in second-life strategies from benefitting from economies of scale that would improve their financial viability.[116]

In recycling, cheaper disposal options (like landfilling or exporting)[117] and limited demand for recycled materials pose significant barriers. Although decommissioned panel volumes will rise sharply soon, current volumes remain too low or inconsistent to sustain large-scale recycling operations.[118] Additionally, recycling silicon-based PVs is complex and costly, and contamination often reduces materials to lower-value open-loop uses.

Without incentives for using recycled content, secondary markets for materials like recycled silicon and glass remain weak. Recyclers must therefore charge for their services, which reduces demand, especially when cheaper non-circular disposal options are available. Competition with virgin materials and concerns over quality and performance of recycled inputs further limit market acceptance, slowing circularity in the PV industry.[119]

Actions to accelerate market growth:

- Make circular economy strategies more attractive to solar PV owners and manufacturers through cost, convenience, awareness and better data.
- Establish secondary markets for recycled materials through the right regulations and incentives.
- Foster collaboration among key stakeholders to encourage the formation of buyers' coalitions.

Slow technological development and limited entrepreneurial experimentation

Key technological barriers hinder the circularity of solar PVs. Weak demand for second-life panels and recycled materials challenges companies to justify R&D investment in circular economy strategies. As a result, the technology readiness level of recycling equipment and processes remains low.

The first challenge is the design of silicon-based PVs, which prioritises efficiency over repairability or recyclability. Decades of R&D have focused on efficiency gains rather than circular strategies, resulting in limited returns for circularity-related innovations compared to efficiency improvements.[120] Had early product development prioritised second life and recyclability, the technological barriers that currently hinder the cost effectiveness of recycling and refurbishing would be less pronounced. Manufacturers of next-generation solar PVs can mitigate these barriers through design features that improve the repairability, refurbishment and recycling of their products. If circularity is valued by consumers and stakeholders downstream in the value chain, investment in more circular designs could improve the competitiveness of businesses that are among the first to invest in it.[121]

The second challenge is the layered, durable design of silicon-based PVs, which complicates the recovery of high-purity materials needed for closed-loop recycling. As a result, high-value materials such as silver and copper[122] are often lost to landfilling. Although some recycling operations can recover bulk materials such as aluminium and glass (which account for 70–80 per cent of the PV's mass), this is often done through a highly manual process that limits the purity of the materials recovered.[123] While emerging recycling technologies, such as thermal and chemical recycling, aim to improve the purity of material recovered, they remain in early stages of development (see Chapter 4).

The third challenge is a lack of standardisation in component design and data on PV material composition. These barriers limit repairability, recyclability and high-purity material recovery. Standardised product declarations of material composition could support closed-loop strategies by enhancing process efficiency and quality control.

Actions to accelerate technology development:

- Direct public sector investment to leverage private sector money into R&D on ecodesign and more effective recycling methods.
- Leverage public funding for upscaling as well as piloting of recycling technologies.
- Foster collaboration among key stakeholders for more standardisation in design and manufacturing.

Fragmented and misaligned policy framework

The policy framework for circularity in PVs lacks alignment with renewable deployment goals, as seen in the Renewable Energy Directive's absence of targets for circular PV designs. While the CEAP provides a broad circular economy strategy, it lacks coherence for maximising impact[124] and fails to ensure systematic change and greater transparency among stakeholders across the PV value chain.[125] EPR mandates also lack clarity, particularly for panels installed before regulations were enacted, placing disposal responsibility on end-users who often choose cheaper, non-circular options.

A lack of comprehensive long-term policy incentives hinders investment in advanced recycling and second-life strategies, such as repair and remanufacturing. Although regulations on the right to repair and ecodesign have recently been introduced, they have not yet significantly impacted the single market due to inconsistent implementation. For example, the WEEE faces practical challenges to effective enforcement, particularly because of unclarity over whether the word 'producer' in the regulation refers to the manufacturer, importer, reseller or installer.[126] As a result, Member States may have different interpretations regarding which stakeholder is responsible for the PV's sustainable disposal.

Experts and stakeholders who participated in this study criticised the CEAP's material recovery targets for PVs for being too low and insufficiently detailed. In particular, they expressed concern that these targets do not specify the proportion of recovery for each material or its level of purity, enabling the 80–85 per cent goal to be met through open-loop recycling of bulk materials that account for a large share of the solar PV's weight, but do little to incentivise recovery of some of the more valuable materials and CRMs that are present in smaller quantities.

According to the experts and stakeholders, including PVs in the WEEE instead of drafting a distinct waste management strategy for renewables directive creates barriers to circularity. In particular, the classification of solar PVs as 'waste' under the WEEE Directive complicates matters for most businesses. Once a product is classed as 'e-waste', there are strict legal rules and regulations for how it can be handled, transported and stored. These restrictions can inhibit the development of viable business models, indicating a need to shift from a 'waste' framework to a 'resource' or 'materials' framework.[127] A shift to a 'resource' framework and a dedicated policy package for PV circularity could better support second-life strategies and closed-loop recycling, fostering a transition away from waste disposal.

Actions that could enhance policy effectiveness:

- Design and implement a dedicated PV policy that prioritises repair, reuse, remanufacture and recycling to waste management.
- Incentivise the recovery of critical materials and materials at a higher degree of purity through targets and mandates while disincentivising non-circular solutions, such as landfilling and export.
- Promote consistent application across EU Member States.

Limited resource mobilisation

While there has been significant public and private investment in knowledge development (see Annex 2 for past and current EU and private funded projects surrounding circularity in PVs), not enough resources are being effectively mobilised to establish, commercialise and upscale circular economy strategies. Given the technological limitations and market immaturity, investment in this space remains risky. The upfront capital required to set up second-life or recycling operations can be significant, especially for closed-loop recycling processes that recover a higher proportion of material at higher levels of purity.

Recycling and second-life businesses for solar PVs require complex logistics to handle collection, sorting and transport, but current PV waste volumes are too low for localised facilities, leading to long transport distances and higher costs. Research suggests that to preserve the environmental benefits of circular strategies, recycling centres should ideally be within 80 km of PV sites[128] or utilise low carbon transport if more distant. However, low volume of demand in many areas means that facilities that operate only within this radius are not able to grow big enough to achieve financial viability.

Experts identified additional barriers to scaling circularity in PVs, highlighting the lack of knowledge, awareness and advocacy skills to effectively communicate the benefits of circular practices, both within their organisations and to external stakeholders, such as customers and regulators.[129] Additionally, a shortage of long-term strategic thinking discourages investment in second-life and recycling technologies, which require upfront costs and have long payback periods. For lasting change, companies across the PV value chain (and the economy more broadly), need to adopt a mindset focused on sustainable materials and resource use beyond just CO2 or GHG targets. As the circular economy gains foothold with EU policymakers and more businesses and stakeholders realise the competitive sustainability aspects of such strategies, this lack of awareness and strategic thinking is set to change.

While EU funding has been instrumental in advancing circular knowledge and pilot projects,[130] future funding should shift towards scaling innovations across the PV industry, prioritising projects that demonstrate a broad impact across circular economy strategies. To maximise circularity, policymakers should prioritise funding for projects that demonstrate the capacity to scale innovations across the spectrum of circular economy strategies.

Actions to help mobilise resources:

- Leverage public funding for innovation as well as upscaling of viable technologies.
- Provide the right financing tools and models to support nascent and incumbent players.
- Foster collaboration among key stakeholders to form industry bodies and manufacturing associations that can aid resource mobilisation.

Insufficient contextual enablers

Immature markets for circular strategies in the solar PV industry, persistent technological hurdles and limited resource mobilisation form a cycle that suppresses investment, innovation and commercialisation. This cycle is reinforced by prevailing practices and mindsets across the solar PV value chain, as well as lacking contextual enablers that would break it.

One major barrier is the lack of collaboration around data-sharing and standardised recording and reporting practices between manufacturers, recyclers and policymakers.[131] Effective circular strategies require robust partnerships and infrastructure to share information on material flows, product design, and recycling methods.[132] However, most industry players lack incentives or capacity for transparent collaboration, stalling progress.

First, accurate data on material composition, product life cycles and end-of-life volumes is essential for enabling effective recycling, reuse and remanufacturing processes. However, there is currently a scarcity of standardised information on the material composition of specific brands of solar PVs, particularly for older models. This makes it difficult for recyclers to optimise processes and recover valuable components efficiently.

Second, the absence of robust testing, tracking and monitoring systems throughout the PV life cycle means that stakeholders often have limited visibility into where panels are located, how they are performing, and when they will reach their end-of-life. This data gap prevents the creation of reliable forecasts for waste volumes, and disrupts the planning and investment in circular infrastructure. As a result, the lack of data hinders the efficiency of circular processes (both for recycling and second-life solutions) and diminishes the economic viability of circular business models in the PV industry.

The lack of reverse logistics and recycling infrastructure also hinders efforts to enhance circularity at scale. Current networks are ill-suited for handling PV waste, resulting in indefinite storage or improper disposal rather than recycling. Dispersed stakeholders across international markets, along with cheaper imported panels, further complicate regulatory measures and infrastructure investment in the EU. Regulating products that are manufactured abroad is extremely hard without close collaboration or resorting to restrictive and protectionist trade measures, such as import bans or high tariffs, which would adversely affect solar PV deployment in the EU.

Together, these barriers – fragmented data, inadequate monitoring, logistical challenges and competitive international markets – mean that current circular economy infrastructure is insufficient and unable to handle the anticipated PV waste volumes. Without robust collection, transportation and recycling systems, the PV industry will struggle to achieve circular economies of scale and realise the economic and environmental benefits of circularity.

Actions to strengthen contextual enablers:

- Establish regional, national and cross-national takeback systems to ensure steady supply of PVs for nascent and incumbent recycling businesses.
- Establish adequate infrastructure to ensure that reverse logistics and transportation costs can be optimised.
- Foster collaboration among key stakeholders to support initiatives and policies that can accelerate the ecosystem, including adoption of standardised ecolabels.

7. How could policy facilitate greater circularity?

The policy framework for more circular solar PV value chains must be ambitious and comprehensive, mapping clearly and explicitly how the EU intends to support and incentivise a transition from a linear to a more circular solar PV value chain. However, it is necessary to balance the need to improve the circularity in the PV value chain in Europe with the urgency of the energy transition, and consider ways to ensure greater circularity of solar PVs in the EU market without excessively restricting the sales of imported solar PVs. The EU should not compromise the energy transition or increase the costs to consumers to protect the nascent EU solar PV industry by reshoring PV manufacturing, but rather use its market influence to encourage circular economy practices globally, including in China. As the demand for circular economy strategies grows globally, investment in business models and technological solutions to enhance circularity in the PV value chain could deliver substantial benefits to EU companies that develop them.

To enable and encourage the shift from a linear to a circular value chain for solar PVs, policymakers need to design and implement policies that:

- **Create demand** for more recyclable PV designs, second-life PVs, recovered and reusable PV components, solar PV recycling services, and materials that can be recovered from recycled PVs. This would help companies focusing on second-life strategies and recycling to make a stronger investment case for R&D.
- **Establish supportive contextual conditions** to encourage innovation and the scaling up of innovative technologies and business models across the solar PV industry, focusing particularly on the design of solar PVs, second-life strategies and closed-loop recycling. This would help bring down the cost of second-life PVs, recycling and recycled materials by enabling economies of scale to develop. Such reduction in cost would make circular alternatives more competitive against virgin PVs and materials.
- **Advocate** international collaboration to push for more circular design of solar PVs globally, including in China where the vast majority of solar PVs in Europe are manufactured. This could help balance the EU's need for large quantities of new solar PVs while also pushing forward the circular economy agenda both within and outside the EU.

To achieve these objectives, policymakers have four types of policy measures at their disposal: mandates, bans, financial (dis)incentives and fiscal (dis)incentives. When talking about policy, bans and mandates are often collectively referred to as '**legal and regulatory measures**', while financial and fiscal incentives and disincentives are referred to as '**financial and fiscal measures**'.

Mandates include various types of regulations and standards that set parameters within which certain operations are allowed. The EU could use a range of mandates to enhance the supply and demand for more circular solutions across the solar PV value chain. These could include:

- product and technology standards relating to solar PV design (such as the Ecodesign Directive)
- recycled content quotas to create market demand for second-life materials
- standardisation of certain PV components that are most likely to require replacing to improve repairability
- mandatory minimum recovery rates for high-value materials embedded in solar PVs.

The EU could also require environmental product declarations for all solar PVs, complete with disassembly and recycling instructions, or mandate responsible disposal of decommissioned solar PVs. To ensure the effectiveness of many of these mandates, the EU would need to develop standardised emissions accounting and reporting protocols and standards, including a monitoring framework and a digital platform that enables data to be shared across the value chain. This tool could be even more effective if developed in collaboration with trade partners to create global markets for more circular solar PVs and associated technologies.

Bans refer to an official or legal prohibition of something, enforced though penalties, such as fines or imprisonment. Effective enforcement of mandates often leads to a *de facto* ban of products and operations that do not meet the standards described in the mandate, which can be strengthened as new technologies become available. To support circularity in the solar PV value chain, the EU could ban the landfilling of solar PVs, or the import of solar PVs that do not meet the EU's ecodesign standards (once these are operational). However, the former might result in 'dumping' (whereby solar PVs are illegally disposed of in nature), while the latter could run a risk of reducing supply and increasing the price of solar PVs in Europe, making it viable only if manufacturers in other countries are given sufficient warning and time to prepare. The effectiveness of an EU import ban will also depend on the perceived value of access to EU markets: if foreign manufacturers do not consider it essential to secure continuing access to the EU markets, they will not be willing to change their practices, especially if doing so would require substantial investment or entail loss of revenue.

Unlike bans and mandates, which seek to enforce certain behaviours or good practices, **financial and fiscal measures** seek to encourage or discourage certain behaviours and choices through monetary penalties or rewards. The term 'financial' refers to all factors, including operating costs, that influence the financial appeal of a certain choice. The term 'fiscal' refers more specifically to financial measures that are related to taxation or government spending.

Financial and fiscal incentives, such as the feed-in tariff, Contracts for Difference (CfD) and subsidies, have been used successfully in many EU countries to encourage energy companies and consumers to adopt solar PVs. Financial and fiscal incentives could also be used to encourage companies to invest in more circular practices and technologies, including new product designs to make solar PVs easier to repair, disassemble and recycle. Different types of tax deductions or tax exemptions could be made available to encourage repairs and the reuse of second-life solar PVs among all consumers (including households and businesses). Some examples include an exemption or reduction of the Value Added Tax (VAT) on solar PVs, replacement parts, or the labour to repair PVs or to install refurbished PVs. Additionally, fiscal incentives could be deployed to reward solar PV importers whose products are easier to disassemble, recycle or reuse.

Financial and fiscal disincentives could be implemented to increase the cost of actions and activities that do not support circularity, such as landfilling. For countries that are not willing to mandate or ban landfilling of solar PVs, high landfill fees could work effectively to create demand for alternative disposal pathways for decommissioned solar PVs, while also generating income that could be channelled into subsidies. Fiscal disincentives, such as higher import tariffs on less circular solar PVs, could enhance the effectiveness of fiscal incentives, while also increasing the price difference to consumers between second-life and new solar PVs.

The advantage of tax-related fiscal incentives (compared to subsidies) is that they require less upfront spending by the government, since the benefit to the recipient accrues from tax income that is foregone. Financial and fiscal disincentives can also generate income to the governments. However, the downside to all fiscal measures, compared to regulation, is that they can only be applied at Member State level, whereas regulations can be implemented at the EU level.

Annex 2 provides more detailed examples of various policy measures that can promote greater circularity within the solar PV value chain. It is important to note that the most effective outcomes are often achieved through a combination of policy measures and government actions working together, as a single policy measure is unlikely to produce significant results on its own.[133] Moreover, policies are highly context dependent; a measure that is successful in one setting may fail in another. Policies may also have unintended consequences, which could either enhance or undermine their effectiveness or interfere with the success of other, unrelated policies. Before implementing any policies, it is therefore advisable to carry out a thorough impact assessment and analysis to identify and address any potential adverse effects.[134]

In addition to the policy measures discussed above, policymakers and governments can also take action to reduce the risk of certain activities through different risk mitigation measures, which fall outside the typical classification of policy measures and are often tailored to address a specific need. These can include measures such as public sector procurement to create active market demand (and certainty of future market demand), for more circular products or materials.

Policymakers can also collaborate with their counterparts from other countries to forge alliances to exploit the joined market power of multiple countries to enforce or incentivise more sustainable practices in their domestic markets, and globally. This type of international collaboration can deploy other policies, such as trade policy, to achieve intended outcomes.

8. Conclusions and recommendations

Circular economy strategies offer various environmental, economic and social benefits. Second-life strategies and technologies that extend the lifespan of solar PVs or maximise material recovery through recycling can help reduce resource consumption, waste, pollution, environmental damage and emissions, especially when powered by sustainable energy.

While EU policy frameworks and technologies for circular economy strategies have improved in the past few years, the supply and demand for second-life solar PVs, recycling and recovered materials remain low, preventing the circular economy from scaling up. Specific factors that hinder upscaling of circular economy strategies in the solar PV industry include:

- layered design of silicon-based PVs, which increases the complexity of recycling and the associated costs, while the limited profitability from resale of recovered materials requires recyclers to charge for their services, discouraging demand
- limited commercial implementation and scaling of recycling methods capable of recovering high-purity or high-value materials
- limited data on second-life PV performance and the lack of certifications, which deter adoption, resulting in limited economies of scale that could improve business viability
- availability of low-cost alternatives to recycling, such as landfilling or exporting
- limited incentives to encourage circular economy practices across the value chain
- underdeveloped secondary markets for recycled silicon, glass and other recovered materials, largely due to the competition from cheaper virgin materials and manufacturers' concerns over quality and durability of recycled inputs.

Given the business development opportunities and potential benefits that greater circularity in the solar PV industry could deliver, stakeholders in the PV ecosystem need to find solutions. The businesses and policymakers that do so in a timely manner will be able to harness many social, economic and technological benefits while contributing significantly to the green transition.

To support the transition to a more circular PV ecosystem, a holistic view of the entire value chain is crucial. Overlooking the interconnection and dependencies between stakeholders across the PV industry value chain can prevent policymakers, existing stakeholders and new market entrants from fully understanding how policy, technology, market trends and consumer behaviours will shape the adoption and diffusion of various circular economy strategies. This lack of insight can hinder the feasibility and success of such strategies, which are vital for maximising the sustainability of solar energy in the long term.

Below, we provide some recommendations for what businesses and policymakers could do to accelerate the circular economy transition in the solar PV industry.

Recommendations for businesses

- **Strengthen collaboration** across the value chain by fostering partnerships among manufacturers, recyclers and logistics providers to streamline end-of-life panel collection, improve recycling efficiency and support circular design standards. Co-ordinated action could boost material recovery, reduce costs and increase circularity throughout the PV life cycle.
- **Leverage digital technologies** by using the Internet of Things (IoT), artificial intelligence (AI), advanced data analytics and blockchain to enhance tracking and predictive maintenance, and optimise recycling. Digital records and predictive maintenance could extend panel life, enable secondary markets and improve resource recovery.

- **Create demand for second-life products and recycled materials** by forming buyers' coalitions. Companies can also incentivise circular design and support marked development by lobbying for shared standards for recycled material quality and recycled content quotas, piloting data-sharing platforms, and favouring PVs that meet the ecodesign criteria in their procurement.
- **Explore opportunities to transition or expand existing business models** to incorporate circular approaches. This could involve companies themselves using second-life PVs, purchasing PVs made of certain amounts of recycled materials or components, or expanding operations to include repair, refurbishment and advanced recycling technologies.
- **Increase investment in workforce and circular economy R&D** through employee training and pilot projects to drive innovation in repair, recycling and sustainable materials.

Recommendations for policymakers

- **Develop a dedicated circular economy policy package for PVs**, focusing on circular economy strategies for PVs, covering second-life (eg, ecodesign standards, VAT exemptions on repair) and end-of-life (waste management and recycling) strategies. A tailored approach, separate from WEEE regulations, would allow for more precise targets and consistent implementation of mandates like EPR, providing industry clarity and operational stability.
- **Align and combine small-scale takeback systems to enable economies of scale** to develop and manage PV panel takeback, tracking and logistics, alongside a regionally distributed recycling network to reduce emissions and support local economies. Larger operations could enhance EPR compliance and efficient panel processing while boosting industry-wide participation.
- **Channel public sector funds (at EU and national level) to support circular innovation and commercialisation**, focusing on scalable projects across reuse, repair and high-value recycling, with clear guidelines for collaboration within the PV value chain. A specific EU funding stream could be established to leverage private sector investments to support the commercialisation of successful pilots, and to establish regional recycling hubs equipped with advanced technologies to build a sustainable and circular PV industry.
- **Create demand** for second-life PVs, recycling and recycled materials by establishing reliable quality standards for second-life PVs and implementing public awareness campaigns regarding the importance of improved circularity. These could be supported by policies that discourage non-circular disposal, support reverse logistics and incentivise recycled content.
- **Develop mechanisms that foster international collaboration** despite the geopolitical sensitivities.

In the past two decades, the adoption of solar PVs has grown more rapidly than anyone anticipated when Germany first introduced the subsidy for residential solar in 2000. The subsequent growth in demand for solar PVs kicked off a virtuous cycle of improved efficiency and declining costs, benefitting not just Germany but the whole world. At the same time, solar PVs have transformed from a niche technology to a widely adopted commodity.

Following the agreement at COP28 in Dubai to triple renewables globally by 2030, the solar boom will expand further. Developing circular economy solutions for solar PVs is essential to avoid causing an environmental crisis by addressing the climate crisis: the economies of scale that benefitted the solar PV industry will need to be replicated in circular economy strategies for them. Investing now in the development of second-life and end-of-life technologies and strategies presents an important economic opportunity for the EU.

The most urgent task is to address effectively the barriers to circularity in solar PV value chains discussed in Chapter 6. Initially, solutions need to be developed and upscaled, particularly for silicon-based solar PVs. In the future, as the market share of alternative solar PV technologies grows, circular solutions will be needed for these as well.

By exploring both the limitations and potential opportunities for improved circularity in the PV industry, this report emphasises the need for collaboration between businesses and policymakers to foster demand, incentivise innovation and implement cohesive policies. Moving forward, co-ordinated actions – such as establishing effective end-of-life strategies, advancing technology readiness and leveraging policy support – will be essential in creating a robust circular economy framework that sustains the growth and sustainability of the solar PV sector.

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