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Environmental, social, and governance actions along the value chain

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SolarPower Europe

Foreword

As we stand at the crossroads of Europe's green transition, the need for ambitious and coordinated action at European level has never been clearer. The solar PV sector is a cornerstone of this transition, serving not just as a solution to the climate crisis, but also as a catalyst for economic prosperity and resilience, job creation, and social progress.

This excellent report underscores the sector's commitment to full circle sustainability. It highlights how the solar PV industry takes its environmental, social, and governance (ESG) performance seriously across the value chain. It is a timely reflection of the collective responsibility to enhance the sector's sustainability practices, from manufacturing to recycling, and ensure that the solar PV industry continues to meet the highest standards, while fostering innovation, transparency, and equity.

It is time for Europe to affirm its leadership and commitment to a cleaner, more resilient economy. The European Parliament is looking forward to the Clean Industrial Deal proposals from the European Commission, as it will be essential to propel Europe to the forefront of the green revolution, securing a competitive edge in the global energy market.

A strong investment programme is key to this effort. We need investments that prioritise affordable renewable energy, not solely to address immediate needs, but also pave the way for the long run. The Sustainable Solar report emphasises the importance of directing such investments towards projects and technologies that foster sustainability throughout their lifecycle. Affordable and accessible renewable energy is the bedrock of the European Green Deal, enabling businesses and consumers alike to benefit from zero-emission solutions, while creating economic opportunities across the continent. The Clean Industrial Deal should aim to create and sustain a steady, growing demand for green products, enabling the solar sector to drive market growth and innovation across the entire supply chain.

At the same time, we must double down on circularity and resource efficiency. Our commitment to sustainability should go beyond reducing emissions; it must also embrace the principle of circularity. The solar sector has a pivotal role to play in this, particularly when it comes to maximising the quality and lifespan of products, ensuring that materials are recycled and repurposed, and reducing waste throughout the value chain. As outlined in the Sustainable Solar report, integrating circular design principles within solar PV production and recycling processes is essential for minimising environmental impact, while promoting long-term sustainability. In addition, these measures will be key to strengthen the strategic autonomy of the EU at a time when the demand for critical raw materials intensifies.

At the same time, Europe must develop a trade policy that protects our interests without falling into the trap of protectionism. While safeguarding European industries is crucial, we must also remain open to international collaboration, promote the exchange of knowledge, and ensure that the green transition is a global effort, not just a European one. Europe can lead by example, advancing the green transition while securing sustainable trade relationships that benefit all.

Lastly, we must ensure that social justice is at the core of the Clean Industrial Deal. The green transition will not succeed without the buy-in of workers. As we scale up renewable energy production and innovation, it is vital that we create quality jobs that are fairly remunerated and make sure workers are supported throughout this transition. The Sustainable Solar report addresses this issue by calling for clear frameworks that promote fair labour practices, ensuring that the solar sector's growth translates into tangible benefits for local communities and workers. Social fairness will be essential in securing broad public support for the green policies that will lead to a more sustainable and prosperous Europe for all.

In this context, the solar sector is an undeniable catalyst for change. SolarPower Europe's commitment to environmental, social, and governance actions, as detailed in the Sustainable Solar report, is a crucial step towards ensuring that the solar industry remains sustainable, equitable, and economically viable in the long-term. This report provides a valuable framework for how we can align sustainability with industry growth, reinforcing the European Union's role as a global leader in clean energy.

Let us work together to build a future where affordable, clean, and sustainable solar power is the driving force behind a resilient, equitable, and prosperous Europe.

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Introduction

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Solar PV plays a crucial role in the world's decarbonisation efforts to limit global temperature rise in line with the UNFCCC **Paris Agreement**. As one of the fastest-growing sources of electricity, solar power significantly reduces greenhouse gas emissions by harnessing energy from the sun instead of burning carbon-intensive fuels. Its scalability and declining costs make solar an essential component of any sustainability strategy, enabling countries to meet their climate targets and move towards a low-carbon economy.

In Europe, the **Green Deal** started a series of new legislative packages to spur on the clean energy transition in the European Union. The **European Climate Law** establishes the EU's goal of achieving climate neutrality by 2050 and cutting emissions by at least 55% by 2030. The **Renewable Energy Directive** (RED) sets binding renewable energy targets for EU Member States, aiming for solar and other renewables to make up at least 42.5% of the EU's energy mix by 2030. In 2022, the **EU Solar Energy Strategy** – a part of the REPowerEU Plan to end the EU's reliance on Russian fossil fuels – set a target of almost 750 GW_{DC} of newly installed solar PV capacity by 2030. The **Energy Performance of Buildings Directive** (EPBD) mandates that all new buildings must be nearly-zero energy buildings (NZEB), with a strong support for rooftop solar panel installations with its **EU Solar Rooftop Standard.** According to SolarPower Europe's analysis, the law has the potential to bring solar PV to the equivalent of 56 million European homes.

The concept of sustainability, however, goes much beyond addressing the issues of climate change and affordable clean energy. **While it is clear that solar PV contributes to economy-wide sustainability, the solar sector – like any other industry – is mindful of its own sustainability and is committed to continuing efforts to reduce its impact across various domains.**

This is well reflected in the **UN 2030 Agenda for Sustainable Development**, which in 2015 outlined seventeen **Sustainable Development Goals** (SDGs) that provide a shared blueprint for advancing sustainability on all scales (see Fig. 1). The goals demonstrate that sustainability is a multifaceted concept encompassing various environmental, social, and economic aspects. For the solar sector, this means that sustainability considerations need to be addressed at all levels of the value chain. This assessment must cover a variety of areas, spanning from ecosystem preservation and biodiversity impacts, to evaluating appropriate working conditions, social inclusiveness, and gender equality.

Another increasingly used and recently also legally grounded framework is the Environmental, Social, and Governance (ESG) framework, which refers to the three key factors used to evaluate an organisation's sustainability and ethical impact. Environmental criteria assess a company's impact on the planet, including its carbon footprint, waste management, and resource usage. Social criteria examine how a company manages relationships with employees, suppliers, customers, and communities,

FIGURE 1 SUSTAINABILITY CHALLENGES AND THE UN SUSTAINABLE DEVELOPMENT GOALS

focusing on issues like diversity, human rights, and labour standards. Governance relates to the internal practices and policies that ensure accountability, transparency, and ethical business operations, including executive compensation, board diversity, and shareholder rights. The ESG framework is increasingly used by investors to identify sustainable and socially responsible companies.

The ESG framework is applied in the **EU Taxonomy Regulation** under the Corporate Sustainability Reporting Directive, linked to the Corporate Sustainable Due Diligence Directive. As these new due diligence frameworks are horizontally connected to all the topics discussed in this report, closer attention is given to them in Box 1 below.

BOX 1 DUE DILIGENCE FRAMEWORKS

The entry into force of the Corporate Sustainability Due Diligence Directive (CSDDD) and the Corporate Sustainability Reporting Directive (CSRD) in 2024 has important implications for corporate sustainability in the EU as they reshape reporting across all environmental, social, and governance dimensions.

The Corporate Sustainability Due Diligence Directive (CSDDD) will ensure that companies identify and address adverse human rights and environmental impacts related to their activities inside and outside of Europe. The law will be translated into the national legislation of EU countries by 2026 and enter into force in stages, starting with the first group of companies in 2027.

The CSDDD builds on the UN Guiding Principles on Business and Human Rights and the OECD Due Diligence Guidance for Responsible Business Conduct. The UN Guiding Principles on Business and Human Rights (2011) set expectations of states and companies on preventing and addressing adverse human rights and environmental impacts, based on existing obligations and practices. **The OECD Due Diligence Guidance for Responsible Business Conduct** (2018), aligned with the UN Guiding Principles, explains due diligence in simple terms and includes actionable examples. According to the OECD Due Diligence Guidance, there are six core principles of responsible business conduct:

1. Embed responsible business conduct into policies and management systems, by developing and implementing clear responsible business conduct policies that are integrated into daily operations and supported by training and supplier contracts
2. Identify and assess adverse impacts. Companies must identify negative impacts in their operations and supply chains through stakeholder consultation, prioritising the most serious impacts, especially those affecting vulnerable groups.
3. Cease, prevent, or mitigate adverse impacts, by stopping harmful activities and creating preventive plans with stakeholder consultation, while determining when to suspend or end business relationships based on risk reduction success.
4. Track implementation and results. Regular monitoring of due diligence efforts and business relationships ensures successful management of risks, as well as timely assessment of the effectiveness of industry initiatives against international standards.
5. Communicate how impacts are addressed, by transparently sharing information about the company's due diligence processes and human rights impacts through accessible annual reports or websites, with updates provided to affected groups.
6. Provide for, or cooperate in remediation, to take responsibility for harm, keeping in mind legal and international guidelines while engaging with affected parties to determine appropriate remedies.

While the CSDDD mandates that companies identify and act on their adverse impacts, the **Corporate Sustainability Reporting Directive** (CSRD) requires companies to report on material impacts within their own operations and value chains, along with the actions taken to address them. The CSRD applies to large companies and listed small and medium-sized enterprises, with the first reports due in 2025 covering information from the 2024 financial year. The CSRD mandates reporting according to a new mandatory framework, the European Sustainability Reporting Standards (ESRS), which consist of general requirements, disclosures, and topic-specific standards (see Fig. 2).

Companies falling under the scope of the CSRD need to publish yearly the extent to which their activities are covered by the **EU Taxonomy for sustainable activities** and comply with criteria set in the Taxonomy Delegated Acts. Companies not falling under the scope of CSRD can decide to disclose this information on a voluntary basis to get access to sustainable financing or for other business-related reasons.

The EU Taxonomy maps activities that contribute to the following environmental objectives:

1. Climate change mitigation
2. Climate change adaptation
3. Sustainable use and protection of water and marine resources
4. Transition to a circular economy
5. Pollution prevention and control
6. Protection and restoration of biodiversity and ecosystems

For an economic activity to be defined as environmentally sustainable, it must contribute to at least one of these six objectives, do no significant harm to any of the remaining objectives, comply with minimum safeguards based on social standards, and comply with the technical screening criteria as set out in the Taxonomy Delegated Acts.

The EU Taxonomy Compass classifies electricity generation using solar PV technology as contributing to the climate change mitigation goal, helping direct financial flows towards solar projects, and encouraging green financing.

FIGURE 2 EUROPEAN SUSTAINABILITY REPORTING STANDARDS (ESRS)

CROSS CUTTING	ENVIRONMENTAL	SOCIAL	GOVERNANCE
ESRS 1 General requirements	ESRS E1 Climate change	ESRS S1 Own workforce	ESRS G1 Business conduct
ESRS 2 General disclosures	ESRS E2 Pollution	ESRS S2 Workers in the value chain	
	ESRS E3 Water & marine resources	ESRS S3 Affected communities	
	ESRS E4 Biodiversity & ecosystems	ESRS S4 Customers & users	
	ESRS E5 Resource use & circular economy		

Source: EU Commission (2023).

Report methodology and scope

The goal of this report is to illustrate how the solar sector is addressing various sustainability challenges across diverse dimensions and throughout its complex value chain. For each sustainability domain, the report first outlines the overall **Context and background** – the current state of play regarding the sustainability challenge, the relevant legislation on the topic, and how the solar industry has advanced on the challenge so far. Secondly, the **Approaches and best practices** section depicts an overview of the most effective actions to address the sustainability challenge. Thirdly, the report outlines several **Case studies**, illustrating the implementation of good practices through hands-on examples and applications.

The report structure follows sustainability considerations along the solar value chain, from the **Supply chain** phase (see Chapter 1), through to the **Use** phase (Chapter 2), to the **End-of-life** phase (Chapter 3).

The Supply Chain phase includes considerations on **Human rights due diligence, responsible sourcing and decent work** (Chapter 1.1), solar **Carbon footprint** (Chapter 1.2), and **Circular design** (Chapter 1.3).

At the Use phase, the report delves into **Community engagement** (see Chapter 2.1), **Land use** (Chapter 2.2), and **Biodiversity** (Chapter 2.3).

Lastly, the End-of-life phase addresses the areas of **Revamping and repowering** (Chapter 3.1), **Reuse and repair** (Chapter 3.2), and **Waste management and recycling** (Chapter 3.3).

This report has been drafted with the invaluable support of SolarPower Europe members, in particular those engaged in SolarPower Europe's Workstreams that are active in the topics described above. Notably, these include the **Supply Chain Sustainability Workstream**, the **Product Sustainability Workstream**, the **Land Use and Permitting Workstream**, and the **Lifecycle Quality Workstream.**

This report, which is a revised, expanded, and updated version of SolarPower Europe's Solar Sustainability Best Practices Benchmark (2021)[1], aims to advance and disseminate knowledge on solar sustainability and contribute to positioning the EU solar sector as a sustainability leader towards achieving the ESG goals.

1 SolarPower Europe (2021): Solar Sustainability Best Practices Benchmark.

1

Supply chain phase

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1.1 Human rights due diligence, responsible sourcing, and decent work

Context and background

The solar PV sector is committed to safeguarding the rights of those who live and work in it. The sector underscores its responsibility to respect and uphold human rights across the entire solar value chain, from raw material extraction to the final product.

To meet this responsibility, companies in the solar sector are implementing environmental and human rights due diligence systems, adopting responsible sourcing strategies to avoid complicity in human rights violations within their supply chains, and enforcing policies that ensure fair working conditions throughout both their supply chains and internal operations.

Human rights due diligence as defined by the OECD, is the ongoing process that businesses should conduct to identify, prevent, mitigate, and account for how they address their impacts on human rights throughout their operations and supply chains. This process aligns closely with the principles of responsible business conduct promoted by various international frameworks, such as the United Nations Guiding Principles on Business and Human Rights and the OECD Guidelines for Multinational Enterprises (see below).

Responsible sourcing is defined by procurement practices that align with internationally recognised environmental, social, ethical, and governance standards. This commitment seeks to ensure that the sourcing of products and services prevents harm to both rightsholders and the natural environment. By adopting responsible sourcing standards, companies within the solar sector ensure that their procurement processes reflect a commitment to sustainability and ethical conduct. This approach fosters transparency and accountability, aligning business operations with the broader goals of social responsibility. Responsible sourcing policies must go beyond addressing first-tier suppliers; they must encompass the entire supply chain, including 'suppliers of suppliers.'

The solar value chain is highly concentrated in one country, which poses notable challenges. Additionally, solar PV system components are complex products composed of several components whose production can be outsourced to multiple third parties.

This complexity needs careful consideration of multiple jurisdictions and risks that can influence procurement practices. Addressing these challenges requires a proactive approach to supply chain management, including thorough due diligence and supply chain transparency in sourcing practices.

Decent work, as defined by the International Labour Organization (ILO), refers to employment that is productive and delivers a fair income, ensuring security in the workplace and social protection for workers and their families. It involves respecting workers' rights, in line with ILO Core Conventions, and providing opportunities for personal development and social integration. The ILO emphasises the importance of equality of opportunity and treatment for all, as well as safe working conditions. Decent work also includes promoting social dialogue between workers and employers, allowing workers the freedom to collectively bargain and participate in decisions that affect their working lives.

Several international conventions and guidelines govern responsible business conduct, decent work, and human rights due diligence. Key instruments include:

- **OECD Guidelines for Multinational Enterprises**: These guidelines provide recommendations on how businesses should integrate human rights considerations into their operations, with a strong focus on responsible supply chain management and due diligence.
- **OECD Due Diligence Guidance for Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas:** This guidance is particularly relevant for the solar industry, as it provides a detailed framework for responsible supply chain management in regions where human rights risks are heightened. The guidance helps companies ensure that they do not contribute to conflict or human rights abuses through their mineral sourcing practices.
- **United Nations Guiding Principles on Business and Human Rights (UNGPs):** These principles outline the corporate responsibility to respect human rights, emphasising the need for human rights due diligence to prevent and address human rights impacts.
- **International Labour Organisation (ILO) Conventions**: Particularly relevant are the core conventions on forced labour and child labour, freedom of association and collective bargaining, equal remuneration, discrimination, and the conventions on working conditions (occupational safety and health, minimum wage-fixing, and social security), which underpin global labour standards.
- **UN Global Compact**: This initiative encourages businesses globally to adopt sustainable and socially responsible policies, including human rights due diligence as a core component.
- **European Social Charter**: A Council of Europe treaty that guarantees fundamental social and economic rights as a counterpart to the European Convention on Human Rights, which refers to civil and political rights. It guarantees a broad range of everyday human rights related to employment, housing, health, education, social protection, and welfare.

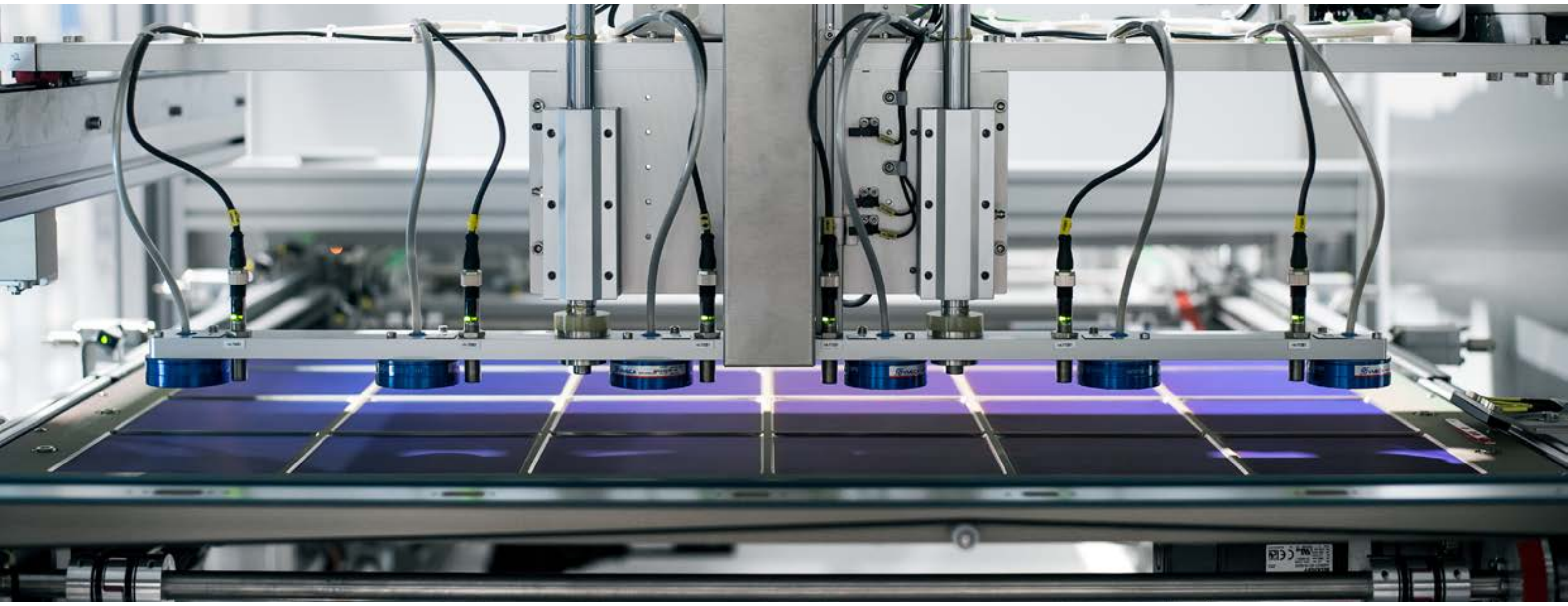
The solar industry is committed to aligning with these international standards to ensure compliance with both global expectations and local regulations. This alignment not only enhances the industry's credibility, but also provides a competitive advantage, as markets increasingly demand proof of responsible sourcing, and human rights compliance. In the case studies section, practical examples are provided that showcase what members of SolarPower Europe are doing to ensure that human rights due diligence, decent work conditions, and responsible sourcing underpin a just energy transition.

Several adopted and upcoming legislative measures within the European Union will have a significant impact on how solar companies implement human rights due diligence and responsible sourcing:

- **Corporate Sustainability Reporting Directive (CSRD):** Starting in financial year 2024, this directive requires publicly-listed solar companies to provide comprehensive reports on their sustainability practices, including detailed accounts of their human rights due diligence processes. This reporting obligation is critical for improving transparency and accountability within the solar supply chain. The directive is complemented by the European Sustainability Reporting Standards (ESRS), which provide information for investors to understand the sustainability impact of the companies in which they invest.
- **Corporate Sustainability Due Diligence Directive (CSDDD):** This directive introduces mandatory environmental and human rights due diligence requirements for companies operating in the EU, compelling solar companies to identify, prevent, and mitigate human rights and environmental impacts throughout their supply chains. Implementation will start from 2027, once transposed into national legislation.
- **Forced Labour Ban Regulation:** Approved by the European Parliament in spring 2024 and waiting for the approval of the Council of the EU, this Regulation aims to ban products made with forced labour from the EU market. It applies to all products, including those produced within the EU for domestic use or export, as well as imported goods, without focusing

on specific companies or industries. The European Commission and national authorities in Member States will enforce the prohibition on forced labour using a risk-based approach, assessing risks from civil society submissions, forced labour risk database, and company due diligence. Investigations will target products suspected of being made with forced labour, with authorities empowered to request information, conduct inspections (even outside the EU), and withdraw or prohibit such products. This regulation is expected to be implemented in 2027.

- **EU Directive on Transparent and Predictable Working Conditions:** This directive improves working conditions across the EU by ensuring that workers are provided with transparent information on their working conditions and rights, impacting solar companies in terms of employment practices.
- **EU Directive on Temporary Agency Work:** This directive aims to ensure protection for workers in temporary agency employment, promoting equal treatment and decent work for temporary workers across all sectors, including solar.
- **EU Posted Workers Directive:** This directive ensures that workers posted temporarily to another EU member state to provide services are entitled to the same core employment conditions as local workers in the host country. This includes regulations on minimum wage, maximum working hours, paid leave, and health and safety standards. The directive aims to prevent social dumping by ensuring fair competition and protecting workers' rights, requiring companies to comply with local labour laws in the country where the work is carried out, while also facilitating the free movement of services within the EU.



- **European Commission guidance on due diligence for EU businesses to address the risk of forced labour in their operations and supply chains**: This guidance provides practical advice for companies to identify, prevent, and address forced labour risks, including state-sponsored forced labour, in their supply chains. It emphasises embedding responsible business conduct into corporate policies, ongoing risk assessments, and transparent communication. The guidance also outlines when and how to disengage from suppliers as a last resort if forced labour risks cannot be mitigated. Drawing on international frameworks, like the UN Guiding Principles and OECD Guidelines, it supports companies in maintaining ethical supply chains, particularly in high-risk regions.

BOX 2 DUE DILIGENCE IN NATIONAL LEGISLATION

Several countries in Europe have adopted legislation to impose obligations on large companies to conduct due diligence in their supply chains and ensure decent work.

- **Germany's Supply Chain Due Diligence Act**, which came into force in 2023, obliges companies to implement comprehensive due diligence measures throughout their supply chains. Companies are required to assess risks related to human rights and environmental standards, particularly concerning forced labour, child labour, fair wages, and safe working conditions. Non-compliance with the law can result in significant fines, highlighting the German government's commitment to enforcing decent work standards globally.

- **France's Duty of Vigilance Law**, adopted in 2017, was one of the first national laws to mandate supply chain due diligence. It requires large French companies to create and implement vigilance plans that identify risks to human rights, health, safety, and the environment within their operations and supply chains. The law holds companies accountable for ensuring decent working conditions and preventing human rights violations, with penalties imposed for failure to comply.

- The **Norwegian Transparency Act**, effective from July 2022, requires large and medium-sized companies that sell goods and services in Norway to conduct human rights and decent work due diligence across their entire supply chain. The law mandates transparency by requiring companies to publicly report on their due diligence processes and respond to public inquiries about how they address human rights risks, including working conditions.

Approaches and best practices

HUMAN RIGHTS DUE DILIGENCE AND RESPONSIBLE SOURCING

When conducting their own human rights due diligence and setting their responsible sourcing strategy, solar companies should, at a minimum, follow the due diligence process described in the OECD Guidelines for Responsible Business Conduct. This process is articulated in six steps, as outlined in Figure 3.

This section analyses how each step applies to the solar sector and what best practices solar companies can adopt.

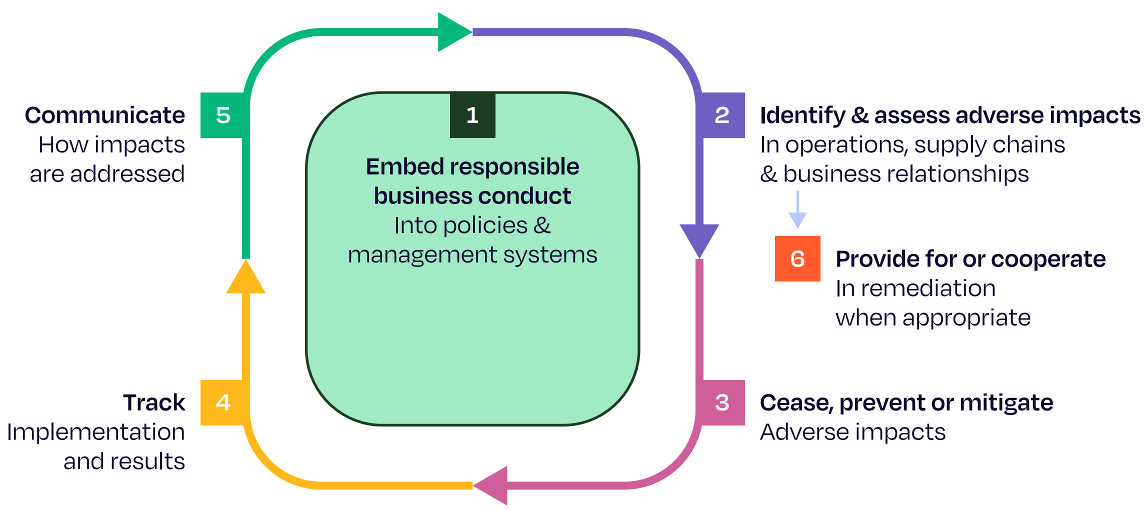
1. **Embed responsible business conduct into policies and management systems**

   To ensure human rights due diligence and responsible sourcing are embedded into the corporate policies and management systems of their suppliers and business partners, companies within the solar sector either develop their own contractual clauses and supplier code of conduct or they adopt and rely on industry or third parties' initiatives, standards, and procurement guidelines. A combination of both approaches is prevalent.

While the first approach may be necessary to ensure a company's legal compliance with EU and national legislation and in the absence of other industry standards, the second may prove more effective because it provides harmonisation and a common way to measure progress and compare different suppliers.

Relying on industry or third parties' standards and initiatives does not, however, exempt the company from continuously monitoring the status, development, and effectiveness of such initiatives, the evolution of legislative requirements, and stakeholders' expectations at a national, European and global level.

FIGURE 3 OECD GUIDELINES FOR RESPONSIBLE BUSINESS CONDUCT



Source: OECD (2023).

Contractual clauses and supplier code of conduct

Companies' commitments regarding human rights and the environment are typically passed on to suppliers through a supplier code of conduct attached to the supply agreement and related contractual clause, setting the obligation for the supplier to comply with the code of conduct.

These codes of conduct generally cover the four pillars of the UN Global Compact: human rights, labour rights, the environment, and business ethics. Another option is for these codes of conduct to be divided into environmental, social, and governance (ESG) topics, similar to the Solar Stewardship Initiative's (SSI) ESG standard. It is crucial that they, at a minimum, cover all internationally recognised human rights (as described above), including the fundamental conventions of the International Labour Organisation.

A supplier code of conduct typically does not entail human rights due diligence commitments for the purchasing party. However, it is important that buyers understand how a company's purchasing practices may contribute to adverse impact in the supply chain, and why shared responsibility is important. A good practice is to ensure that the same policies and requirements expected of their suppliers are implemented in their own operations (see section on Decent Work below) as well as their purchasing practices. This also contributes to a fairer and better business relationship with the supplier(s) and increases the likelihood of a successful negotiation.

A good practice for improving the capacity to meet ethical standards is to establish long-term partnerships with suppliers. Financial and technical assistance empowers suppliers to prioritise ethical practices and align their performances with the company's sustainability goals. Moreover, companies which maintain ongoing communication and foster collaborative approaches to problem solving with suppliers, by providing feedback and addressing concerns, better understand suppliers' challenges and are able to work together to find solutions. Regular communication is, therefore, key to increasing ethical standards. Another activity several companies undertake to help smaller suppliers, or those that are not knowledgeable on these topics, is to invest in training on supply chain transparency and the importance of ethical sourcing. The training covers topics, such as how to identify risks, how to report concerns, and how to comply with policies and regulatory requirements.

Adopting industry or third parties' standards, initiatives, or procurement guidelines

Companies within the solar sector may also rely on industry or third-party schemes and frameworks to set their supplier expectations on corporate policies and management systems requirements.

There are several schemes that are applicable to the solar sector. While there are significant differences in terms of governance, verification, and scope of these schemes, they all cover the human rights requirements that should be included in minimum supplier expectations.

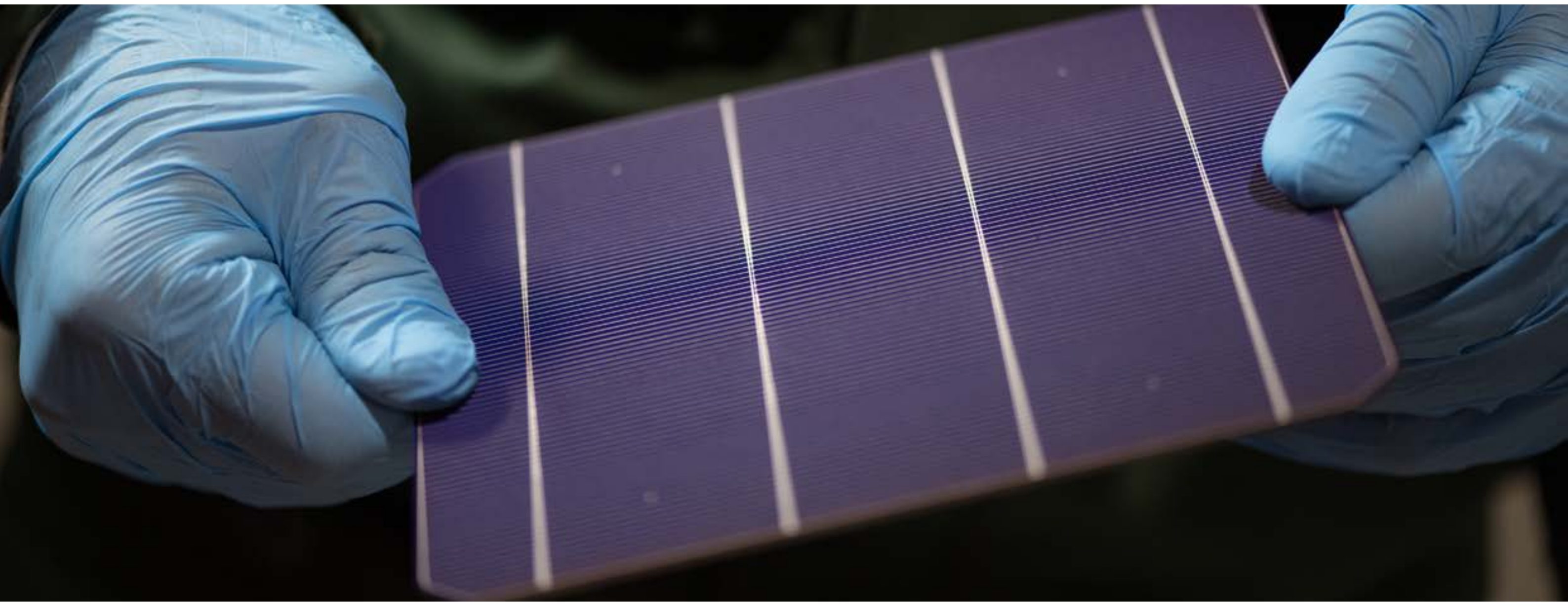
The Solar Stewardship Initiative (SSI) is the first solar-specific supply chain sustainability assurance scheme, driving a more sustainable and transparent solar global value chain. In December 2023, the SSI published its ESG Standard, and in December 2024, it will publish a Supply Chain Traceability Standard. By assessing production sites with these two standards, stakeholders and consumers will be reassured that the solar panels they use are manufactured and sourced ethically. More information is available in the case studies section below.

The International Responsible Business Conduct Agreement for the Renewable Energy Sector brings together wind and solar energy companies, industry associations, the Dutch government, knowledge institutions, civil society organisations, and trade unions. This partnership aims to prevent and address significant adverse impacts on people, the environment, and biodiversity within renewable energy supply chains. Signatory companies commit to the OECD Guidelines for Multinational Enterprises and the UN Guiding Principles on Business and Human Rights, with annual progress assessments. Key focus areas include: 1) enhancing company due diligence through capacity-building and knowledge sharing; 2) fostering collective action on human rights, environment, and biodiversity; and 3) integrating responsible business practices in procurement. In its second year, the Agreement oversees projects on worker welfare, solar sector due diligence, and human rights in copper supply chains. More details are in the annual report.

The Responsible Business Alliance (RBA) is the world's largest industry coalition dedicated to responsible business conduct in global supply chains. The RBA Code of Conduct is a set of social, environmental, and ethical industry standards. The standards set out in the Code of Conduct reference international norms and standards, including the Universal Declaration of Human Rights, ILO International Labor Standards, OECD Guidelines for Multinational Enterprises, ISO, and SA standards, and more. While the Code of Conduct originated with the electronics industry in mind, it is applicable to and used by many industries beyond electronics.

The SA8000 certification provides a framework for organisations of all types, in any industry, and in any country to conduct business in a way that is fair and decent for workers and to demonstrate their adherence to the highest social standards.

For companies to meet broadly accepted due diligence standards and best establish their internal processes and policies, participating in industry or multi-stakeholder schemes can accelerate and simplify the environmental and human rights due diligence and compliance processes by providing useful sector-specific data, updates on legal requirements and new trends, identifying cross-sector risks, overall providing a platform for stakeholder and industry engagement.



2. Identify and assess adverse impacts

Mapping the company's supply chain, conducting risk assessments, evaluating supplier practices, and determining areas of high risk to intervene is a good basis for assessing adverse impacts. Achieving transparency in long and complex value chains, like solar PV (see Figure 2 below), requires time and effort, as it involves coordinating with hundreds of suppliers across various geographic regions — many of them remote and lacking direct contractual relationships, particularly when dealing with sub-suppliers. An additional technical challenge is presented by the fact that quartz, silicon and aluminium are often mixed and melted and not exclusively dedicated to the solar sector. These challenges can be most effectively addressed by collective action, which is one of the key drivers behind the creation of the Solar Stewardship Initiative.

Assessing adverse impacts in the value chain is important, as it helps prevent risks of worker exploitation, such as forced labour, excessive working hours, unsafe labour conditions, and lack of freedom of association. Special focus when assessing adverse impacts should be given to vulnerable groups, such as indigenous communities and migrant workers.

Furthermore, solar companies must pay attention to environmental and human rights risks in related segments, such as in battery supply chains, and the extraction of minerals, like cobalt and lithium.

In terms of prioritising risks, the solar industry is particularly vulnerable to exposure to forced labour risks in the polysilicon production segment of the supply chain, as highlighted by academic research[2] and NGO reports. Additionally, other materials present in solar products such as zinc and copper are at risk, too. While the Solar Stewardship Initiative aims to address forced labour concerns in the polysilicon supply chain, other schemes, like the Copper Mark[3], focus on mitigating risks associated with materials such as zinc and copper.

FIGURE 4 SUPPLY CHAIN STEPS IN SOLAR PV MODULE MANUFACTURING FROM RAW MATERIAL TO FINAL PRODUCT

Source: Bernreuter (2020); Fraunhofer CSP (2020).

2 Sheffield Hallam University (2021): In Broad Daylight: Uyghur Forced Labour and Global Solar Supply Chains.

3 Business and Human Rights Centre (2024): Transition Minerals Tracker.

In February 2021, SolarPower Europe issued a statement[4] condemning all forms of forced labour, and together with its members has been dedicating substantial effort to increasing transparency and responsible practices in the supply chain. This effort later led to the creation of the Solar Stewardship Initiative.

Once risks are identified, it is essential to assess potential and actual adverse impacts using reliable sources and supplier audits. Given the highly complex nature of the solar supply chain, companies have increasingly relied on independent auditors to conduct regular supplier audits. These are typically third-party audits where an auditing company is hired by the potential buyer to conduct regular audits on its suppliers. This approach has enabled them to better report compliance with labour standards and other ESG requirements.

Following the recommendations provided in the European Commission Guidance on due diligence for EU businesses to address the risk of forced labour in their operations and supply chain[5], solar companies are also including suppliers' or subcontractors' participation in government sponsored labour programmes in their risk assessment to avoid the risks associated with instances of state-sponsored forced labour. This also includes communicating concerns to relevant governments, requesting transparency and independent audits, and engaging with international organisations to promote human rights standards. When prevention and mitigation are not feasible, it is advisable to conduct responsible disengagement.

Engaging directly with affected stakeholders, particularly in manufacturing, enhances understanding and contributes to a more comprehensive assessment of potential and actual adverse impacts. However, the possibility to engage with rightsholders and stakeholders in the upstream segments of the complex solar value chain can be limited. When direct engagement is not possible, collaborating with human rights defenders, civil society organisations, and academia can offer valuable insights.

3. Cease, prevent, and mitigate adverse impacts

A systematic approach to supplier selection ensures that ethical, environmental, and social standards are upheld across the supply chain. By modifying purchasing practices and communicating clear expectations and policies, companies prevent adverse impacts, while supporting suppliers in adopting responsible practices. In high-risk areas, where alternative suppliers may be limited, it is important to take proactive steps to mitigate risks and maintain business relationships responsibly.

As outlined in the EC Guidance mentioned in the previous section, disengagement is not always feasible, particularly when suppliers provide critical raw materials that are not easily sourced elsewhere. Per the Guidance, "in such cases, companies continue to monitor these relationships closely, report to senior leadership, and apply leverage to encourage improvements. Transparent communication with stakeholders about the decision to stay engaged, along with efforts to mitigate risks, is essential. By following this approach, solar companies ensure that they maintain ethical practices without disrupting essential supply chains."

Collaboration through initiatives, like the Solar Stewardship Initiative, amplifies collective influence, driving sector-wide improvements in responsible practices. Companies are also contributing to the establishment of clear guidelines for the temporary suspension or termination of relationships, in line with regulations, such as the Corporate Sustainability Due Diligence Directive (CSDDD). However, disengagement is considered only as a last resort, when all other options have been exhausted, ensuring that companies remain committed to supporting suppliers and engaging in remediation efforts, wherever necessary.

4 SolarPower Europe (2021): Statement on Forced Labour.
5 EU Commission (2021): Guidance on due diligence for EU businesses to address the risk of forced labour in their operations and supply chain.

4. Track implementation and results

The optimal method for tracking implementation and results of due diligence commitments is to regularly monitor internal goals and activities to ensure compliance with ethical standards, to conduct assessments of business relationships — ideally every twelve months — to evaluate progress, and to engage directly with impacted or potentially impacted rightsholders and their representatives. This is particularly crucial among first-tier suppliers, ensuring that tracking efforts are transparent and credible.

Industry schemes and initiatives are also an effective method for tracking implementation of a responsible business conduct, as these provide valuable data on its members' commitments, its third-party assessments, and the progress of the entire value chain, as well as a platform to engage with civil society and other non-industry stakeholders. Additionally, staying updated on methodologies and actively contributing to guidance from regulatory bodies, like the European Commission, is a reliable way to ensure that the tracking systems in place remain effective and compliant with evolving standards and stakeholder expectations.

5. Communicate how impacts are addressed

The best practice for communicating how human rights impacts in the supply chain are addressed, is to provide public reporting on due diligence processes through annual sustainability reports, company websites, and other accessible platforms. This reporting ensures stakeholders are informed about the way companies are identifying, preventing, and mitigating adverse impacts within their supply chains.

In alignment with the obligations set out in the Corporate Sustainability Reporting Directive (CSRD), it is key to publish comprehensive and transparent reports of companies' compliance with environmental, social, and governance (ESG) standards. For human rights impacts that companies cause or contribute to, clear communication with affected or potentially affected rightsholders is essential. This includes engagement with workers and impacted communities within the supply chain. Transparency fosters accountability and ensures that all stakeholders understand how adverse impacts are being addressed.

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6. Provide for or cooperate in remediation

   A key aspect of a company's commitment to responsible business conduct is providing for or cooperating in remediation efforts. Best practices include recognising that certain negative impacts, such as inadequate wages or excessive working hours, may stem from business practices, like aggressive price negotiations or late orders. Remediation efforts focus on restoring affected individuals or areas to their original state wherever possible, with responses proportional to the severity of the impact. For example, fair compensation can address wage inadequacies, while paid time off can remedy excessive working hours.

   In cases involving complex issues like state-imposed forced labour, it is crucial to increase indirect support for affected communities and prioritise collaboration with impacted rightsholders and their representatives. This approach ensures that remediation is both effective and tailored to the specific needs of those impacted, building trust and accountability throughout the supply chain.

DECENT WORK CONDITIONS

It is important to not only ensure decent work standards in a company's supply chains through responsible sourcing practices, but also within their own operations. Decent work encapsulates the aspirations individuals hold regarding their professional lives. It provides opportunities for productive employment that delivers fair income, workplace security, and comprehensive social protection. It also includes prospects for personal development, social integration, freedom to voice concerns, and participation in decision-making processes, ensuring equal opportunity and treatment for all, regardless of gender.

Ensuring decent work standards is vital across all sectors, including the rapidly growing solar energy industry. Within this sector, developers and their engineering, procurement, and construction (EPC) partners often rely on posted workers to perform temporary construction and installation tasks at project sites. The rights of these workers are protected under the EU Posted Workers Directive, which has been integrated into national legislation across EU Member States. In the Netherlands, for example, foreign workers on temporary postings are entitled to core provisions of Dutch employment terms, such as wage levels and working hours, for the first 12 months of their assignment. Similarly, in Germany, the Act on the Posting of Workers ensures equal pay for equal work at the same location, meaning posted workers in Germany must receive the same wages and working conditions as their locally contracted colleagues.

Given the reliance on posted workers in the construction of solar projects, companies must undertake thorough assessments to verify that these workers are treated in accordance with the legal requirements stipulated by the EU Posted Workers Directive. Evidence from other sectors reliant on posted workers, such as horticulture and meat processing, indicates frequent violations of workers' rights, including poor housing conditions, unsafe working environments, and inadequate social security. Solar companies, by committing to rigorous assessment and compliance with legal standards, play a pivotal role in ensuring that the principles of decent work are upheld.

To ensure compliance and protect workers' rights, these are the best practices for improving working conditions:

- **Transparent employment practices:** Companies provide clear, written employment contracts to posted workers, outlining their rights and obligations in a language they understand. Compliance with local wage laws and collective bargaining agreements ensures that workers receive fair compensation.
- **Monitoring working hours and compensation:** Companies regularly check compliance with regulations on maximum working hours, mandatory rest periods, and overtime compensation. Posted workers also receive paid leave and public holidays in line with local legislation.
- **Prioritising health and safety standards:** Solar companies ensure posted workers have access to health insurance that meets the host country's requirements and that their work environments comply with local health and safety regulations. Providing proper safety training and equipment is essential to protect worker well-being.

- **Assessing transport and accommodation quality:** Safe and reliable transportation between accommodation and work sites is ensured, along with sanitary living conditions that meet local standards.

- **Fostering social integration and representation:** Access to trade unions and providing language support or translation services helps workers understand their rights, responsibilities, and safety instructions, promoting an inclusive workplace environment.

To effectively assess and ensure compliance with posted worker regulations, companies should implement a multi-faceted approach:

- **Regular audits and inspections:** Conduct regular audits and on-site inspections to verify compliance with employment, wage, and health and safety regulations.
- **Worker interviews:** Conduct confidential interviews with posted workers to gather first-hand accounts of their working and living conditions.
- **Training programmes:** Develop and implement training programmes for both posted workers and local management to ensure awareness and understanding of applicable regulations and workers' rights.
- **Partnership with unions and NGOs:** Collaborate with trade unions, non-governmental organisations (NGOs), and other stakeholders to monitor and support the enforcement of workers' rights.
- **Reporting mechanisms:** Establish clear and accessible reporting mechanisms for posted workers to report grievances or violations of their rights without fear of retaliation.
- **Continuous improvement:** Use the findings from audits, inspections, and worker feedback to continuously improve policies and practices, ensuring ongoing compliance with posted worker regulations.

EQUAL TREATMENT AND OPPORTUNITIES FOR ALL

In addition to ensuring decent work conditions, the solar sector recognises the importance of fostering a diverse and inclusive workplace. Diversity is defined as the dimensions of race, ethnicity, gender, sexual orientation, socio-economic status, age, physical abilities, religious beliefs, political beliefs, or other differing backgrounds or perspectives. According to IRENA, solar is the most gender-balanced renewable energy technology, with women making up 40% of the solar workforce.[6] However, more efforts are required to improve gender equality and diversity more widely, at all levels of an organisation, particularly related to the share of underrepresented groups in Science, Technology, Engineering, and Mathematics (STEM) careers, as well as senior management. In 2022, women held less than 20% of senior management positions (17%), and under a third of STEM positions (32%) within the solar industry.

Fostering a diverse and inclusive workplace includes structuring recruitment processes to incentivise hiring diverse candidates, tracking workforce diversity through indicators, such as wage and career progression, and establishing specific policies to eliminate discrimination.

In addition to building a diverse workforce, the solar sector must also direct its efforts towards supporting these initiatives and promoting what is known as 'inclusion', defined as the practice of ensuring that through their work, people feel they belong, are engaged, valued, and connected to the goals and objectives of the organisation.

The solar sector also includes companies tracking the positive impacts of their diversity efforts, such as designing products that improve accessibility for people with disabilities, and ensuring work-related incidents or complaints are addressed. These efforts are showcased in SolarPower Europe's Solar Diversity Champion Awards[7], which aims to increase visibility and awareness around the importance of Diversity, Equity, and Inclusion (DEI) in the solar sector, as well as to highlight successful initiatives and practices that can serve as examples for others.

6 IRENA (2024): Renewable energy and jobs: Annual review 2024.
7 SolarPower Europe (2024): Solar Diversity Champion Awards 2024.

Case studies

The Solar Stewardship Initiative

Designed as a multi-stakeholder Initiative, the **Solar Stewardship Initiative (SSI)** is a solar-specific sustainability assurance scheme, gathering companies from across the global solar value chain, as well as civil society, academia, and the international finance community. Working with all relevant stakeholders, the SSI fosters responsible production, sourcing, and stewardship of solar materials.

These efforts aim to address key risks in the solar industry's global supply chain, particularly those related to transparency and human rights risks, as outlined above.

The SSI's Environmental, Social, and Governance (ESG) Standard is the initiative's key tool to improve responsible practices in solar supply chains. It is based on international standards, input from supply chain sustainability experts, and civil society, including human rights and environmental groups. Prior to its publication in October 2023, it was tested through public consultation and a pilot phase.

As of the end of 2024, over a dozen solar PV module factories, with a combined annual production capacity of around 100 GW, were in the process of going through independent third-party assessments against the SSI ESG Standard. After the assessments, sites are awarded bronze, silver, or gold ratings. Sites not awarded gold certification are given an improvement plan to achieve gold at reassessment. Sites with major non-compliance, breaching human rights, or using forced labour, are not certified at any level. Furthermore, by refusing to conduct assessments or certifications in sites or regions that are not freely accessible, the SSI contributes to the marginalisation of businesses and sites which fail to uphold strong ESG standards.

Currently, the SSI is working on its second Standard, the SSI Supply Chain Traceability Standard. This is the SSI's key tool to enhance supply chain transparency. It is set to take the SSI assurance scheme further. With the combination of the ESG Standard and the Supply Chain Traceability Standard, the SSI will be able to certify how each link of the supply chain is connected, creating the so-called Chain of Custody. Similarly to the ESG Standard and in accordance with ISEAL good practice, the SSI Traceability Standard has been subject to public consultation and piloting. The SSI published the Supply Chain Traceability Standard in December 2024.

The SSI's Assurance Process is based on third-party audits that follow a rigorous methodology of unsupervised worker interviews, site walkthroughs, and documentation review. All these components are non-negotiable and are based on international standards of good auditing practice. Facilities or regions that cannot be freely accessed, and accordingly assessed, will not be able to achieve SSI certification.

Prior to being admitted to the SSI membership, companies must commit to apply the SSI Standards to their entire operations and require their suppliers to operate accordingly. Manufacturers joining the SSI also commit to completing an assessment against the SSI Standards for at least two of their production sites within the first 12 months, with increasing commitments for each following year. When joining the SSI, solar developers also commit to source a certain share of PV modules from SSI members, with increasing commitments for each following year. Targets for both manufacturer and developer members are set by the SSI's Board of Directors. The SSI Policy of Association applies when a member is found in violation of its commitments. The SSI Complaints and Appeals Mechanism provides further accountability from external stakeholders.

The SSI is aligned with and will continue to ensure its alignment with EU and relevant legislation on sustainable supply chains, such as the above-mentioned CSDDD, CSRD, and Forced Labour Ban Regulation. The SSI is committed to supporting the implementation of the legislation by helping businesses understand their compliance obligations and the efforts required to meet them. The SSI is working to provide guidance on how to incorporate due diligence in their procurement practices both to its members and the broader solar industry, including Small and Medium Enterprises (SMEs). However, it is important to note that the SSI, or any other sustainability scheme or standard, does not act as a replacement for businesses responsibilities under the above-mentioned laws.

Multi-stakeholder initiatives can support the intended impact of, and compliance with, law. The CSDDD recognises the role of multi-stakeholder initiatives in supporting businesses in fulfilling their obligations under the law. Industry and civil society must work together to reinforce supply chain traceability and ESG standards, and this is feasible through multi-stakeholder initiatives.

Beyond compliance with law and the non-negotiable respect for human rights, the SSI employs OECD guidance on leveraging buyer pressure. Efforts, like the SSI, empower product buyers to join forces to demonstrate demand for high performing ESG products, supporting a race to the top for ESG standards.

The SSI as of December 2024 counts about 50 members across the whole solar value chain, representing a significant global market share both in terms of supply and demand. The strong industry buy-in, combined with support from non-industry stakeholders, including civil society, and an approach tailored specifically to the solar industry's needs, is enabling the SSI to make a significant contribution toward enhancing responsible practices and transparency in solar supply chains.

Responsible sourcing within the inverter supply chain

Fronius, an Austrian inverter manufacturer pursues a global procurement approach with a focus on European suppliers, which ensures compliance with legal, social, and environmental standards through a robust supplier and risk management system. This approach encompasses both the direct procurement of raw materials and components for products and indirect procurement for internal needs, such as operating resources and infrastructure.

The supplier management process involves the continuous evaluation and development of suppliers using standardised methods. New suppliers register through a platform and provide detailed information about their activities and products. These suppliers are evaluated based on ESG criteria.

Additionally, Fronius has drawn up a code of conduct for business partners that defines the sustainability requirements for all business partners within the value creation network and incorporates them into contracts. Fronius systematically collects and evaluates data from suppliers to ensure compliance and identify risks. Early identification and assessment of risks in the supply chain is critical, and Fronius works with external partners to address sustainability risks and violations.

Logistics partners are also regularly assessed, with a focus on sustainability and performance. Deviations from the required standards are addressed through joint improvement measures. Sustainability information is obtained from existing suppliers as part of regular audits and self-assessments.

The processes for complying with material requirements are continuously reviewed to ensure that products fulfil environmental requirements. A special software platform helps to analyse harmful substances and comply with regulations, such as REACH and RoHS, to replace hazardous substances.

Fronius employees are trained in sustainable procurement and corporate due diligence to ensure a sustainable supply chain. Ongoing training programmes support these efforts. This comprehensive approach minimises environmental risks and underlines Fronius' commitment to responsible and sustainable business practices.

Case studies

Responsible procurement of traceable raw materials

UK investment management business **NextEnergy Capital (NEC)** has developed a comprehensive approach to responsible sourcing to identify environmental, social, and other risks, relating to the components in which NEC invests, and to work with supply chain partners to address risks, where they may arise.

First, they make sure that policies meet and exceed relevant national and international standards. NEC publicly commits to the highest supply chain standards and ensures its sustainability policies are aligned with the requirements of international ESG performance standards. NEC expects all business partners to abide by its Code of Conduct for Suppliers and is a signatory of key anti-forced labour pledges, such as Solar Energy UK's Supply Chain Statement.

Second, they carry out comprehensive due diligence and engage with supply chain partners, in particular to increase the traceability and visibility of the solar supply chain, including upstream impacts on nature. These efforts are implemented by using a proprietary assessment tool to review the product and material origins, working practices, and environmental and social standards of potential supply chain partners. The assessment is based on responses to a detailed due diligence questionnaire, interviews, and publicly available information. NEC implements contractual safeguards to address any critical issues identified, such as the potential to source from areas considered to be at risk of human rights abuses. NEC has successfully procured solar modules with traceable polysilicon and is supporting action by the industry to move towards full raw material traceability, including quartz.

Third, NEC supports industry action to drive best practice and learning from other supply chain experts by being at the heart of industry initiatives to drive a more responsible solar industry, notably the Solar Stewardship Initiative (SSI). NEC engages with industry, government, and NGOs to inform solar sector developments and participates in external research on responsible procurement, wherever possible.

Supply chain mapping platform

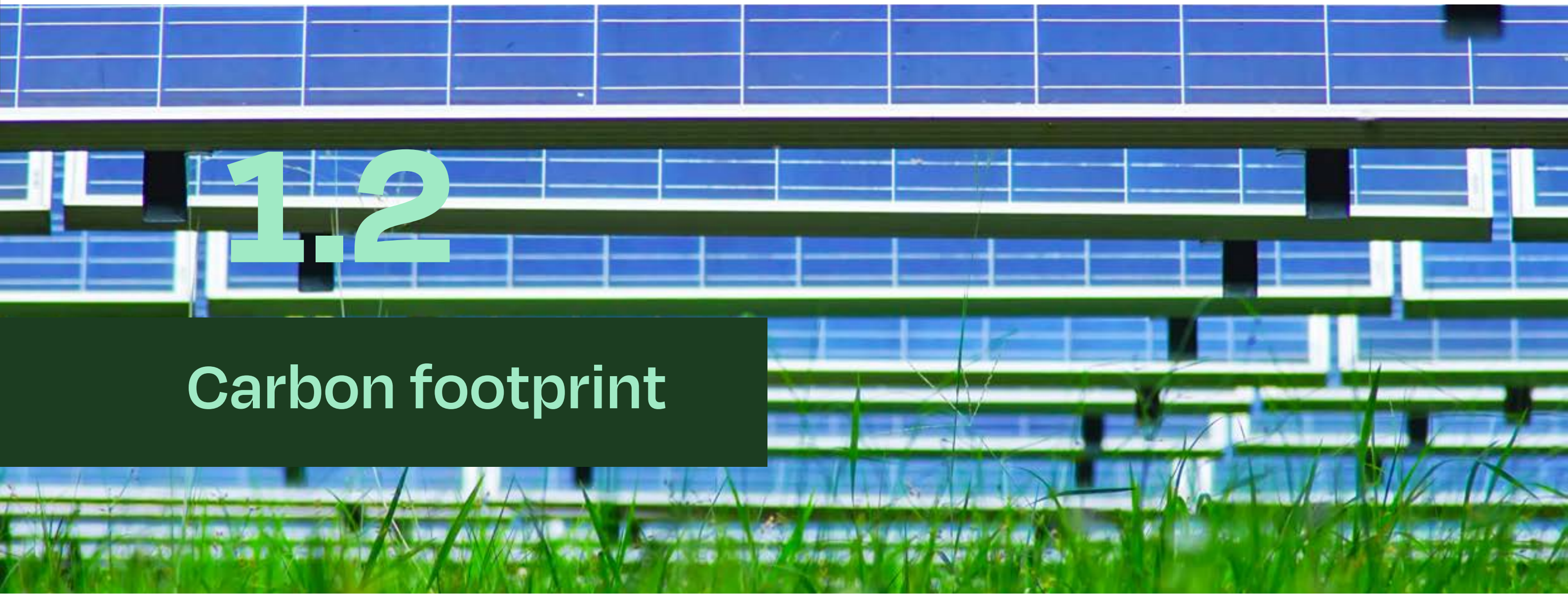
Sunrock is leveraging the Open Supply Hub[8] platform to publicly disclose its supply chains, providing transparency down to tier 4 suppliers. Through a structured process, supported by a template from Open Supply Hub, Sunrock systematically traces each level of its supply chain, collaborating closely with EPC partners and manufacturers to gather essential data. This transparency enables stakeholders, including workers, to identify and report potential human rights or environmental issues linked to Sunrock's suppliers. By making its supply chain more visible, Sunrock aims to initiate meaningful dialogues with stakeholders and encourage its suppliers to adopt transparent sourcing practices, reinforcing Sunrock's commitment to sustainable and responsible business operations.

Inclusive workplace

Relight focuses on fostering an inclusive work environment. This is exemplified by its bespoke smart working policy, tailored to the needs of an employee with epilepsy. To support their transition from an administrative role to a position in Human Resources after completing a master's degree in HR, Relight offers flexible working arrangements, covering the cost of taxis for their commute to facilitate in-person interactions. Additionally, Relight organises inclusive team-building events tailored to the employee's needs, ensuring they feel valued and integrated within the team.

Relight is committed to equal treatment and the professional growth of employees with disabilities. By providing career development support, transportation facilitation, and inclusive events, Relight aims to create a cohesive work environment that promotes the well-being and full participation of all team members.

8 https://opensupplyhub.org/



1.2 Carbon footprint

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Context and background

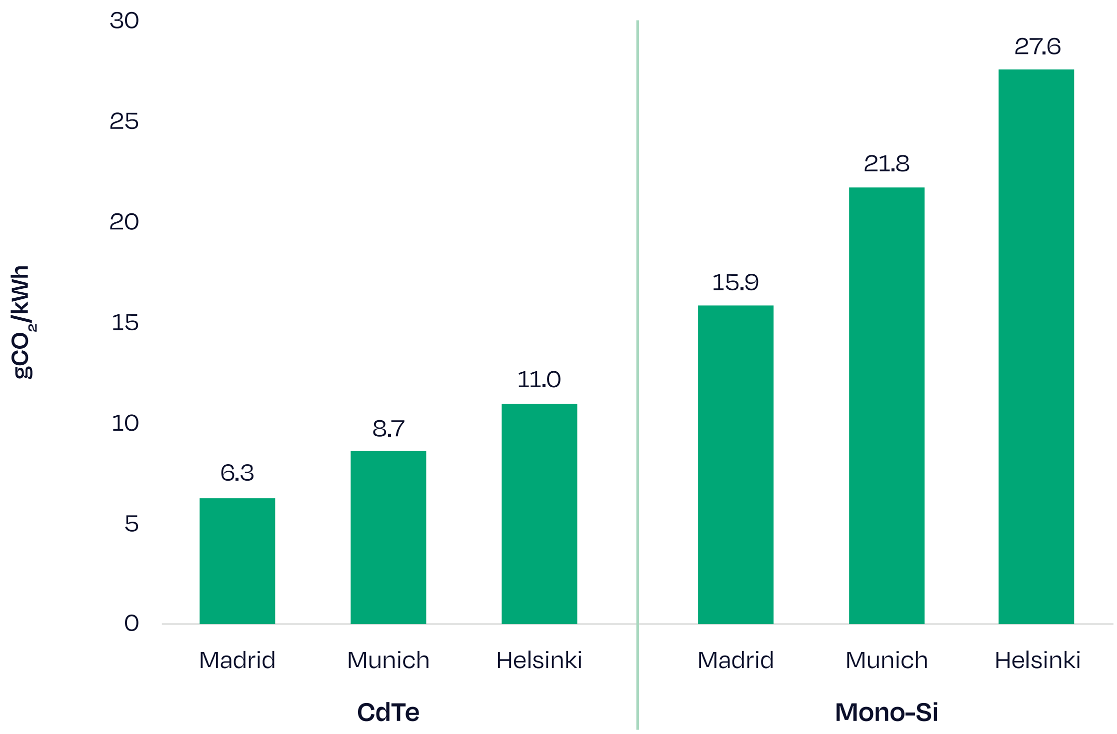
The solar industry sits at the core of the green energy transition and the achievement of climate neutrality, a major force towards the UN Sustainable Development Goals (SDGs), particularly Goal 13 – Climate Action. Solar energy has an undisputable advantage in reducing greenhouse gas (GHG) emissions for electricity generation compared to fossil fuels. Considering the GHG emissions generated throughout its lifecycle, solar produces over 95% less emissions than coal and over 90% less compared to gas.[9] Furthermore, thanks to steep improvements in PV production processes and a progressive switch to low-carbon electricity usage, the GHG emissions from solar PV manufacturing have fallen 45% in the decade 2011-2021, according to the IEA.[10]

Looking at the full lifecycle of solar PV technologies – from raw material extraction, through the manufacturing process, transportation and installation, use phase, to decommissioning and end of life – the majority of emissions are associated with the manufacturing of components and materials used in PV products. Electricity used in the production of energy-conducting materials, ingots, and wafers, constitutes 80% of the total energy used in the manufacturing process. Emissions associated with the distribution phase – the transportation of PV products to their destination – are smaller, yet notable, whereas emissions at the planning, construction, installation, and operational stages are negligible. Lastly, dismantling end-of-life systems does not generate significant GHG emissions either, but rather offers the possibility to reduce the carbon footprint by reusing and recycling components and materials.

Today, solar lifecycle GHG emissions have reached new lows. According to SolarPower Europe's analysis, electricity produced from solar PV modules installed in the EU has an embedded carbon footprint ranging between 6 and 28 gCO_2/kWh_{DC}, depending on the technology and the installation location (Fig. 5). This is a theoretical simulation of average reference products using standard assumptions; however, PV manufacturers can further lower lifetime carbon emissions of their products through different strategies (see the following sections of this chapter).

9 UNECE (2022): Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources.
10 IEA (2022): Special Report on Solar PV Global Supply Chains.

FIGURE 5 THEORETICAL SOLAR PV MODULE LIFECYCLE GHG EMISSIONS IN DIFFERENT EU LOCATIONS WITH AVERAGE ELECTRICITY MIX IN MANUFACTURING



Note: Embedded carbon footprint values are assumed as 289 $kgCO_2/kWp$ for CdTe modules and 724 $kgCO_2/kWp$ for Mono-Si PERC modules. The values are a simple average of embedded module carbon footprint with production in China, Germany, and Italy, using national electricity mixes, based on available EF 3.0 datasets complemented by data from the Ecoinvent database v3.8 (cut-off approach). These theoretical values should be considered a conservative estimate of carbon footprint performance compared to reality since the use of renewable electricity contracts and renewable self-consumption in the manufacturing processes are not considered in the calculation. The reference annual yield is assumed to be 1650, 1200, and 950 kWh/kWp/year for Spain, Germany, and Finland, respectively. The lifetime is assumed to be 30 years, with annual degradation rate of 1% for the first year and 0.5% for the following years. The calculation does not capture improvements in module efficiency, which result in less area needed to generate the same amount of electricity.

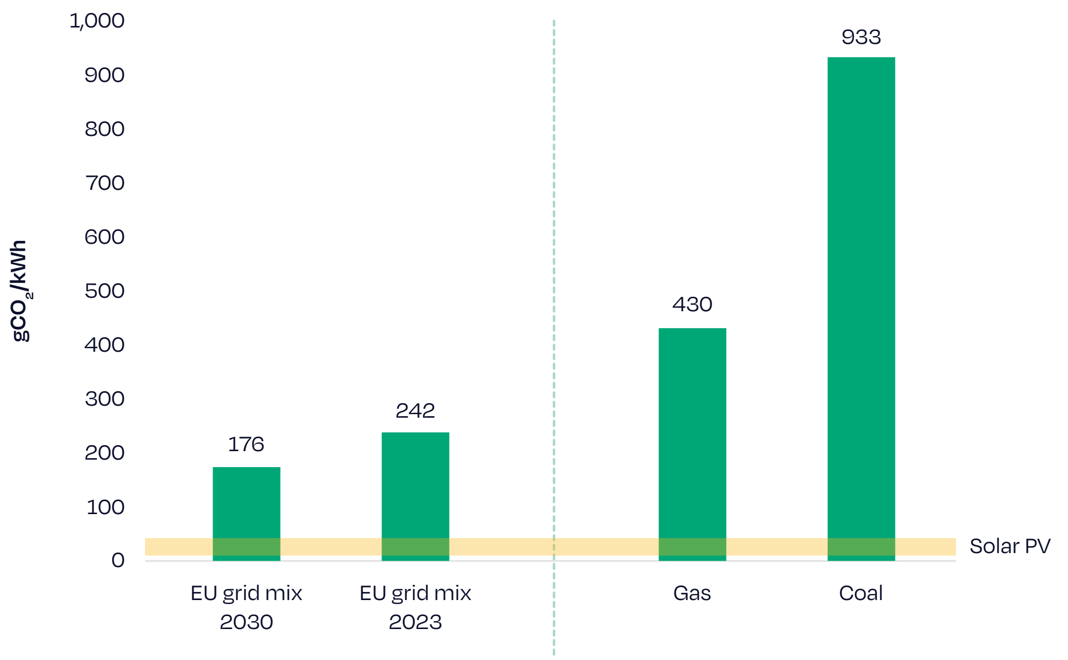
Assuming that solar PV modules are associated with 75% of the lifetime carbon emissions of a PV system and considering the conversion from DC to AC-based electricity to allow for comparison with other electricity sources, this results in lifetime solar PV system carbon emissions ranging between 10 and 43 grams of CO_2/kWh (AC). This indicative range is 82-96% lower than the average carbon intensity of EU electricity in 2023 and 75-94% lower than the target for the EU electricity grid mix for 2030 (see Fig. 6).[11, 12]

In terms of payback period – the amount of time needed for solar energy to offset its manufacturing emissions – solar PV modules require only 4 to 8 months of operational use to compensate their embedded carbon footprint, according to IEA data.[13] This is compared to a lifetime of 30 years or more, meaning that throughout their lifecycle, solar PV modules provide much more energy than was required for their production.

Thanks to massive improvements in the production process and technology efficiency gains, the rapid deployment of solar PV capacity worldwide has not led to an uncontrollable growth in solar manufacturing emissions. According to the IEA, carbon emissions associated with solar PV manufacturing only accounted for 0.15% of energy-related global CO_2 emissions in 2021, despite solar being for many years the fastest-growing renewable energy source worldwide. Simultaneously, as solar is poised to become the primary source of electricity globally

11 Ember (2024): European Electricity Review 2024.
12 European Commission (2021): EU Reference Scenario 2020.
13 IEA (2022): Special Report on Solar PV Global Supply Chains..

FIGURE 6 PV SYSTEM LIFECYCLE CARBON EMISSIONS IN COMPARISON WITH OTHER ELECTRICITY SOURCES



Source: UNECE (2020), EU Commission (2021), Ember (2024), SolarPower Europe.
Note: Solar PV system carbon footprint values are derived from module carbon footprint values described above, assuming modules constitute 75% of total system emissions and applying a 0.85 performance ratio correction. This indicative range is a theoretical simulation of average carbon footprint performance and should be considered a conservative estimate.

within the next ten years and the largest renewable electricity provider by 2030[14], it is essential to continue lowering the carbon footprint of solar PV even further.

In recent years, various industry stakeholders have focused their attention and efforts on further reducing the footprint of solar, both at corporate and cross-industry level (e.g. the Global Electronics Council's EPEAT Ecolabel, the Ultra-Low Carbon Solar criterion[15], and the Global Alliance for Sustainable Energy). In parallel, from the policymakers' perspective, some jurisdictions from across the world have already introduced or are in the process of setting up various rules to promote low-carbon solar. Examples include the EU Green Public Procurement[16], currently applied to computers, smartphones, and various other products, as well as the US Recommendations of Specifications, Standards and Ecolabels for Federal Purchasing[17], which includes PV modules, inverters, and other electronic products. In the European Union, the introduction of **Ecodesign measures for PV modules and inverters** has been under preparation for several years. The PV Ecodesign measures aim to increase the sustainability performance standards of PV products through requirements for all solar products in the EU Single Market. Among those requirements, companies selling PV modules in the EU will be mandated to disclose information on the carbon footprint of their products under a standardised methodology. The PV Ecodesign measures are set to be introduced alongside a **PV Energy Label**, which is planned to provide information on module performance and its carbon footprint.

14 IEA (2024): Renewables 2024.
15 GEC (2023): Criteria for the Assessment of Ultra-Low Carbon Solar Modules.
16 European Commission: Green Public Procurement Criteria and Requirements.
17 United States Environmental Protection Agency: Recommendations of Specifications, Standards, and Ecolabels for Federal Purchasing.

Besides the introduction of access-to-market rules on solar carbon footprint, the EU is advancing another piece of legislation promoting sustainable solar through the **Net-Zero Industry Act (NZIA)**. The legislation sets the framework to boost net-zero technologies in the European Union, including solar PV, through the introduction of resilience and sustainability criteria in national renewable energy tenders and other forms of public procurement. Solar PV is one of the technologies in scope. Although the implementing acts setting out the specific criteria to be applied by the Member States are still in preparation, it is clear that carbon footprint will be the key criterion under the sustainability dimension, applied either as pre-qualification or award criteria.

The **EU Construction Product Regulation (CPR)** is another piece of legislation that is relevant to solar carbon footprint. The CPR sets harmonised rules for marketing construction products in the EU, including building-integrated solar PV modules and, in most cases, also mounting structures. Under the CPR, manufacturers of BIPV modules must declare the environmental sustainability of their products in accordance with the relevant harmonised standards.

At the national level, some countries already have a framework in place that rewards low-carbon solar. In **France**, for over ten years, a carbon footprint calculation has been required for modules participating in public tenders. Modules with low carbon footprints can collect bonus points and thus afford higher electricity price bids. **South Korea** introduced a similar system in 2020.

Approaches and best practices

CALCULATE THE PRODUCT CARBON FOOTPRINT

The first step towards carbon footprint improvements is the analysis of the current carbon footprint performance, which helps in understanding the initial state of play and allows comparison between products.

The solar PV carbon footprint can be calculated using a series of methodologies, each with distinct methodological approaches. Key differences include the choice of functional unit – whether the carbon footprint is measured per module capacity (kilograms of CO_2 per kWp) or per solar electricity generated by the modules (grams of CO_2 per kWh). Other differences relate to the product assessed, which could be at the module, system, inverter, or component level, the system boundaries, the accounting of electricity usage, and more. An overview of carbon footprint methodologies is provided below.

Product Environmental Footprint Category Rules (PEFCR)

The Product Environmental Footprint (PEF) is the EU's lifecycle assessment tool. First introduced in 2013 and applied on a voluntary basis, the PEF methodology is embedded in existing and upcoming EU legislation such as the Batteries Regulation Article 7 Implementing Act, the Ecodesign for Sustainable Products Regulation, and the PV Ecodesign measures.[18] Building on global standards, the PEF sets out various environmental criteria from carbon content to water depletion and human toxicity, starting from raw material extraction to waste management, using the kWh functional unit for carbon content.[19]

While the PEF provides an EU-wide LCA methodology, it recognises the need for product-specific rules. Therefore, the PEF foresees the development of Product Environmental Footprint Category Rules (PEFCR) for better comparability within sectors and product groups. For the development of PEFCR, a multi-stakeholder technical secretariat is set up under the supervision of the EU Commission. The technical secretariat develops system boundaries and representative products to ensure comparability and accuracy. The content developed by the technical secretariat undergoes public consultations and panel reviews prior to the adoption and publication of the category rules. The EU solar industry developed the PEFCR for solar PV modules in 2019. Other existing PEFCR of renewables products are batteries and accumulators. The PEFCR system boundary includes the solar PV module, mounting structure, operation, and dismantling, but excludes the inverter and AC cabling. The electricity production system boundary within PEFCR covers five lifecycle stages: raw material acquisition, distribution and storage, production, use, and end-of-life.

To adjust the existing methodology to the upcoming PV Ecodesign carbon footprint measures, an

18 European Commission (2022): Ecodesign requirements for photovoltaic modules and photovoltaic inverters (Working document, version 2).
19 European Commission (2020): Product Environmental Footprint Category Rules (PEFCR) Photovoltaic modules used in photovoltaic power systems for electricity generation (Version 1.2).

adaptation of the PEFCR is being developed. These and other aspects remain under discussion at the time of this report's publication.

Environmental Product Declaration (EPD)

Solar PV manufacturing companies can report their GHG emissions by certifying their product with an EPD, where the environmental impact of their product is measured, quantified, and reported. The EPD includes not only GHG emissions, but also other environmental impact categories throughout all manufacturing stages, from raw material extraction to the final product, including transport and end-of-life aspects.

Depending on the product, specific Product Category Rules (PCRs) can be followed as methodological guidelines to develop the EPD to facilitate its validation and certification. For solar PV, PCRs are currently available at wafer[20], module[21, 22], and system levels.

At the system level, PCR 2019:14 – C:24 includes the inverters, battery energy storage systems, combiner boxes, and tracker systems. These complementary product category rules (c-PCRs) complement the PCR 2019:14 for Construction Products. For mounting structures, EPDs can be prepared directly under PCR 2019:14 for Construction Products. EPDs for corrosion protection of steel mounting structures are covered by PCR 2011:16, which is currently being revised as a c-PCR to PCR 2019:14.

At the module level, NPCR 029 Part B for solar PV modules is used in the building and construction industry and includes the production of cells, wafers, ingots, solar-grade silicon, solar substrates, solar superstrates, and other solar-grade semiconductor materials. This has also been adopted by the international EPD system as c-PCR-016 Photovoltaic modules and parts thereof.

To compare various products based on the results published in their EPD, it is always best practice to report GHG emissions per component unit (e.g. 1 m^2 of solar PV module, 1 module with a specified area, 1 kWp of installed capacity with specified module efficiency). The module unit includes cells, metallisation, encapsulants, backsheets, glass, frame, junction box, diodes, and connection cables. When reporting results in kWh of electricity generated, the document should include not only the GHG emissions of the module, but also those of the balance of system (BOS) components. Moreover, it should report the module efficiency in kWp/m^2, lifetime, performance ratio, annual degradation ratio, and irradiation level or installation location, as recommended in the IEA PVPS T12 LCA guidelines.[23]

Electronic Product Environmental Assessment Tool (EPEAT) solar PV ecolabel and carbon footprint criteria

The Global Electronics Council's EPEAT Ecolabel for solar PV modules and inverters is a Type 1 ecolabel awarded to products that meet a set of sustainability criteria, including carbon footprint thresholds. In particular, the Low Carbon and Ultra-Low Carbon Solar criteria set thresholds intended to identify the top performers in terms of carbon emissions.

The carbon footprint of the solar PV module is assessed based on a kWp functional unit. The solar PV module's total embodied carbon, including the frame, must be at or below 630 kgCO_2/kWp for the Low Carbon Solar label, and equal to or less than 400 kgCO_2/kWp for the Ultra-Low Carbon Solar label. A standardised tabulated value method (Path A) or an additional LCA data method (Path B) can be used; in the latter case, independent third-party verification aligned with GEC's requirements must adhere to international standards.

For the Low Carbon Solar criterion, Path B requires the use of national electricity mixes used in manufacturing processes to calculate emissions related to electricity usage. For the Ultra-Low Carbon Solar criterion, Path B may use either national or sub-national electricity mixes or market-based electricity purchases. Market-based electricity, however, is capped at 25% of the total, with the remaining share calculated based on the national or sub-national electricity mixes.

In addition to the carbon footprint criteria, the EPEAT PV Ecolabel assesses several other environmental impact categories, such as the use of materials, management of substances, end-of-life handling, and product packaging.

20 EDP Norway (2021): NorSun's wafers first in the world to receive Environmental Product Declaration (EPD), certifying its low CO_2 footprint.
21 EDP Italy (2020): EPDItaly 014: PCR for PV Panel – rel. 1.1.
22 PCR 2019:14, c-PCR-016 Photovoltaic modules and parts thereof (adopted from EPD Norway 2022-04-27).
23 IEA Task 12 (2020): Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity (4th edition).

Carbon Footprint in French tenders

In France, a methodology has been used for ten years as part of the PV tendering regime, with periodic reviews. Following the latest methodological review process by the French energy regulatory commission (CRE), carbon footprint calculation in one segment now relies almost entirely on default tabulated values assigned to each production stage, based on the place of origin and the tabulated CO_2 intensity of its national grid electricity mix. Low-carbon electricity generated at the manufacturing site for self-consumption can be counted, as long as it is verified by French certifying body Certisolis. According to the latest CRE tender guidelines, the carbon footprint thresholds for accessing the premium are set at a maximum of 550 kg CO_2/kWp, with a lower threshold of 420 kg CO_2/kWp.

PERFORM A LIFECYCLE ASSESSMENT, IDENTIFY HOTSPOTS, AND SET UP TARGETS

Performing a Life Cycle Assessment (LCA) is a popular method to carry out the environmental assessment of products and services, incorporating their lifecycle from raw material extraction to end-of-life. While manufacturers face challenges in predicting real-world values for lifecycle stages beyond their control, such as the use and end-of-life phases, other value chain actors can provide data and input.

Top performers have also established in-house decarbonisation plans, focusing on the most impactful processes regarding GHG emissions. Decarbonisation strategies typically include targets for reducing energy use and in particular, curbing the impact of carbon-intensive electricity. Commonly mentioned measures include on-site PV installations to power operations, green electricity purchase, energy conservation measures, energy consumption reduction, and others.

FOCUS ON PRODUCT DURABILITY, IMPROVED PERFORMANCE AND RESOURCE EFFICIENCY

Increasing the durability of solar PV products helps protect the materials needed for manufacturing new products, thereby reducing their embedded emissions. Several approaches can enhance durability, including the selection of durable materials, the application of a coating, or the design of products that can be easily repaired. More information about this best practice can be found in Chapter 1.3.

Higher product durability also implies a longer product lifetime. For solar PV, given that almost all GHG emissions are generated during the manufacturing stage, this means that the embedded carbon emissions can be diluted over a longer period, resulting in lower emissions per kWh of generated solar electricity. Likewise, improving solar PV performance and extending the lifetime energy yield will also result in lower solar electricity GHG emissions.

From a material and component standpoint, selecting materials with lower built-in carbon footprint and decreasing the number of materials with high carbon footprint are actions that contribute to lowering the product carbon footprint. More about resource efficiency from the design perspective can be found in Chapter 1.3.

REDUCE THE CARBON FOOTPRINT OF INVERTERS

As the inverter serves as the brain of a solar PV system, its carbon footprint must be taken into consideration. Although the CO_2 emissions from the inverter constitute only a small fraction of the total emissions from the solar PV system, it remains a critical component with unique challenges. Scientific environmental analyses highlight various measures to further reduce the inverter's carbon footprint.

Firstly, certain inverter components, such as some plastic elements, electronics, or aluminium, can come from energy-intensive processes. A better understanding of the supply chain, combined with more data, traceability, and guarantees, can provide opportunities to reduce the carbon footprint.

Secondly, repair processes or on-site component replacement can extend the lifespan of the inverter or help reduce the need for full replacement. In this context, the inverter should be designed to facilitate repairs or replacement of components to minimise the need for new materials and reduce the carbon footprint.

Thirdly, recycling strategies should also be considered. In some cases, inverters are already covered by existing standards, but differences may occur depending on the power class or size of the inverter. In addition, complex electronic devices, such as inverters, offer opportunities for material recovery that should be further developed or implemented.

Global Ecolabel EPEAT

GLOBAL ELECTRONICS COUNCIL®

EPEAT is the premier global ecolabel for electronics and technology products and it is used by more electronics purchasers than any other ecolabel worldwide. Ecolabels, like EPEAT, help consumers and institutional purchasers identify and select environmentally preferable products from socially responsible companies. EPEAT combines rigorous and comprehensive criteria with ongoing independent third-party verification.

The solar PV-dedicated EPEAT PV Ecolabel addresses the whole product lifecycle, including managing substances in the product, manufacturing energy and water use, product packaging, end-of-life recycling, corporate responsibility, and human rights. Furthermore, the EPEAT Climate+ designation makes it the only global ecolabel to address GHG emissions during the different stages of solar module production.

The EPEAT PV Ecolabel is currently the only approved ecolabel for solar PV modules and power purchase agreements in the US Environmental Protection Agency's recommendations for public procurement. Currently, solar PV modules from **First Solar** and **Qcells** are listed under the EPEAT registry, while more manufacturers plan to register their products in the upcoming year. In June 2024, the Ultra-Low Carbon Solar criteria were launched, setting the industry's first embodied carbon threshold limits. First Solar's Series 6 Plus and Series 7 US products are the world's first solar PV modules to achieve the EPEAT Climate+ designation, establishing a new benchmark for the solar technology and manufacturing industry.

EPD application in wafers, modules, inverters, BIPV, and mounting structures

In 2021, the first EPD specific to wafers was published by EPD Norge. The results of this EPD were reported based on a functional unit of 1 kg of monocrystalline silicon wafer, derived from an ingot produced using the Czochralsky process and sliced with diamond wire cutting.

A best practice for reporting GHG emissions for solar PV module is **Longi's** EPD, published in 2023, which uses a functional unit of 1 kWp, but reporting the module efficiency as a conversion factor to 1 m^2.

Regarding the solar PV balance of system components, only one EPD specific to the inverter has been available since 2023, following the latest complementary product category rules (c-PCRs) for solar PV components.

Concerning BIPV systems, the current best practice for reporting GHG emissions and other environmental impacts is to follow EPDs for both construction products and solar PV systems, as there are no ad-hoc PCRs available. A good example of this type of reporting is available for roof integrated solar PV, following the PCR for construction products EN 15804:2012+A2:2019 and two complementary standards (NPCR 029:2022 v1.2 for PV modules, and NPCR 022:2022 v2.0 for roof waterproofing).

The recommended best practice for mounting structures is to follow PCR 2019:14. For corrosion protection of steel mounting structures in particular, the best practice is to follow PCR 2011:16, which is under revision as a complementary PCR to PCR 2019:14. PCR 2011:16 ensures that the reference service life of various steel corrosion protection systems with differing durability is taken into consideration by defining the functional unit on a 'per year of protection' basis. This prevents lower environmental impacts from being claimed solely by reducing long-term durability.

Case studies

Inverter LCA and decarbonisation strategy

Austrian inverter manufacturer **Fronius** conducted a comprehensive LCA of its GEN24 Plus and Tauro product families, highlighting the significant impact of the supply chain on embodied emissions. In order to decrease its carbon footprint, more than 90% of recycled aluminium is being used in the main metallic component of the inverter. The LCA methods used comply with the ISO 14040 and 14044 standards.

The entire product lifecycle was analysed using the cradle-to-grave approach. This analysis began with raw materials, assessing the sustainability of production, transport routes, product longevity, reparability, and recycling. Fronius utilised primary data from its production and logistics, as well as data from upstream and downstream partners. To support its sustainability efforts, the company also integrated secondary data from various sources, including validated databases and recent studies.

The environmental impact categories, such as global warming potential (GWP) and cumulative energy demand (CED), were calculated based on the PEF/ILCD-2019/EF 3.0 guidelines. The complexity of the assessment was significant due to the intricate technology and engineering required for quality inverters. For instance, the GEN24 consists of 490 components, leading to the analysis of 2,533 individual parts for the Primo GEN24 6.0 Plus. The LCA for the GEN24 Plus encompassed four inverter types, seven countries, and five waste scenarios, resulting in 140 variants for each outcome. The 120 calculated result values amount to approximately 16,800 results.

For Tauro, Fronius disassembled various components, such as DC disconnects, fuses, and fans, collecting detailed data on 960 parts. They also treated semiconductor and gold components with concentrated sulfuric acid to precisely determine weight, due to insufficient existing data, and improved the Ecoinvent database based on their findings. Tauro's LCA covered two inverter types, seven countries, and five waste scenarios, generating 8,500 theoretical results.

Detailed LCA reports were conducted for both inverters and are available online. Key findings from the LCA include:

PV on the rooftop of the Fronius office in Wels, Austria. © Fronius

Case studies

- The environmental benefits of the entire solar PV system exceed its impacts by 10 to 52 times when using a Tauro inverter and by 9 to 45 times with a GEN24 inverter, depending on the calculated scenario.
- The payback time for the climate impacts ranges from 0.6 to 3 years for the Tauro and 0.7 to 3.3 years for the GEN24 Plus.
- A 130 kW solar PV system with a Tauro inverter can save up to over 6.7 ktCO_2, equivalent to approximately 3,000 flights from Vienna to New York, while a 10 kW solar PV system with the GEN24 Plus can save up to 512 tCO_2.

Decarbonisation is a key focus for Fronius, in all three business units (Perfect Charging, Perfect Welding and Solar Energy), particularly in promoting renewable energy and sustainable technologies. Sustainable production methods, EU manufacturing, energy savings, and the use of renewable energies are integral to Fronius's approach, along with continuous investment in R&D to advance decarbonisation technologies.

Fronius plans to fully transition to renewable energy at its Austrian sites, supported by an energy management system compliant with ISO 50001, which was established in 2023, and is set for certification in 2024. In 2023, 95% of Fronius's energy came from renewable sources, meeting the TÜV Süd's stringent standards. The company has replaced crude oil and is committed to eliminating natural gas use by 2025. Fronius also focuses on self-generating electrical energy through solar PV systems, with a capacity of 4.15 MW at Austrian sites in 2023, generating 2.12 GWh per year. The expansion of solar PV systems is also a priority worldwide. Resource-saving technologies are integrated across the company, and energy consumption is optimised through various initiatives, including the 'Young Resources' apprentice project, which was launched in 2022. This project identifies energy savings in production, such as detecting compressed air leaks and comparing the efficiency of LED lamps to fluorescent tubes. An internal energy monitoring tool tracks energy flows and consumption, while regular internal audits assess and evaluate energy use.

Decarbonisation strategy for solar PV manufacturing

With the mission of achieving net-zero by 2050 and transitioning to 100% renewable energy use in its own manufacturing and operations by 2030, **Trina Solar** aims to lead the industry's decarbonisation agenda and revolutionise the way solar modules are produced.

Trina's decarbonisation strategy builds on three main pillars: net-zero operations, net-zero value chain, and net-zero products. The company partners with international third-party organisations, including BSI, TÜV Rheinland, and other entities, to guide and verify the decarbonisation process and its status. By incorporating sustainability into all procurement and research processes, Trina is committed to working with key global partners to promote a net-zero value chain and establish a green ecosystem.

In line with its three-pillar decarbonisation strategy, in April 2023, Trina became the first company in the solar sector to be third-party certified against the T/CECA-G0171-2022 standard and receive the Zero Carbon Factory Award for its industry-leading zero-carbon production site in Yiwu, China. In 2024, the company further improved its award performance and obtained the prestigious four-star ranking. The "Zero-Carbon Trina Solar Factory Design" sets the company's new blueprint for factory design and this green factory concept has already enabled the reduction of more carbon emissions than those emitted during its operation. Between 2015 and 2021, total carbon emissions emitted during production, operation, and R&D at all Trina manufacturing centres amounted to 4.5 million tonnes. During the same period, the company's initiatives, including solar PV stations, green electricity purchase, energy conservation, and consumption reduction, reduced the total carbon emissions by 4.8 million tonnes, resulting in carbon-negative operations as of today.

The company plans to save 1 TWh of electricity in global operations by 2030 through energy saving and decarbonisation measures. These strategies include energy efficiency improvements at both product and operational levels, the use of renewable energy on-site and

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through green energy purchases, the implementation of waste management to increase resource efficiency and circularity. This approach will result in minimising material usage while enabling the circular utilisation of waste across operations, such as repurposing waste heat for cooling. Furthermore, a newly developed energy-carbon digitisation management system will be employed to help monitor, steer, and control energy and emissions data.

In terms of energy savings, in 2023, Trina achieved a 47.5% decrease in energy consumption for cell manufacturing and a 38.3% decrease in module manufacturing, compared to the 2020 baseline. The reduction of GHG emissions intensity amounted to 42.7% for cells and 61.5% for modules during the same period.

Regarding renewable energy use, the installations of self-consumption solar PV systems have resulted in a total of 136 GWh of on-site renewable electricity generation in 2023, representing a 2.4-fold increase compared to 2022. To complement on-site renewable self-consumption, Trina also invests in the acquisition of green electricity, either via certificates or directly through the regional electricity grid. Trina's factory in Viana, Spain purchases 100% renewables-based electricity as of today, while at four of Trina's factories in Quinghai, China, the renewable share in the electricity mix reached 84.5%. In addition, the Qinghai Crystal factory purchased 205 GWh of green electricity certificates to further increase the renewable energy share.

Today, Trina's decarbonisation strategy has made it possible to offer industry-leading low-carbon, high-efficiency solar PV modules. Trina's solar PV modules are certified against ISO 14067:2018, ISO 14040:2006 and ISO 14044:2006, as well as under EPD Italy, EPD UL (Germany), the French CRE, RPS Korea KNREC, and EPD Norway.

Commitment to science-based net-zero targets

First Solar has committed to science-based targets to reduce absolute Scope 1 and Scope 2 GHG emissions by 34% by 2028, aiming for net-zero GHG emissions by 2050 based on a 2020 baseline. In July 2023, First Solar became the first among the world's largest solar manufacturers to have its net-zero target officially validated by Science-Based Target Initiative (SBTI). Additionally, in 2020, First Solar joined RE100, pledging to power all global operations with 100% renewable energy by 2028.

Carbon footprint verification for inverters

The PV industry plays a pivotal role in the global transition to renewable energy, propelled by climate goals like the EU's target of achieving climate neutrality by 2050. As demand for solar increases, the need for sustainable, low-carbon solutions becomes critical. Despite the clean energy generated by solar, the carbon footprint of PV products remains an important factor throughout their lifecycle. Establishing comprehensive carbon footprint management systems is therefore essential for ensuring that the PV sector contributes meaningfully to global decarbonisation efforts.

In 2022, **Huawei** became the first company in the world to receive the Global First Carbon Footprint Verification (CFV) for its PV inverter products from the British Standards Institution (BSI). This prestigious recognition underscores the importance of building the ability to evaluate and reduce the carbon footprint products, aligning with green, low-carbon, and sustainable development principles. Huawei has integrated low-carbon strategies throughout its value chain, from product innovation and supply chain management to its business operations. The company has also led the way by guiding 92 suppliers in reducing their carbon footprints and establishing a green, near-zero-carbon campus that utilises advanced energy-saving technologies. But the commitment to sustainability must extend beyond product design. In addition to the CFV, the company became the world's first digital energy solution provider to have its net-zero targets validated by SBTI. These science-based targets include a 50.4% reduction in scope 1 and 2 emissions by 2032 and a 90% reduction across all emissions scopes by 2040. These initiatives can help organisations to not only drive decarbonisation within operations but also shape the future of sustainable manufacturing in the PV industry.

Case studies

Zero Carbon Manufacturing

JinKo Solar was the first solar manufacturer to commit to the RE100 and EP100 initiatives in September 2019, unveiling its roadmap to achieve 100% renewable energy usage across its global operations by 2025. They also plan to implement an energy management system across all operations and improve energy productivity.

The company had its near and long-term emissions reduction targets approved by the SBTI in December 2023, making it the first Chinese solar PV company to have all these targets officially validated.[24] In order to achieve these targets, the company is focusing on carbon management systems and the construction of "Zero-Carbon Factories", while increasing the ratio of electrification and renewable electricity usage. By having four of its factories awarded the Zero-Carbon Factory certification by TÜV Rheinland, JinKo has become the first solar PV module manufacturer to vertically integrate the entire in-house manufacturing industry chain, from silicon to module, with Zero-Carbon factories.

Regarding suppliers engagement, JinKo leverages its position as an industrial leader in the supply chain by assisting its suppliers in initiating and supporting them throughout the decarbonisation process. Under JinKo's green supply chain program, strategic partners have been empowered in both training and auditing on the scope of GHG emission reduction plans and targets setting. Over the long-term, JinKo will also cooperate with the value chain to reduce GHG emissions through additional efforts in the areas of renewable electricity procurement, low-carbon raw materials research, lightweight packaging exploration, low-carbon transportation implementation, and product recycling and reuse.

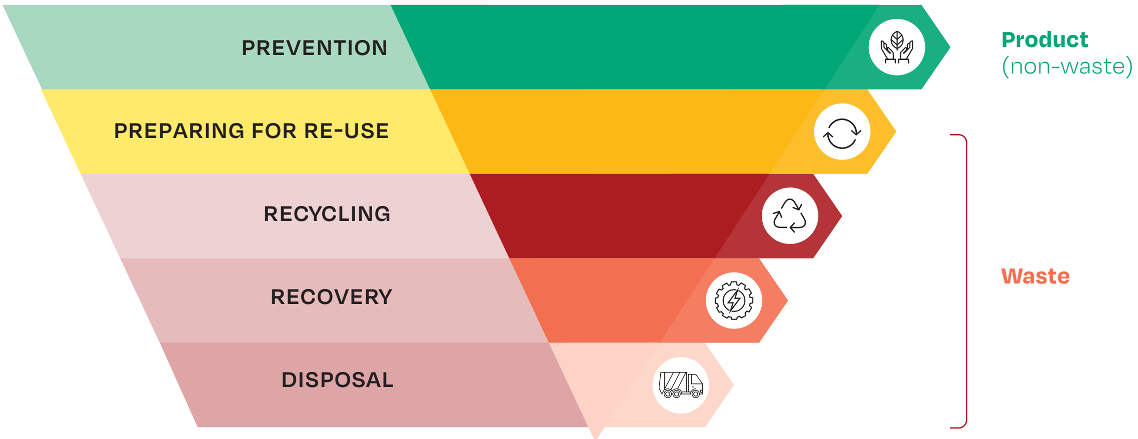
Shangrao module factory, powered by solar energy. © JinkoSolar

24 According to the target dashboard from the Science-Based Target Initiative.

Context and background

In a traditional linear economy, products are manufactured from raw materials, used throughout their lifespan, and disposed of as waste at the end of their life. A contrasting approach, the circular economy, seeks to maximise the value of materials and energy at each stage of the product value chain to prevent waste. In an ideal circular economy system, there is no waste. The main challenge of transitioning to a circular economy is that products are often made of complex materials, posing challenges to the recovery process. The waste hierarchy, also known as the "5R" or "10R" framework is a conceptual framework ranking waste management actions from first to last, with the aim to guide waste management decisions. It redefines the approach to waste by putting "refuse" or "prevent" at the top of the list, underlining the fact that thinking about circular economy at the end of a product's life may be too late. This approach is already reflected in The Waste Framework Directive's waste hierarchy, putting prevention as the highest priority (see Figure 7).

FIGURE 7 OVERVIEW OF THE WASTE HIERARCHY AS DEFINED IN THE WASTE FRAMEWORK DIRECTIVE



Source: EU Commission (2008).

Applying the waste hierarchy to solar PV shows a similar approach in a more granular manner for the sector (see Figure 7).[25] Solar PV circular economy activities start with smarter manufacturing and operation (1). This includes rejecting harmful processes and proposing sustainable alternatives (R1), followed by restructuring and optimising the design and life cycle planning of solar PV modules (R2). Furthermore, efforts should focus on optimising the consumption of natural resources (R3). Collectively, these interventions are defined as circular solar PV design.

Extending the lifespan of solar PV modules (2) can be achieved through several strategic approaches, each contributing to more sustainable solar energy systems. The first step is reuse (R4), which involves using discarded yet functional solar PV modules, giving them a second life without any additional modifications. If modules are not functional, it is important to repair (R5) defective or faulty modules and restore them to their best possible functionality prior to sending them for reuse. Following repair, refurbishment (R6) comes into play, focusing on upgrading older modules to meet the highest technical standards, improving their performance. When modules or components can no longer be repaired or refurbished, remanufacturing (R7) is the subsequent option, which includes dismantling the module and reusing components in the production of new solar PV modules and technologies. The module components can also be repurposed (R8) to manufacture entirely new products that serve a different purpose. Several of these aspects are further examined in Chapter 3.2.

Once all circular design strategies and lifespan extension options are exhausted, finding applications for the remaining solar PV materials and by-products (3) is essential for minimising waste. Recycling and recovery (R9, R10) of glass and raw materials such as aluminium and silver are relatively common, but more efforts are needed to prevent downcycling.

FIGURE 8 CIRCULAR ECONOMY FOR SOLAR PV – 10R FRAMEWORK

Smarter solar PV manufacturing and operation	Refuse (R_1)	Reject harmful processes or propose sustainable alternatives
	Rethink (R_2)	Restructure and optimise the designing and lifecycle planning of solar pV modules
	Reduce (R_3)	Optimise and decrease the consumption of natural resources in solar PV manufacturing
Solar PV lifespan extension	Reuse (R_4)	Utilise discarded solar PV modules that are still in a working condition
	Repair (R_5)	Maintain defective and faulty solar PV modules to their best possible functionality
	Refurbish (R_6)	Restoring older solar PV modules to catch up with the highest technical specifications
	Remanufacture (R_7)	Utilise discarded parts in manufacturing new solar PV modules and technolgies
	Repurpose (R_8)	Utilise discarded parts in manufacturing new products for a different purpose
Useful applications of photovoltaics' materials and byproducts	Recycle (R_9)	Processing materials delivered from dismantling techniques to obtain solar PV modules with the same or a lower quality
	Recover (R_{10})	Optimise processes to recover as much materials and energy as possible

Source: Rabaia et al. (2024).

25 Rabaia et al. (2024): Enabling the circular economy of solar PV through the 10Rs of sustainability: Critical review, conceptualization, barriers, and role in achieving SDGs.

More information about best practices and the newest research can be found in Chapter 3.3. Energy recovery may be pursued when none of the nine steps from the waste hierarchy are feasible, and it is the last measure to prevent materials from being sent to the landfill. The 10R framework ensures that the most efficient and resource-conscious options are prioritised, contributing to higher sustainability of solar PV technologies.

Legislation may also motivate the transition to circular product design. Ecodesign rules for PV, which are currently being prepared by the European Commission, are not only expected to introduce carbon footprint requirements on solar PV modules (see Chapter 1.2), but will likely also set several new rules for circular design of solar PV modules and inverters. These planned measures may include information requirements and minimum performance requirements aiming to improve efficiency, reliability, repairability, and recyclability of solar PV products. The requirements will mandate producers to disclose information on material content, accessibility and replaceability of components. Producers will also be required to ensure the availability and quick delivery of spare parts for inverters, providing detailed disassembly and repair instructions, such as guidelines on tools and required skills. The design of solar PV modules and inverters should facilitate easier repairs. To ensure durability, solar PV modules and inverters must undergo stringent quality control, such as accelerated testing to verify their performance and reliability under outdoor conditions.

While the concept of solar PV circular design is not yet widely recognised, an increasing number of solar manufacturers are incorporating elements of circular design into their processes to enhance the sustainability of their products. By minimising the use of harmful materials, extending product longevity, and promoting responsible use of natural resources, solar PV systems are set to contribute to a regenerative circular economy.

Approaches and best practices

FOCUS ON RESOURCE EFFICIENCY

Resource efficiency can be approached in two ways. The first approach focuses on reducing the material consumption of a product by minimising the use of materials with a high carbon footprint, toxicity, and critical supply risk. Besides reducing emissions, this approach also reduces materials costs. The consumption of certain materials in solar PV modules has been steadily decreasing. For example, the use of silicon in solar PV cells has been reduced by 86% from 16 g/W in 2004 to 2.2 g/W in 2023, and is projected to further decrease by 36% to 1.4 g/W by 2034 thanks to increased efficiencies, thinner wafers, and larger ingots.[26] Similarly, as silver is one of the most expensive materials used in solar PV modules, its price also drives a decline in its consumption. Compared to 2023 levels, silver consumption by 2034 is projected to decrease 40% from 15 to 9 mg/W for TOPCon and 38% from 9.6 to 6 mg/W for PERC.[27]

The second resource efficiency approach is centred on selecting materials that are easy to recycle, enabling multiple reuses. This often entails eliminating the use of hazardous materials in the product.

INCREASE DURABILITY OF PRODUCTS

Increasing the durability of solar PV products helps conserve the materials needed for manufacturing new products, thereby reducing their embedded emissions. This is also an effective method for waste prevention as products with a longer lifecycle do not end up as waste until the end of their operational lifetime. To improve the durability of solar PV products, manufacturers may implement longer warranties, which assure their longevity and reliability. Technological solutions, such as adding protective layers to solar PV modules and their components, can further enhance product durability by shielding them from environmental factors, such as UV radiation, moisture, and physical damage.

26 Fraunhofer ISE (2024): Photovoltaics report.
27 VDMA (2024): International Technology Roadmap for Photovoltaic (ITRPV): 2023 results.

DESIGN FOR REPAIRABILITY

Repairability of solar PV systems and especially certain PV components needs to be factored into product design, as the ease of dismantling is a determining factor in making repairs cost-effective. Moreover, spare components need to be available for a set number of years to enable the repair of the specific module or inverter type. Essentially, there should be a trade-off between repairability and durability, especially for solar PV modules, since ensuring accessibility and repairability may come at the expense of a longer warranted lifetime.

MANUFACTURE USING RECYCLED MATERIALS

Recycling can provide an important stream of raw materials, especially in Europe, where mining activities of various materials necessary for solar PV modules and inverters are limited. The use of recycled materials in manufacturing may also provide opportunities for cost reduction and more resilient supply chains. The materials may come as a by-product of the manufacturing process itself (e.g. silicon ingot scrap), or from recycled products (e.g. aluminium). A potential limitation of using recycled materials is material purity. Case studies in Chapter 3.3 illustrate innovative recycling technologies that can recover high-purity glass, among other materials.

Case studies

Design for optimal durability of mounting structures

Mounting structures are a vital element of solar PV installations. Their proper specification during the design stage ensures that they offer maintenance-free support for the initial project design lifespan and throughout subsequent repowering phases (see Chapter 3.1). However, lack of attention to corrosion protection specification for steel mounting structures may lead to premature failures, unplanned maintenance, limited scope for reuse, as well as other consequences that consume resources and reduce circularity.

An example highlighting the importance of careful consideration during the design stage, is the selection of the optimal zinc coating thickness applied to the steel depending on the location of the solar PV installation. Although they may appear similar and are often referred to as 'galvanised', there are diverse types of zinc coatings that can be applied to steel, each with varying coating thicknesses and, in some instances, incomplete coverage of the steel component, particularly if the component has been made from pre-coated steel sheets. The lifespan of galvanised mounting structures is directly linked to the thickness of the zinc coating, meaning that halving the coating thickness to reduce costs will also halve the expected lifespan. Notably, full coverage of the component is only achieved through immersion in molten zinc after the mounting structure components have been manufactured.

Proper specification for optimal durability and reuse can be achieved through ISO standards for the life expectancy of galvanised coatings: ISO 14713-2 and ISO 9224. The specification to ISO 1461 ensures that components are galvanised after manufacturing, enabling full coverage and preventing cut edge corrosion.

PFAS-free and antimony-free modules

Solarge has developed and produces PFAS-free solar modules in its 100 MW facility in the Netherlands. The solar PV modules are circular by design, due to a patented technology developed by the polymer multinational organisation SABIC. The solar PV module can contain any cell type, including mono PERC, TOPCon, and heterojunction cells. The cells are assembled on a so-called organo-sandwich backplate and covered with a custom-developed polyolefin front sheet, providing a guaranteed 25-year lifespan. The modules do not use solar glass and therefore contain no antimony.

At the end-of-life stage, the solar PV modules can be fully disassembled and reused. The materials extracted are of high purity and are used for the production of new solar PV modules.

Additionally, **Trina Solar** also manufactures PFAS-free solar PV modules, which have received a third-party certification, further highlighting the industry's shift towards sustainable, PFAS-free solutions.

Solar PV modules made with recycled materials

In 2024, **Trina Solar** produced the world's first fully recycled crystalline silicon module, using recycled materials, such as silicon, silver, aluminium frames, and glass recovered from end-of-life modules. The manufacturing process utilised multiple innovative techniques, including the use of self-developed interlayer separation reagents, chemical etching technology, and wet chemical silver extraction technology. The recycled solar PV module uses n-type TOPCon technology, and the module efficiency is 20.7%.

Producing solar PV modules with reused materials

There are multiple ongoing EU-funded projects that focus on the recovery of high-purity materials and their application in new solar PV modules.

The application of silicon in new solar PV modules and EV batteries is the topic of the project **FORESi** (Fostering a Recycled European Silicon Supply). This Horizon Europe-funded project, which includes consortium members **CEA-INES** and **Carbon**, focuses on the recovery of silicon from solar PV products and its application in new PV modules and EV batteries. FORESi will demonstrate a circular recycling process from end-of-life modules to new solar PV and EV batteries applications, including technical, economic, and environmental viability of the entire recycling process. The project also aims to provide efficient design recommendations on a recycling factory for end-of-life modules.

To ensure the sustainability of the recycled silicon for high-efficiency solar PV modules, FORESi will assess its compliance with the manufacturing standards, by comparing the properties of ingots, wafers, cells, and modules made from recycled silicon with the reference material. Based on the results, the production and evaluation of new modules containing a portion of recycled silicon may proceed.

Not only can silicon be used in new products, but solar PV modules also need to be designed for easy disassembly and recycling. The **APOLLO** project focuses on both aspects. This Horizon Europe-funded project aims to manufacture new solar PV modules using recycled materials and to utilise recycled silicon in ingot growth for new solar PV modules. A pilot line, which will extract all material fractions, will be set up. This line will process 40 tonnes of solar PV waste, producing materials for 1 tonne of remanufactured silicon and 30 example solar PV modules. New modules will incorporate new designs, materials, and manufacturing methods, and will be designed for easy disassembly and recycling. Led by **Fraunhofer CSP**, the project started recently, and it will last until 2026.

The recovery of high-value materials, such as silver, gallium, and indium, as well as their reuse in new products is still a largely untapped area. **PHOTORAMA**, a Horizon 2020-funded project, has designed and set up a pilot line including more than six technologies to separate the components of end-of-life PV modules. The high-value recycling scheme has been developed to treat PV crystalline-Si and CI(G)S thin film waste. Besides bulk materials such as aluminium frame and glass, solar PV cells are isolated from organics to recover, respectively: aluminium (back side contact), silver, silicon, indium (HJT) from c-Si and indium, gallium from CI(G)S. The secondary raw materials extracted from solar cells are mainly recovered from leaching processes followed by electrowinning that allows for recovery under metallic form, except for aluminium chloride that is recycled directly for water treatment in the paper industry. The high purity of other metals is suitable to high-value applications. Target products are silver-based conductive pastes, silicon-based alloys for surface coating in the automotive industry, and indium and gallium to be re-used in material components dedicated to sputtering targets for thin film deposition for PV or microelectronic applications.

PHOTORAMA's focus on high-value recycling is further explored in Chapter 3.3. SolarPower Europe is a member of the Advisory Board for this project, which is coordinated by CEA-INES and features participants, such as **Soren**, **ENEA**, and **Enel Green Power** in the project consortium.

2

Use phase

Solar PV on the rooftop of the Fronius office in Wels, Austria. © Statkraft

2.1 Community Engagement

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Context and background

The multiplication of renewables and solar installations needs to go hand in hand with the participation of citizens, indigenous communities, local municipalities, and renewable energy developers, to guarantee citizens' empowerment and, ultimately, public support for the energy transition. The effective and credible involvement of local communities from the early stages of projects until the operational phase is, therefore, crucial.

Moreover, it is particularly important to respect indigenous peoples' rights when developing solar PV projects, based on Free, Prior, and Informed Consent (FPIC). FPIC must be respected to the greatest degree possible on lands that are traditionally owned by or under customary use of Indigenous Peoples, and which are likely to have impacts due to facility operations.

There are several new policy developments which foster community engagement in solar PV projects. Corporate Sustainability Due Diligence Directive (CSDDD) requires companies to carry out 'meaningful engagement' with affected stakeholders to enable genuine interaction and dialogue. The Corporate Sustainability Reporting Directive (CSRD) acknowledges, through the ESRS (European Sustainability Reporting Standards) S3 ("Affected Community") the potential impacts of businesses on communities and underlines the need for clear communication of these effects. There are other important tools in EU regulation that can support developers to meet their obligations to conduct meaningful engagement.

The 2018 Renewable Energy Directive (RED II) introduces the concept of energy communities, granting them specific rights to produce, consume, and sell renewable energy. These Renewable Energy Communities (RECs) are defined as legal entities that operate under national laws, with open and voluntary participation, autonomy, and control by shareholders or members in the proximity of the renewable energy projects they develop. RECs primarily aim to provide environmental, economic, or social benefits to their members or local areas, rather than focusing on financial profit. REC members cannot make the energy market their primary economic activity and typically co-own the renewable energy assets. The 2023 Renewable Energy Directive (RED III) introduces provisions for permitting and public participation, requiring Member States to promote local community involvement in renewable projects, especially in the designation of renewable acceleration areas.

The 2024 Electricity Market Design Directive (EMD) introduces the concept of energy sharing, which allows small-scale projects to trade electricity with nearby consumers, while being exempted from grid fees. However, the energy sharing regime is only applicable to projects up to 6 MW, thus, most ground-mounted projects need to find other solutions for meaningful engagement with local communities.

Community engagement in developing solar PV projects fosters local support and ensures that the project aligns with local needs and values, leading to greater acceptance and long-term success. Additionally, involving the community can create local economic opportunities and strengthen trust between developers and residents. Best practices of community engagement and successful case studies are described below.

Approaches and Best Practices

Community engagement in local energy projects can be fostered through different means. There are two types of non-mutually exclusive community participation in solar projects: engagement at early stage and during the lifetime of the project, and direct or indirect financial engagement.

EARLY ENGAGEMENT AND LIFETIME ENGAGEMENT

Site selection and planning. Involving citizens and local communities from the early stages of project planning is beneficial, as it builds transparency and trust. The first step of spatial planning that could foster a dialogue between public authorities, local communities, and the private sector is the designation of favourable areas (under Article 15b of the Renewable Energy Directive). Project developers may bring their expertise in site selection, and then consult with local communities via website or public meetings. The designation of renewable acceleration areas (as a subset of favourable areas) should also be later done in concertation with the public, especially during the phase of Strategic Environmental Assessment.

Project design and impact assessment. Local populations may also be involved in the design stage of the project by providing feedback on the design of the installation, or by actively participating in the environmental impact assessment, and help set up avoidance, reduction, and compensation measures. They may also participate in the project through public consultation, or simply stay informed and discuss project features on a web platform.

Construction and operational phase. It is also beneficial for project developers to pursue early engagement during the whole lifetime of the project, such as monitoring of environmental benefits, sharing knowledge through setting up on-site visits for university students and/or the wider public, and by communicating the energy production of the solar plant and analysing the climate, economic or environmental impacts and benefits of the project.

DIRECT OR INDIRECT FINANCIAL PARTICIPATION IN SOLAR PROJECTS

Distant self-consumption. One of the simplest ways to involve citizens in a solar project is by offering them locally produced energy from the plant at a lower rate than standard grid tariffs. Several developers and local authorities have, therefore, considered providing citizens located in the vicinity of solar plants with economic benefits, such as reductions on electricity bills or participating in distant self-consumption schemes. A best practice for engaging local energy consumers is involving them in local projects via innovative schemes, including energy sharing (up to 6 MW) or distant self-consumption (for large-scale utility projects), enabling them to benefit from lower electricity tariffs. According to the EU Market Design Directive, energy sharing schemes are solely feasible for projects below 6 MW, but several countries, including Lithuania, Belgium, and Slovenia, place no capacity cap on shared electricity to facilitate the participation of distant ground-mounted PV installations. Regular grid tariffs usually apply in such cases. Supportive energy sharing frameworks are also present in Italy and Austria, showcasing the close connection between energy sharing and the REC organisational framework.

Crowdfunding. Local citizens and communities may also participate financially in large-scale solar projects, either directly or indirectly. One of the developing trends for renewable energy projects is the concept of crowdfunding, which often includes the participation of local authorities in the funding scheme. The possibility for citizens to purchase shares in the project without setting up a REC is also an effective way to involve local stakeholders.

Direct contribution to local energy ambitions and policies. Solar project developers may join forces with local municipalities and share the benefits of the solar PV installation with local citizens. The contributions from the project are typically used to support local climate and energy policies at the municipal level, including building renovation, decentralised renewable generation, investments in community-owned assets, and more. In certain Member States, the contribution to local energy policies is mandatory for large-scale projects. In Denmark, for example, it is required that RES owners contribute by 125,000 DKK/MW (16,800 EUR/MW) for PV to a city Council "Green Pool" that provides RE-bonuses to local citizens.

Renewable energy communities. A best practice is creating enabling frameworks for the development of more citizen-led energy communities in line with the EU legal definition of energy communities, which can be done by local and regional authorities. The private sector, can also play a role in developing hybrid projects with a community dimension, such as acting as service providers, managing and setting up an energy sharing scheme or other forms of collective energy initiatives. They may also participate in the financial setup of community-based projects.

Cedillo Solar Village

PV Cedillo power plant is a large plant located in Cedillo, Extremadura and developed in 2023 by Iberdrola, spanning around 800 hectares. The solar PV park is 295 MW_{AC} and 375 MW_{DC}. This project was designed to enable natural vegetation to grow between solar modules, acting as an ecological corridor to support environmental integration and make the project more permeable.

The main challenge was creating the first Spanish solar community. Cedillo Solar Community consists of the installation of a large project for self-consumption, bringing additional benefits to the population of Cedillo as it reduces the electricity costs of 316 households in the 'Pueblo Solar Cedillo' Association.

To enable this, the required rated power for the plant was calculated by adding up the total energy consumption in Cedillo during 2021. Once the input data was determined (355 kW_{AC} and 416 kW_{DC}), several solar PV modules were installed on the municipal land owned by the city council, including the roofs of municipal buildings and urban orchards. Registered citizens of Cedillo and those who will be registered within the next five years can benefit from this installation. Similarly, the same money-saving benefits are extended to businesses operating within the municipality. Members of the solar community can save up to 50% on their energy bills.

This project aims to both encourage people to remain in Cedillo, helping to prevent depopulation, while also creating attractive conditions for new residents and businesses. Simultaneously, it strengthens the communities that are powered by green energy. Iberdrola is driving the acceptance of renewable energy projects in rural areas, while addressing global challenges, such as rural exodus and demographic issues.

Urban solar farm in Cedillo solar village. © Iberdrola

Case studies

Community engagement through distant self-consumption

Better Energy is planning to build a new solar park in Andst, which will be located in Vejen and Kolding municipalities in Denmark. The total project area will be around 500 hectares, and approximately 300 hectares will be used for renewable energy, while the rest of the project area will be utilised for nature and recreational spaces through an inclusive process involving the local community. The plant installation will result in an installed capacity of approximately 343 MW_{AC}, sufficient to meet the power needs of around 96,000 households.

Better Energy has presented a solution allowing nearby neighbours to buy electricity directly from the solar park. It also offers participating households the opportunity to purchase a fixed amount of electricity based on their home size and household needs according to the average power consumption calculations of the Danish Energy Agency in Denmark. Thus, incentives are given for energy optimisation and energy savings, despite the fixed low price. To further support and promote the green transition, Better Energy offers schemes for purchasing electricity to charge electric cars or power heat pumps.

This initiative has received significant support from neighbours, who are generally positive about the solar park being developed in their area.

Community engagement through crowdfunding

The site where **ENGIE Green** built the French Marcoussis solar power plant was a former wasteland. Today, it is the largest solar PV power plant in the region of Paris, France, with 62,900 solar PV modules and a total installed capacity of 21 MW supplying electricity to over 11,000 people annually. The project presents a unique governance scheme that involves the town of Marcoussis, the SIGEIF (Syndicat Intercommunal pour le Gaz et l'Electricité en Île-de-France), the Paris-Saclay community, and ENGIE Green.

The consultation process with local authorities and the project developer took five years to deliver an integrated approach involving all relevant stakeholders. The first contact was made with the Marcoussis town hall in 2016, followed by partnership with the town council and SIGEIF in 2017 to find an operator. ENGIE Green was chosen due to its co-development offer and environmental integration. Planning permission was submitted and granted in 2018, site preparation began in 2019, construction started in 2020, and the solar power plant was commissioned in 2021.

The project was funded partially through a crowdfunding scheme that enabled more involvement of local stakeholders, and, ultimately, an enhanced public acceptance. Overall, nearly 1.3 million EUR were raised within six weeks from 500 investors, including 528,000 EUR from Marcoussis residents. SIGEIF owns 20% of the project company.

Solar PV plant in Cedillo solar village. © Iberdrola

2.2

Land use

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Context and background

The world is witnessing an increase in urbanisation and artificialisation. In Europe, approximately 80% of land surface is already extensively used, and built-up areas are projected to expand by up to 7% by 2030.[28, 29] This is putting significant pressure on natural habitats. According to various estimations, the degradation of nearly 75% of the Earth's land is due to human activity, namely, deforestation, urbanisation, agriculture, and more.

The current land-use footprint of solar PV is relatively small; only 0.26% of EU land would be required to supply current EU power consumption with solar. In some countries like Germany, estimates have shown that solar PV takes up less land area than golf courses, indicating a manageable impact on land uptake.

There is a growing trend in solar applications that allows for sustainable development of project sites which are compatible with local nature, biodiversity, agriculture, and water surfaces, therefore reducing the pressure on local ecosystems and habitats. Based on appropriate siting, design and management of solar projects, solar PV may restore degraded land, improve a site's ecological status, and provide significant biodiversity net gains.

Additionally, solar applications, such as Agri-PV or floating PV, allow dual land use, adding energy production to land already used for economic activities. Solar PV projects may also provide broader land benefits, such as increasing water use efficiency, protecting flora and fauna from adverse weather, soil-health enhancement, and support for natural ecosystems. Solar PV can also be added to non-productive artificial land, including carports and other types of sealed land, with minimal biodiversity and environmental impacts.

In the European Union, the **Nature Restoration Law** (NRL) has been under preparation for several years and entered into force in August 2024. The NRL marks a critical step for land use and biodiversity, as it sets quantitative goals for restoration of land and marine ecosystems. More information can be found in Chapter 2.3.

The **Renewable Energy Directive** (RED) is a legal framework setting EU definitions and targets for renewable energy generation. The revised Directive, adopted on 31 October 2023, proposes a streamlined process to accelerate the deployment and grid connection of renewable energy projects that are critical to ensure Europe's energy independence. It includes an obligation for Member States to carry out a mapping exercise of future renewable installations and to design Renewable Acceleration Areas (RAAs). RAAs are zones that are suited for renewable energy projects, where environmental impacts are expected to be minimal, such as 'no-regret' areas. These zones may include, but are not limited to: rooftops, carparks, industrial areas, mining sites, artificial inland water bodies, and more. RAAs should be incorporated in a strategic environmental assessment. When designing these areas, Member States should avoid protected areas, as well as considering restoration plans and appropriate mitigation measures.

28 European Environment Agency (2021): Land take and land degradation in functional urban areas

29 EU Commission (2020): Developments and Forecasts on Continuing Urbanisation

Another important piece of legislation is the **Common Agricultural Policy (CAP).** The main goal of the CAP is to support farmers and ensure continuous development of agricultural and rural sectors, while tackling climate change and guaranteeing sustainable management of natural resources. As part of the CAP strategies developed on a national level, contributions towards climate change mitigation and sustainable energy deployment are included. Additionally, it incorporates Member States' national renewable energy targets for 2023-2027. Currently, 14 Member States have incorporated solar PV under their CAP Strategic Plans, with the Agri-PV term integrated into four Member State Strategic Plans: Germany, Italy, the Netherlands, and Slovenia. In the case of Agri-PV and floating PV, country-specific regulations may apply, providing a legal definition that sets clear rules for both of these technologies and facilitates access to public funding. An overview of pioneers in national legislation can be found in Box 3: Agri-PV in national legislation and Box. 4: Floating PV in national legislation.

Approaches and best practices

Solar PV projects can increase land value by producing electricity on previously abandoned, unused, or degraded sites. Solar PV can also enhance existing land use - such as water dams or agricultural fields - offering diverse benefits, including land restoration, ecosystem enhancement, and support for agricultural practices. The value that solar PV brings may vary, with various considerations and benefits applying in each case. This chapter focuses on four cases where solar PV increases land value:

1. **Degraded artificial land**
2. **Land in arid and semi-arid climates**
3. **Agricultural land (Agri-PV)**
4. **Body of water (Floating-PV)**

DEGRADED ARTIFICIAL LAND

Solar PV may be used to regenerate artificial land which has lost its original use, is degraded or is in the vicinity of a polluted area.

For the case of **brownfields**, the installation of a solar PV plant enables efficient land use that may otherwise be challenging to repurpose, such as former mines, landfills and ponds, amongst other altered areas, resulting from activities of a former dam or quarrying.

Governments typically support the use of this type of land for solar PV plants. In some countries, such as Italy, financial incentives or other benefits, particularly simplified authorisation procedures, are allocated for brownfield renewable energy projects.

A key consideration is the possible need for site preparation, hence the increased CAPEX, to make the land suitable for the solar PV installations, depending on its current status. In some instances, however, the installation of solar PV systems can be implemented with minimal or no site remediation, helping to reduce costs and speed up project development.

It is also important to note that installing solar PV on brownfield sites may present certain technical challenges. Construction and costs may be impacted by specific brownfield conditions, such as uneven terrain, unsuitable subsoil, chemical pollutants, or building rubble. For this reason, additional assessments, such as environmental or geological assessments, are usually required when constructing solar PV on brownfield sites. Despite these possible impacts, using brownfields for solar PV construction offers an opportunity to revitalise neglected sites and can improve and develop its surroundings.

In Europe, many **industrial buffer zones** near high-risk industrial sites remain unused. Under the Seveso Directive, EU Member States must identify high-risk industrial sites where hazardous substances, which are dangerous to humans and the environment, are produced or stored. A site is classified as a Seveso site based on the presence and quantity of these hazardous substances. These sites are subject to strict regulations to prevent accidents and minimise their potential impact.

For example, in France, Technological Risk Prevention Plans (PPRT) are required for these sites. These plans regulate urban development by restricting building construction within designated areas, keeping these zones largely underdeveloped. However, solar PV plants which require minimal human presence are generally permitted within these areas. Similarly, in Italy, zones within 500 meters of an industrial area, referred to as a "solar belt," are considered suitable for solar PV projects and enjoy a streamlined approval process.

This approach presents an opportunity to repurpose industrial buffer zones for electricity generation, supporting self-consumption or local consumption through bilateral power purchase agreements (PPAs). Additionally, the installation of solar PV plants near production sites is expected to have a lower environmental impact.

LAND IN ARID AND SEMI-ARID CLIMATES

Arid and semi-arid climates are defined as climates with very little rainfall (up to 250 mm, and between 250 and 500 mm per year, respectively), limited vegetation and for arid climates, year-long hot temperatures. In these areas, the installation of solar PV modules not only offers clean energy production, but also brings significant environmental benefits by modifying the local microclimate underneath the solar PV modules. Several studies confirm that partial shading by solar PV modules in arid regions can enhance biodiversity, increase floral abundance, and delay flowering time, benefiting late season pollinators.[30] In 2019, a case-study in a semi-arid location in Arizona compared yields of tomato, chiltepin, and jalapeño peppers grown under traditional conditions with those in an Agri-PV system. The results showed that under an Agri-PV system, the tomato and chiltepin peppers yields were 2.9 and 2 times higher, respectively, while the jalapeño yields were the same in both systems.[31]

Water shortages are a growing concern, and their impact on local biodiversity is becoming a significant issue. Solar PV plants can help mitigate this challenge by reducing evaporation through increased shading, thereby improving soil moisture and humidity. A study by Omer et al. (2022) explored the effects of solar PV modules on evaporation in Anhui province, China. The findings indicated that evaporation from the areas covered by solar PV modules was 14 to 33% lower compared to uncovered land, depending on the conditions and module type.[32] These microclimate changes can support the growth of vegetation and potentially contribute to maintaining or even enhancing local biodiversity.

By fostering a more hospitable environment for plant life, solar PV installations can play a vital role in preserving biodiversity in areas at risk due to high temperatures and limited water resources.

For more information regarding the multiple uses of solar and what benefits these projects can bring, you can read SolarPower Europe's reports Agrisolar Best Practice Guidelines[33]; Solar, Biodiversity, Land use best practice guidelines[34]; and the Agrisolar Handbook.[35]

AGRICULTURAL LAND (AGRI-PV)

Agricultural activities can be combined with solar PV installations in various settings, such as co-locating solar PV modules on agricultural fields, placing them on agricultural sheds, or integrating them into irrigation systems, offering numerous opportunities for sustainable advancement of agricultural practices and rural development. This practice is referred to as agrisolar or Agri-PV. In Europe, several countries have defined Agri-PV in their legislations, to allow the development of PV plants on agricultural fields, to streamline the permitting process of Agri-PV and to allocate public funding. An overview of best practices in national legislations can be found in Box 3: Agri-PV in national legislation.

There are many potential benefits of Agri-PV for the farmer, agricultural land, and biodiversity. Various studies indicate that Agri-PV systems can increase land productivity by up to 70%.[36]

The deployment of Agri-PV can significantly improve the **economic situation of farmers** by offering numerous financial benefits. Firstly, in cases where farmers do not own the land, they may receive free access to land and land lease payments from developers, irrespective of land ownership. In instances where the land is leased, the revenue generated can be reinvested in farming activities. Additionally, farmers may gain access to the electricity generated by the solar PV plant in

30 Graham et al. (2021): Partial shading by solar panels delays bloom, increases floral abundance during the late-season for pollinators in a dryland, agrivoltaic ecosystem.
31 Barron-Gafford et al. (2019): Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands.
32 Omer et al. (2022): Water evaporation reduction by the agrivoltaic systems development.
33 SolarPower Europe (2024): Agrisolar Best Practice Guidelines v2.
34 SolarPower Europe (2023): Solar, Biodiversity, Land Use Best Practice Guidelines.
35 SolarPower Europe (2024): Agrisolar Handbook.
36 Sarr et al. (2023): Agrivoltaic, a Synergistic Co-Location of Agricultural and Energy Production in Perpetual Mutation: A Comprehensive Review.

exchange for continuing agricultural activities under the modules, thereby reducing the operational costs related to agricultural activity. Agri-PV also provides opportunities for financing farm infrastructure and supports capital inflow, helping to preserve the use of agricultural land even on less fertile soils. This is particularly beneficial for grazing activities, such as sheep farming, which can lead to soil improvement.

The revenue and savings generated from Agri-PV can help support farmers in transitioning from intensive agricultural practices to more sustainable, regenerative, and organic farming, which may require additional costs during the transitional period. As part of the project, developers may even promote organic farming practices.

BOX 3 AGRI-PV IN NATIONAL LEGISLATION

In June 2023, in **Croatia**, the Physical Planning Act established a legal basis and definition of Agri-PV for the first time. Agri-PV power plants can be built on all types of agricultural land, whether on a permanent plantation registered in the agricultural land registry or on farms and greenhouses, while still maintaining the agricultural use of the land. In December 2023, the Regulation on simple and other construction works was amended to streamline the procedure for solar PV plants and Agri-PV plants with installed power of up to 10 MW. According to the new provisions, investors who have settled property rights are no longer required to obtain energy approval, building and location permits for solar PV and Agri-PV plants of up to 10 MW of installed power.

In 2024, in **Czech Republic**, an updated law 'Protection of the agricultural land fund' introduces the first legislative framework for Agri-PV, prohibiting the use of over 1 hectare of agricultural land for commerce, storage, or traditional solar PV energy production. Simultaneously, the legislation paves the way for Agri-PV on agricultural land, including hop fields and fruit orchards. It also permits the potential development of Agri-PV-focused subsidy schemes in the future.

In 2023, in **France**, the government published a law accelerating the production of renewable energy, aiming to facilitate the installation process for renewable energy systems. One of its chapters focuses on the implementation of solar projects and includes a definition of Agri-PV. An Agri-PV installation is described as an "electricity production installation using the sun's energy, the modules of which are located on an agricultural plot where they make a lasting contribution to the installation, maintenance or development of agricultural production".

To qualify as Agri-PV, a solar plant must be developed on agricultural land, ensuring significant agricultural production for an active farmer and providing a sustainable income. Moreover, the solar PV plant must offer at least one of the following benefits to the agricultural plot: improvement of the agronomic potential and impact, adaptation to climate change, protection against hazards, or improved animal welfare. An installation will not be classified as Agri-PV if it substantially undermines any of these services, damages two of them, does not maintain agricultural production as the main activity on the plot, or lacks reversibility. Agri-PV installation projects will be subject to the evaluation of the departmental commission responsible for the preservation of agricultural, natural, and forest areas.

In **Germany**, the first European Agri-PV technical norm – DIN SPEC 91434:2021-05 – has been developed to introduce requirements for planning, operation, documentation, and operational monitoring, as well as for the quality assurance of these projects. Additionally, the newly-adopted Renewable Energy Source Act includes a subsidy category for dual-use solar, including Agri-PV and floating PV. A new bill, Solar Package 1, is also introducing an annual solar tender of 3 GW for Agri-PV, floating PV, and carports.

Furthermore, Agri-PV can sustain land use by encouraging agricultural practices and reintroducing biodiversity, particularly in areas where traditional farming may not be economically viable. This new economic model can also revitalise historical agricultural practices and attract younger generations to the agricultural sector.

Agri-PV can also provide additional jobs for local communities and rural areas, as well as secure economic stability for farmers. Moreover, it may also offer additional advantages to farm workers, such as additional shade generated by the modules, which can help create cooler temperatures and offer protection from rain and other adverse weather events.

Solar PV plants can significantly benefit both crops and farm animals. By providing shade, the solar PV installations help protect crops from excessive sunlight and temperatures. These systems also safeguard plants and animals from various hazards, such as hail and frost, which can harm leaves and fruits. For livestock, the shade provided by solar PV modules serves as a shelter during adverse weather conditions, including heavy rain, hail, and intense sunlight, significantly enhancing overall animal wellbeing. Additionally, the careful design and continuous monitoring of agricultural land optimises its land use and offers additional benefits. In the design stage, a detailed assessment conducted by agronomists helps identify the most suitable type of crop, or replace existing crops affected by illness. In some instances, equipment integration in the solar PV plant, such as the installation of a rainwater collection system, may optimise water use.

More detailed information on the topics of Agri-PV can be found in SolarPower Europe's reports: Agrisolar Best Practice Guidelines[37]; Solar, Biodiversity, Land use Best Practice Guidelines[38]; and Agrisolar Handbook.[39]

BODY OF WATER (FLOATING-PV)

Floating PV systems consist of solar PV modules installed on bodies of water, such as lakes, reservoirs, or ponds, instead of being placed on land. These systems are mounted on floating platforms that keep the PV modules afloat and stable. In Europe, several countries have established definitions of floating PV within their legislation, to streamline the permitting process for floating PV projects and to offer public funding. A summary of best practices in national legislation can be found in Box4.

Floating PV systems can be categorised into two types: onshore floating PV, which is built on any type of inland water body; and marine floating PV, which is designed for salty and brackish waters. Additionally, there are fixed structures placed on areas, such as tidal flats or fishponds, that do not float but share many technical and operational characteristics with floating PV.

Floating PV offers several advantages. These PV systems do not require land, placing them in an advantageous position where land is scarce, expensive, or already in use for other purposes. Water bodies can also help cool the solar modules, which may improve module efficiency and performance compared to land-based systems, where heat can reduce energy output. Floating PV can also provide solutions for both energy generation and water conservation, with the potential to reduce water evaporation by up to 42%. Thanks to these systems, the growth of algae can be further minimised by decreasing the sunlight infiltration through water surfaces, while also reducing the overall temperature of the water. Since these systems do not use land, they typically have less impact on the ecosystems compared to ground-mounted solar farms.

The potential for floating PV in the European Union is significant. According to a study by the Joint Research Centre, the total technical potential installed capacity of floating PV systems on reservoirs can reach up to 157 GW.[40] More information on the topic of floating PV can be found in SolarPower Europe's report Floating PV Best Practice Guidelines.[41]

37 SolarPower Europe (2024): Agrisolar Best Practice Guidelines v2.
38 SolarPower Europe (2023): Solar, Biodiversity, Land Use Best Practice Guidelines.
39 SolarPower Europe (2024): Agrisolar Handbook.
40 Kakoulaki et al. (2024): Communication on the potential of applied PV in the European Union: Rooftops, reservoirs, roads (R3).
41 SolarPower Europe (2023): Floating PV Best Practice Guidelines.

BOX 4 FLOATING PV IN NATIONAL LEGISLATION

Floating PV may be affected by existing national building, water, and nature protection laws. The anchoring and mooring systems for securing the floating PV modules must be aligned with the national **building law**, technical regulations, and spatial planning and zoning laws. Moreover, in several EU Member States, **water authorities** must be consulted during the permitting process for floating PV installations, and various water-specific regulations, such as water protection laws and water use acts, will apply based on the type of water body. It is also important to take into consideration the **environmental impact and nature protection regulations**, as stricter nature protection laws generally apply to natural water bodies, particularly those publicly-owned.

However, in several EU countries, there are examples of legislation that facilitate the deployment of floating PV.

In **Croatia**, the legal provisions on regular solar power plants are applicable to floating PV, with specific variations in the permitting process tailored to the use of water resources. In June 2023, several amendments to the Physical Planning Act prostornom uređenju) expanded the construction of solar power plants to include lakes and ponds. The next step was applying legal provisions on regular solar power plants to floating PV, with variations in permit granting process specific for the exploitation of water assets.

In **Germany**, the EEG (Renewable Energy Act 2023) recognises the dual land use for solar projects, including floating PV. The law proposes a new tender category for special PV plants with higher bidding limits and it includes floating PV, as well as other innovative technology categories. Fraunhofer ISE elaborated a process model for floating PV in the country that is based on data of an analysis of legal documents and interviews with approval authorities and project developers of six floating PV projects in five federal states. Based on the findings of this research, a flow chart for the permitting procedure model for floating PV was established in Germany, particularly referring to quartz sand and active gravel mining lakes, as well as former sandpit and lignite mining lakes. This research was conducted as part of the "PV2Float" research project.

In **Italy**, Decree-Law No. 39, containing urgent provisions to combat water scarcity and strengthen and adapt water infrastructures, was converted into law. The law includes measures focusing on the energy sector, with a specific focus on floating PV. It particularly simplifies procedures for installing floating solar plants in Italy. The intervention pertains to PV systems situated on water bodies, including reservoirs, water basins, mining quarries (both closed and active), public or state-owned areas, and solar systems covering irrigation canals. To facilitate their installation, the granting body is required to publish the concession application on its website within 30 days.

In the **Netherlands**, the SDE++ (Stimulation of Sustainable Energy Production and Climate Transition), is a subsidy scheme applicable to all large-scale renewable energy investments, including inland floating PV.

Case studies

Alqueva dam

The Alqueva dam is the largest artificial lake in Europe, located in Alentejo, Portugal. The development of the floating PV project in Alqueva by **APREN** began after the 2021/2022 competitive procedure (auction) for the allocation of electricity injection capacity into the grid. Through this auction, EDP Renewables was awarded a 70 MVA grid connection capacity at the 400 kV substation of Alqueva, as well as rights to use an area of approximately 100 hectares of the Alqueva water surface.

An estimated installed capacity of 154 MW, divided between floating PV and wind, is expected to be commissioned in 2025, pending grid availability. Monitoring of birdlife, archaeological prospecting work, and water quality are part of the Environmental Impact Study submitted to the Portuguese Environment Agency and are already underway. These efforts will enable the project promoter to create a rigorous conditioning plan to ensure the project's compatibility with the current and future uses of the Alqueva reservoir.

Bollendok landfill site

In the Netherlands, **Statkraft's** project, Bollendonk, was a former landfill site that was converted into a solar park. The site covers nearly 10 hectares with a total production of 11.3 GWh per year. In addition to transforming the landfill into a renewable energy plant site, the solar project enhances the surrounding area by creating designated areas for different species.

The project was developed in collaboration with the landowner, the municipality, and various local parties, including Duurzaam Etten-Leur and the MEC Etten-Leur Foundation. Improving natural value at the site has yielded several improvements. The southern point of the plot is reserved for plants, introducing more greenery to the site. Moreover, a foraging area has been developed, and 1.3 hectares have been allocated as a food forest to support the growth of species such as weasels, stoats, and stone martens.

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Case studies

Solar park in a former military camp

The Fontenet 2 solar park in France, operated by **BayWa r.e.**, is a significant example of renewable energy development in an ecologically sensitive area. The project, built on a former military camp, is designed to restrict and mitigate adverse impacts on the local environment, particularly focusing on protecting rare habitats and species, including the Large Blue butterfly, bird species, such as the Dartford warbler, as well as flora, like the Stone Curlew. Sensitive areas, including 17 hectares of functional dry lawns, were identified at the early stages of the project, and were largely avoided during its construction. The construction activities were planned to avoid sensitive periods for local wildlife, and workers were contractually obligated to adhere to environmental guidelines aimed at safeguarding biodiversity, minimising pollution risks, and reducing noise.

In collaboration with the local environmental NGO Conservatoire d'Espaces Naturels de Nouvelle-Aquitaine, the project also focused on restoring native vegetation, using seeds sourced from nearby natural meadows. The conservation strategy included the compensation of 35 ha of pre-forested areas to support bird populations, ensuring a balance between habitat conservation and energy production.

Since the park's operation began in 2022, the ongoing monitoring has indicated positive outcomes, particularly with the stabilisation of the Large Blue butterfly population, which was at risk of decline due to habitat loss. External ecological organisations have also been involved to help monitor and report on the site's environmental progress, ensuring adaptive management throughout the project's lifespan. The close collaboration with local authorities and environmental groups ensures that the Fontenet 2 solar park contributes not only to the renewable energy goals but also to ecological restoration and conservation efforts.

© BayWa r.e.

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Study on the welfare of sheep on PV plants

Integrating solar PV systems into sheep grazing is a form of Agri-PV that benefits both agriculture and renewable energy production. The potential benefits for the sheep's welfare include shade provided by solar PV modules and improved grazing conditions. Simultaneously, sheep maintain the vegetation around the solar PV modules, reducing the need for mechanical mowing.

In a pioneering study, **Statkraft**, along with the French renewable energy producer CVE and research organisation INRAE, took a closer look at the effects of the presence of solar PV modules on sheep grazing from 2022 to 2023, primarily focusing on the animal welfare.[42] The research aimed to determine if these solar installations influenced the sheep's welfare and in particular, behaviour, health, and environment. For several months, a flock of 24 sheep grazed on a 6-hectare solar farm, wearing sensors which collected data on brightness, movement, and position. Environmental factors and observations derived from behavioural data grids provided additional insights.

The results of the study indicated that solar PV modules provided shade, reducing heat stress and potentially extended grazing. Additionally, it was found that solar PV modules may protect the grass against frosts, improving grazing conditions. The sheep's daily activities, such as grazing time or movement within a flock were not affected by the solar PV modules. The shading effect was also present. While the solar modules did not entirely prevent the sheep from feeling heat stress during extreme weather events, they mitigated the intensity of the stress and the heat load index (HLI) was lower under the modules compared to uncovered areas. Sheep health was also measured by observing possible negative changes, such as injuries, parasites, or nasal discharge. Initially, the sheep were herded using dogs, leading to stress and resulting in injuries. However, the herd management strategy was later adjusted to include dividing the plot into several zones through adapted fencing, and by grouping the sheep using food supplements to group the sheep. This new method reduced the sheep's stress levels and prevented any further injuries.

Study on the impact of solar PV modules on sheep welfare. © Statkraft.

42 Statkraft, CVE and INRAE (2024): Rapport d'étude sur le bien-être animal – Centrale solaire de CVE à Bissey-sous-Cruchaud

2.3 Biodiversity

© Statkraft

Context and background

Biodiversity is an integral part of human livelihoods, supporting resources vital to life, such as food, clean water, and overall ecological stability. However, human activities have severely impacted ecosystems globally, leading to an unprecedented biodiversity crisis. Simultaneously, rapidly rising climate temperatures bring substantial harm to health economies, and natural environments. Climate change poses a significant threat to biodiversity, endangering habitats and species alike. In Europe, biodiversity is declining at an alarming pace. Data suggest that 39% of 463 bird species and three-quarters of habitats are currently in poor or bad conservation status.[43]

Adopting solutions that align with natural ecosystems is essential. Investing in nature-based approaches to reduce carbon emissions can support a swift climate change adaptation and its associated risks. Protecting and restoring ecosystems supports climate mitigation, helps to adapt to climate change, and secures a sustainable future for generations to come.

Nature-inclusive solar PV parks, aiming at increasing biodiversity net gains, can be an important solution to support local flora and fauna, restore degraded ecosystems, and offer clean energy sources. Several studies indicate that nature-positive solar power plants can enhance biodiversity by up to 281%, increasing local wildlife and providing a home to a wide range of local species.[44] In a study conducted on a solar site that combined sheep grazing, results revealed an increase in carbon stock up to 80%.[45] Besides, solar PV parks can also protect and provide shelter for wildlife during extreme weather conditions.

In Europe, the **EU's Nature Restoration Law** (NRL) sets ambitious goals to restore resilient and biodiverse land and sea ecosystems, contribute to climate change mitigation and adaptation, promote land degradation neutrality, and enhance food security. The law mandates restoring at least 20% of ecosystems by 2030, with the aim of restoring all ecosystems in need of restoration by 2050. Specific targets under Article 4 require Member States to restore 30% of degraded land ecosystems by 2030, 60% by 2040, and 90% by 2050, with similar targets for marine ecosystems under Article 5. Additional goals include reversing pollinator decline by 2030, increasing biodiversity in agricultural ecosystems, and restoring organic soils on drained peatlands. Member States must submit National Restoration Plans (NRPs) within two years of the regulation's entry into force, setting out targets and revisions for 2032 and 2042, with monitoring every three years. The NRL prioritises nature conservation, with restoration goals covering wetlands, forests, grasslands, rivers, lakes, urban areas, and marine habitats. It also highlights opportunities for synergy between solar energy projects and ecosystem recovery, such as repurposing degraded agricultural land for solar farms, while enhancing biodiversity and carbon sequestration. The European Environment Agency will monitor the progress, reporting regularly to the European Parliament and Council.

43 European Environment Agency (2024): Biodiversity: state of habitats and species.
44 WSP (2023): Independent WSP audit of Lightsource bp solar farms shows positive biodiversity boost around UK sites.
45 Towner et al. (2021): Managed sheep grazing can improve soil quality and carbon sequestration at solar photovoltaic sites.

Solar parks that offer ecosystem services can play a significant role in achieving NRL targets. When properly designed, solar parks can support pollinator populations, recover degraded ecosystems, and rewet drained peatlands, providing overall benefits to nature and biodiversity. Acknowledgment of these solutions must be included in the NRPs that Member States will develop during the implementation phase of the NRL. Solar parks that contribute to nature restoration should be explicitly mentioned in these plans and receive appropriate incentives to support European restoration objectives.

In England, 'mandatory biodiversity net gain' is a policy under the UK Environment Act 2021, mandating new developments, including solar parks, to deliver a 10% increase in biodiversity compared to pre-development levels. This requirement, formally known as **Biodiversity Net Gain (BNG)** effective from November 2023, uses the Defra Biodiversity Metric 4.0 to measure habitat quality, size, and ecological condition. If a project cannot meet the 10% target, it must acquire offsets, whereas projects that exceed this requirement can sell biodiversity credits, providing a financial incentive that benefits solar parks, particularly those situated on degraded lands.

This chapter examines relevant EU and national nature policies and their relevance for solar development to provide a framework for sustainable management practices. Lastly, it will outline several nature-inclusive best practices across Europe.

For more information, read SolarPower Europe's reports: Agrisolar Best Practice Guidelines[46]; Solar, Biodiversity, Land use best practice guidelines[47]; policy paper on rewarding and incentivising nature-inclusive solar through EU policy.[48]

Approaches and best practices

IDENTIFY SUITABLE LAND AND CREATE A MANAGEMENT PLAN

The process of identifying suitable land and creating a plan begins with the careful selection of the site, ensuring that it meets the necessary criteria for development, while also taking into consideration other environmental factors. Once a site is chosen, an evaluation of the area's biodiversity is performed, focusing on the condition of ecosystems, endangered species, and any nearby protected areas. Drawing on the findings, biodiversity management plans are developed and adapted to benefit the local environment, prioritising conservation and protection efforts. Consulting local experts is essential to gain valuable insights into the specific biodiversity challenges and opportunities in the area, which enables the refinement of management strategies and ensures positive ecological outcomes.

MINIMISE IMPACT ON EXISTING BIODIVERSITY

Preserving existing biodiversity and minimising the impact of the solar project on local ecosystems involve several important measures. A primary focus is the protection of endangered species in both agricultural and natural areas. In the agricultural areas, careful plant selection is essential, along with the use of regenerative practices, such as cover cropping to enhance soil health and biodiversity. Additionally, minimising the use of pesticides is crucial to lessen the environmental strain. In the natural areas, the selection of native plants based on their ecosystem services helps sustain ecological balance. Implementing low-impact management techniques, such as avoiding herbicides and minimising the number of cuts, further reduces disruption. Efforts are also aimed at restoring habitats to support specific species, thereby enhancing biodiversity conservation in the region.

46 SolarPower Europe (2024): Agrisolar Best Practice Guidelines v2.
47 SolarPower Europe (2023): Solar, Biodiversity, Land Use Best Practice Guidelines.
48 SolarPower Europe and The Nature Conservancy (2024): Rewarding and incentivising nature-inclusive solar through EU policy.

INCREASE BIODIVERSITY ON-SITE

Increasing biodiversity on a site involves several strategic actions aimed at promoting ecological health and sustainability. One key approach is to create conservation corridors, which allow for the movement and protection of wildlife. Reseeding the land with native plants is essential for restoring local ecosystems and supporting native species. Biodiversity net gains can be achieved when biodiversity assessments are performed both prior and following the construction of solar installations, showcasing that solar sites improve biodiversity and surpassing the current baseline. Various best practices can be implemented to enhance biodiversity. This includes, but is not limited to, creating diverse habitats around the solar parks, planting native vegetation, and sustainably managing the sites throughout the lifecycle of the solar PV project. Other practices, such as carbon farming, can also contribute to increased biodiversity by capturing carbon and improving soil health.

MONITOR THE RESULTS

Access to clear and quantitative data that measure biodiversity performance (e.g., number of pollinators) creates transparency, enabling clear communication and reporting. This data can further support mitigation action plans to promote biodiversity, ensuring the preservation and growth of a variety of species.

EDUCATE AND TRAIN THE OPERATORS

A solid understanding of practices that maintain biodiversity on site is also an essential component of a solar PV project. Understanding local biodiversity and the necessary management strategies allows for optimised land use.

THE MITIGATION HIERARCHY FRAMEWORK

The mitigation hierarchy framework is a holistic methodology for assessing biodiversity impacts. It is helpful in defining how nature-inclusive solar can reduce the overall effects on biodiversity and achieve net gains. This framework can guide infrastructure development through a decision-making process that minimises adverse impacts on biodiversity. It consists of four stages and includes a final step focused on achieving biodiversity net gains.

The first step in the mitigation hierarchy is to avoid biodiversity loss and land degradation by requiring the completion of an environmental assessment, including a biodiversity baseline, as a condition for granting planning permission. This assessment helps identify sensitive habitats and species, as well as establishing a baseline for existing biodiversity.

The subsequent step is to prevent net biodiversity loss by taking measures to avoid impacts and by proactively creating suitable habitats for native species on-site. Following this, ongoing site management is essential to maintain and enhance biodiversity throughout the solar plant's lifecycle. Finally, biodiversity net gains can be achieved when there is a measurable and enduring improvement in biodiversity relative to pre-development conditions. For more information regarding the Mitigation Hierarchy and achieving biodiversity net gains, refer to the latest report by SolarPower Europe and The Nature Conservancy, *Rewarding and incentivising nature-inclusive solar through EU policy.*[49]

49 SolarPower Europe and The Nature Conservancy (2024): Rewarding and incentivising nature-inclusive solar through EU policy.

Case studies

Åhus solar park

At the 7.2 MW solar park in Åhus, Sweden, **Alight** implemented numerous measures to promote biodiversity on-site. The former agricultural field was sown with a mix of blueweed, chicory, common bugloss, and seven other species chosen to thrive in the previously cultivated soil and attract pollinators.

The park, which is built, owned, and operated by Alight, has been producing energy since 2022. The agricultural land had undergone intense management for many years, resulting in lower productivity compared to the surrounding landscape. This situation presented an opportunity to not only produce solar energy but also to enhance the land's natural characteristics and achieve biodiversity net gain.

By establishing a less intensely managed grassland habitat that offers food sources for pollinators, the solar park contributes to strengthening the ecosystem services that pollinators provide to the surrounding agricultural areas. As of 2023, sheep have been introduced to the land in collaboration with a local farmer. This initiative provides a more natural grazing regime, while also contributing to food production.

The Åhus solar park demonstrates how solar sites can coexist with and actively support ecological enhancement, establishing a model for sustainable land use that benefits both nature and local communities.

© Alight

Case studies

Including biodiversity by design with technology

Element-E is a platform developed by **3Bee** to integrate diverse data sources, including satellite imagery and public databases on endangered species and protected areas, as well as data from field surveys and sensors. The platform enables comprehensive biodiversity assessments and optimal project design. By calculating the current level of biodiversity in a given area, it identifies the most suitable native species to introduce and their optimal locations for their planting. This design process considers all constraints and aims to maximise biodiversity benefits. Additionally, it integrates with existing agricultural activities, both within Agri-PV sites and surrounding areas. So far, this approach is actively utilised in over ten solar PV sites across Europe, ranging from 1 up to 200 MW, and involving key players, such as Cubico and RWE.

The platform also tracks performance over time, enabling continuous monitoring and ensuring that biodiversity objectives are achieved and sustained, validating the effectiveness of the design. In the example below, pollinator activity recorded through bioacoustics sensors is used to assess changes in abundance and diversity of functional groups, thereby confirming the effectiveness of the nature-based solutions chosen for the site.

© 3Bee

© 3bee

Ground-mounted solar park in southwest France

BayWa r.e. developed a solar project of 41.2 MW in the southwest France with the objective of minimising ecological effects and offsetting any residual impacts through restoration and management strategies, aimed at achieving a global net gain for biodiversity.

The solar project prioritised biodiversity-sensitive areas throughout the site selection, design, and development stages, actively preventing or reducing impacts on these areas whenever possible. The mitigation measures implemented during construction and operation were in line with the mitigation hierarchy. Offsetting measures encompassed 173 hectares beyond the project site. These measures were discussed with the local authorities during the permit instruction phase and implemented in collaboration with a local environmental organisation. The project has been in operation since 2017.

The project incorporates comprehensive conservation and restoration strategies aimed at enhancing local biodiversity and protecting sensitive ecosystems. A primary component is the conservation of over 50% of wetlands in the project area, which includes preserving old trees known for their rich biodiversity and maintaining nearby small ponds. Additionally, specific measures are taken to protect vulnerable species of birds, reptiles, and amphibians by planning heavy construction activities to avoid overlapping with their nesting periods. The preservation of ecological corridors is also crucial, with the installation of fences specifically designed to facilitate safe wildlife movement. To manage vegetation effectively, rotational sheep grazing is employed as an ecological practice, particularly aimed at protecting the butterfly species False Ringlet (Coenonympha oedippus). Furthermore, the project includes the restoration of 173 hectares of degraded wetlands beyond the site, encompassing wet meadows, forests, and moors, in collaboration with a local environmental organisation that has been implementing ecological management techniques, such as late mowing and sheep grazing, since 2018.

© BayWa r.e.

© BayWa r.e.

Case studies

The monitoring and adaptive management programme has been in place since 2017, involving a 25-year environmental monitoring initiative conducted in partnership with a local environmental organisation. The programme employs standardised field protocols to assess habitats, flora, birds, insects, and amphibians. Measures are continuously refined based on monitoring results. The management strategy, for example, transitioned to fixed grazing on certain plots after positive outcomes from itinerant grazing, and pond management was modified in response to the species observed. Monitoring has indicated improved wetland functioning in compensation areas due to hydraulic works and successful moorland restoration through the clearing of pine plots. Target species, including the protected butterfly False Ringlet, bird Dartford warbler, and flora Oblong-leaved sundew, have shown population increases as a result of these wetland and moorland restoration efforts. Additionally, small ponds adjacent to the solar park and within compensatory areas have been found to support diverse amphibian and insect populations, further underscoring the effectiveness of these management strategies in enhancing local biodiversity.

The project focuses on collaborative partnerships and community engagement through the active inclusion of local stakeholders, including authorities and NGOs, in an annual monitoring committee. This committee is tasked with overseeing project progress, discussing management choices and operational constraints, and adapting measures as needed. To further enhance community engagement and awareness, a path near the park has been equipped with educational materials that explain solar energy and its environmental significance. This path is frequently visited by school students, providing them with valuable learning experiences and fostering a deeper understanding of sustainability and ecological responsibility.

EcoCertified solar parks

Research focused on improving natural value and soil health in solar parks during the design phase, including vegetation management, is currently underway in the Netherlands from 2021 to 2025. This study will provide guidelines for the design and vegetation management through a quality certification EcoCertified Solar Label. The EcoCertified Solar Label ensures the protection of soil quality in solar fields, while contributing to biodiversity recovery in the surrounding landscape. This research is supported by a consortium which includes research institutions, eight provinces, Rijkswaterstaat, the Nature & Environment Federations, and solar park developers, such as **Statkraft**.

The study examines park management and maintenance practices, as well as their effects on local biodiversity, including birds and mammals. It will also assess overall soil quality and explore various innovative techniques for evaluating biodiversity, all while undergoing a cost-benefit analysis. Additionally, as part of the project activities, a labelling system will be developed. This scoring system will enable developers, stakeholders, and government actors to evaluate solar parks based on their overall ecological and environmental value.

More information about this case study can be found in the report Solar, Biodiversity, Land use best practice guidelines.[50]

50 SolarPower Europe (2023): Solar, Biodiversity, Land Use Best Practice Guidelines.

Case studies

Nature management plans

Nature Management Plans (NMPs) are an effective way to improve the level of biodiversity within and around solar farms. These plans are designed and implemented on sensitive or high-priority solar assets to mitigate impacts and restore biodiversity values on-site. Each plan outlines the strategies, interventions, and actions necessary to protect, conserve, and enhance natural ecosystems beyond defined minimum compliance.

NextEnergy Capital identified an opportunity to implement NMPs in Poland to provide additional nature-positive outcomes that exceeded permitting and regulatory requirements across 25 sites. The sites selected are part of a portfolio within NextEnergy Capital's flagship international solar infrastructure fund, NextPower III ESG. The chosen sites are near designated areas of landscape and nature protection, including ecological corridors. NextEnergy Capital is developing bespoke management plans for these assets. These plans complement the adjacent protected areas and support ecological resilience for flora and fauna. The biodiversity interventions on these sites will be tailored to enhance landscape connectivity and support site-specific conservation objectives.

The NMPs will also offer the opportunity to pilot new nature and biodiversity management techniques in Poland. Alongside a monitoring programme, this initiative provides a framework to measure the success of management techniques and inform future decision-making for nature conservation across NextEnergy Capital's assets.

3

End of life

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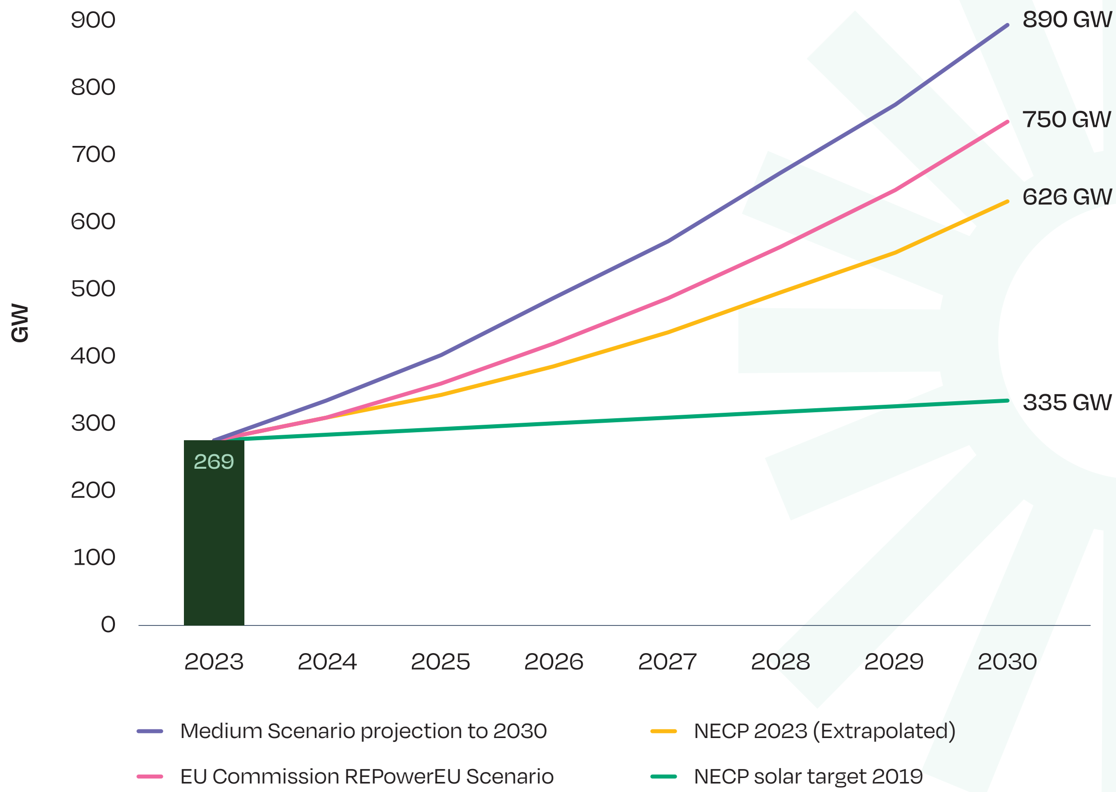
Revamping and repowering

Context and background

A unique advantage of solar PV technology is the durability, reliability, and long-lasting performance of its components. Plenty of PV modules currently on the market come with performance warranties of 30 years or more, while inverters, with an expected lifespan of approximately 10 to 15 years, can also be easily repaired or replaced. Several of the first PV systems installed in Europe at the turn of the century remain fully operational, providing green energy to early adopters that pioneered the solar race at that time despite their

FIGURE 9 EU-27 SOLAR PV CUMULATIVE CAPACITY SCENARIOS 2023-2030



Source: SolarPower Europe (2024).

lower performance compared to today's advanced technology. Consequently, the majority of solar PV systems in today's EU solar fleet are not expected to reach the end of their technical lifetime till around 2040, when solar PV waste streams are expected to significantly grow compared to today's low levels.

However, looking more broadly at the solar PV end-of-life considerations, the impressive adoption of solar energy and its long-term impacts should also be acknowledged. The growth of solar energy in the EU and globally has been unprecedented and was anticipated only by a few energy experts until recently. The EU solar fleet is expected to reach 890 GW of installed capacity by 2030, up from 269 GW at the end of 2023 – exceeding both combined national solar targets and the REPowerEU target of 750 GW (see Fig 9). At a global level, the total operating solar PV capacity, which stood at 1.6 TW at the end of 2023, is projected to increase by 356% by 2030, reaching 7.4 TW.[51]

The massive increase of solar PV deployment is therefore poised to result in a significant long-term increase of PV waste streams. As the sector prepares for this challenge and recognises the importance of setting up effective end-of-life management activities well ahead of reaching large waste volumes, several initiatives are taking place to improve this dimension of sustainability.

In the EU, this topic is particularly crucial for two primary reasons. First, the Waste from Electrical and Electronic Equipment (WEEE) Directive, which categorises and sets clear targets for the collection and recycling of all WEEE, includes solar PV components in its scope (examined in more detail in Chapter 3.3). Second, an increasing number of PV systems are approaching the end of their lifespan or are being revamped or repowered with newer and more efficient technologies. Revamping and repowering refer to the replacement of old PV system components in a power plant with newer ones to enhance its overall performance. Revamping involves component replacement without substantially altering the plant's nominal power, whereas repowering involves increasing the plant's capacity.[52] Solar PV repowering activities continue to grow; the solar sector has developed best practices to guide these initiatives. For more technical guidance, consult SolarPower Europe's End-of-Life Management Best Practice Guidelines.[53]

Notably, when PV systems are decommissioned, the lifespan of the modules can be extended, giving them a "second life", a practice that is described as 'reuse' under the Waste Framework and WEEE Directives. Activities on this field are described in Chapter 3.2.

Currently, the earliest EU PV systems, which were installed during the feed-in tariff schemes in the mid-2000s, have been in operation for 15 to 20 years. Thus, the EU solar PV sector is experiencing an unprecedented surge in revamping and repowering activities, aimed at improving the performance of existing large-scale solar PV systems by replacing old PV modules and inverters with newer, more efficient, and higher-performing ones. This approach contributes to an increasing number of PV modules being decommissioned before they reach their expected lifespans.

The premature replacement of PV modules constitutes a significant sustainability trade-off. On the one hand, shortening the lifetime of long-lasting products goes against the circular economy principles of waste avoidance and reduction. On the other hand, the steep advancement in solar PV technology has allowed the sector to increase the efficiency and performance of today's products. In this regard, the sector engages in revamping and repowering activities that replace old PV system components with newer ones to enhance its overall performance. While these activities may lead to the early generation of PV waste, it also enables PV systems to produce much more energy, contributing to a higher reduction of energy-related GHG emissions.

The early replacement of PV modules also presents new opportunities for optimising the performance of existing PV assets without requiring new land. Simultaneously it poses challenges for operation and maintenance service providers, local waste consortia, and recyclers who must collect and properly handle the incoming volumes of decommissioned PV modules.

Regarding the inverters, age and wear increase the likelihood of failures and breakdowns. If the warranty of a device has expired, manufacturers or service providers offer repair and spare parts services. The new components might also increase the efficiency of an older inverter.

Both revamping and repowering activities present challenges and opportunities. Developers considering premature upgrades to optimise their fleet performance should carefully evaluate the sustainability trade-offs.

51 SolarPower Europe (2024): Global Market Outlook 2024-2028.
52 SolarPower Europe (2021): O&M Best Practice Guidelines, Version 5.0.
53 SolarPower Europe (2023): End-of-Life Management: Best Practice Guidelines.

Approaches and best practices

REPLACE ONLY PART OF THE PV SYSTEM

Focusing on partial replacement instead of replacing the full solar PV system enables the integration of newer, more efficient technology, while keeping a relatively low embedded carbon footprint of new materials or components. However, it is also recommended to replace more modules than technically necessary, as this ensures that old modules remain available as spare parts for future use.

MAKE SURE NEW MODULES ARE COMPATIBLE WITH EXISTING MOUNTING STRUCTURES

Before proceeding with revamping or repowering solar PV parks, it is crucial to assess the compatibility of new modules with the existing mounting structures. Keeping existing mounting structures is preferable; high-quality and durable mounting structures provide maintenance-free support for the initial project design stage and through subsequent revamping and repowering phases. Durable mounting structures use materials, such as galvanised steel with appropriate zinc coating thickness, to withstand multiple repowering cycles over the PV system's lifespan. More about the choice of durable mounting structures can be found in Chapter 1.3.

Conducting a structural assessment is necessary to ensure that the mounting structures meet the specific criteria for weight, load capacity, and adaptability for new modules and to proactively adjust them, such as by repositioning them or adding purlins to accommodate larger new-generation modules. These interventions conserve materials and enhance the sustainability of the revamping or repowering process.

CARRY OUT COMPREHENSIVE ELECTRICAL PLANNING ACTIVITIES

When replacing PV modules, it is crucial to ensure that the electrical design is aligned with the specifications of the new modules, including power, voltage, and connector types. Mixing different electrical characteristics within the same inverter or Maximum Power Point (MPP) tracker to minimise inefficiencies and potential issues should be avoided. Reviewing regulatory requirements and ensuring proper testing of the entire system post-repowering is also key to comply with safety standards.

Conversely, prior to selecting new inverters, it is essential to ensure that they are compatible with the existing physical communication cables and that the data logger can support the new inverter's data protocol. If this is not the case, updates or replacements may be necessary. Additionally, it is important to consider the mechanical installation requirements and grounding system integration to enable compliance with applicable standards, ensuring that all components function harmoniously. A proactive approach will minimise disruptions during installation and optimise the performance of the solar PV system.

DEVELOP INVERTER REPLACEMENT STRATEGIES

When planning inverter repowering, an assessment of the partial exchange of inverters is possible. Some manufacturers or service providers offer repair and spare parts services. New components increase the efficiency of an older inverter (e.g. by replacing an old control board with a new device with better performance characteristics, such as MPP tracking). This can potentially reduce the overall costs, but it can also increase the complexity of the electrical design or the integration of two different inverter types into one communication concept on-site. Replacing inverters with the same power class is easier for the DC and AC integration. Replacing multiple devices with one that has a larger power class can increase the system efficiency and reduce the component costs, as well as future maintenance costs. If an identical replacement inverter, repair services, or spare parts is not available, the use of a new component is necessary.

REFER TO EXISTING GUIDELINE DOCUMENTS

Additional approaches and best practices for revamping and repowering in the solar PV sector have recently been prepared by SolarPower Europe's Lifecycle Quality workstream through the End-of-Life Best Practice Guidelines, which contain additional technical specifications for effective end-of-life strategies.[54]

54 SolarPower Europe (2023): End-of-Life Management: Best Practice Guidelines.

Case studies

SONNEDIX plant revamping in France

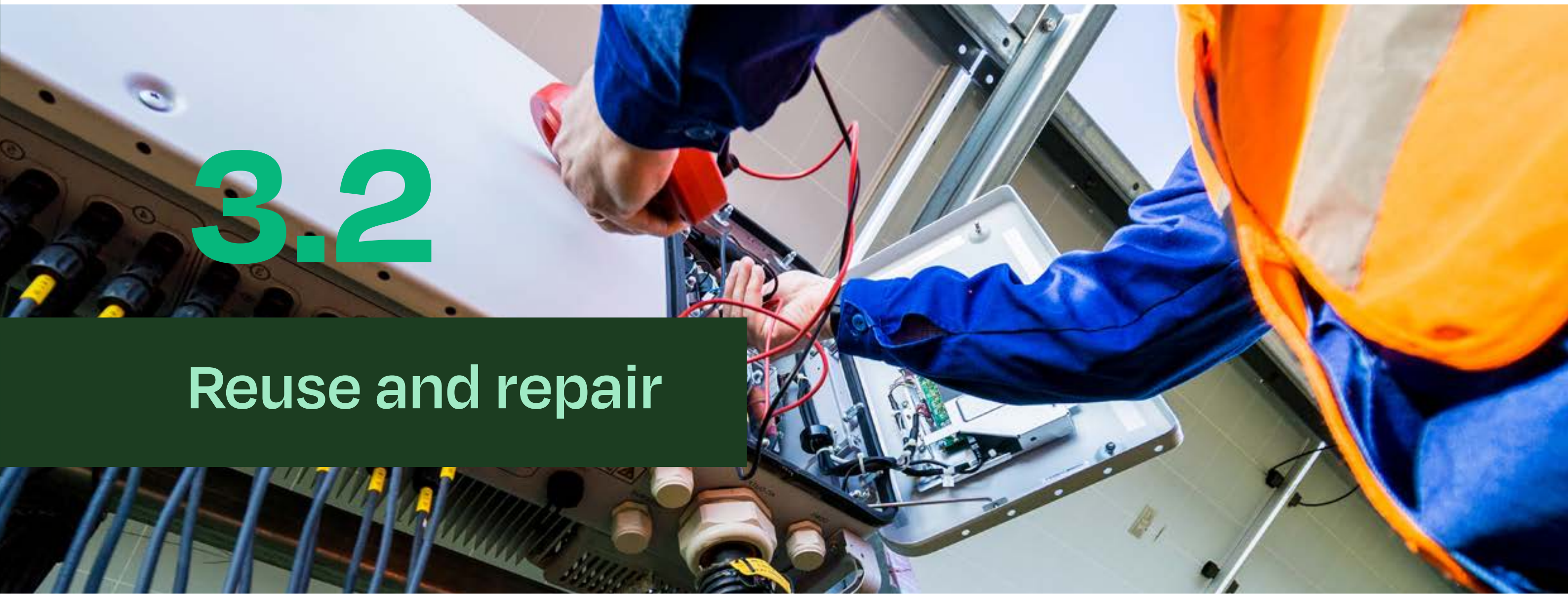
Sonnedix, the owner of the Saint Martin Lalande solar plant in the Aude department in southern France, commissioned a revamping project to BayWa r.e., originally built in 2011. The repowering project took place in 2019 and aimed at finding and implementing the optimal revamping solution for a solar plant with a total installed capacity of 5.4 MW. It featured 60,000 amorphous-silicon thin-film PV modules, which were over ten years old and with a high risk of underperformance.

Following a careful assessment of the site, BayWa r.e. proposed to replace the old PV modules, keep the existing galvanised steel mounting structures, and only adapt them, when necessary, to support the new modules. They also suggested maintaining the existing central inverters and designing the new solar PV system to ensure that the electrical characteristics were compatible.

The project came with a series of challenges, including working on a live site, keeping the plant partially operational to provide output during the revamping process, delivering the project in a timely manner, implementing a sustainable disposal process to recycle the old modules and the materials that were decommissioned. However, the project was successfully completed and exceeded expectations. Due to the increased efficiency of the new modules, the plant needed less land and the authorities approved a 10% increase in the total installed capacity, bringing it to 5.9 MW. Therefore, a new plant layout was produced to optimise these two conditions, leading to enhanced land use.

Within six months, the 60,000 old thin-film modules were replaced with 18,000 new, more efficient crystalline modules. This process was carried out in several phases to ensure that the plant remained operational at a minimum of 65% of its usual production.

With the new modules installed during the revamping, the plant has achieved improved efficiency. An annual measured operation revealed that its average performance ratio has increased by 37.1%, while its energy efficiency has improved by 38.1%. The original feed-in-tariff has been maintained, allowing the financing of the revamping. Additionally, due to the increased efficiency of the newly-installed modules, around half of the land has been redirected towards repowering. Further to the original installation, an additional 4.1 MW PV system has been installed between 2023 and 2024. Upon completion, the area that once hosted 5.4 MW now accommodates a PV system with a capacity nearing 10 MW.



3.2 Reuse and repair

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Context and background

As illustrated in Chapter 3.1, currently a comparatively small but growing volume of solar PV module capacity installed in the EU reaches the end of its economic lifetime and enters the end-of-life phase. While part of this decommissioned capacity presents damages or failures and is destined to become waste, a significant portion of it remains in good operating condition and has potential to contribute to decarbonising Europe's electricity. For this reason, the solar industry is looking with increased interest into ways to efficiently sort, repair, and reuse these solar PV components. This area becomes even more relevant as the sector notices an increase in repowering and revamping activities, whereby the decommissioning of PV products is mostly due to economic considerations rather than failures or damages (see Chapter 3.1).

Preparing functional PV modules or inverters for reuse not only prevents waste and pollution and unlocks economic benefits, but it also serves as a means of complying with existing legislation and contributes to the sustainability and circularity of the sector.

'Preparing for reuse' is defined in the European Waste Framework Directive (WFD) as "checking, cleaning, or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be re-used without any other pre-processing". Reuse is referred to as "any operation, by which products or components which are not waste are used again for the same purpose for which they were conceived". Recovery is defined as "any operation the result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy." Within the current WEEE requirements, Category 4, which includes PV modules and inverters larger than 50 cm among other EEE, must achieve an 85% recovery target and an 80% preparation for reuse and recycling target. However, the same Directive does not clearly define how this target should be met. Moreover, currently there is no standard, norm, or technical specification related to the preparation for reuse of PV modules, although there is a European norm for electrical and electronic equipment consuming electricity (EN 50614-2020 Requirements for the preparation for reuse of waste electrical and electronic equipment).

To tackle some of the challenges of preparation for reuse of PV modules, a guideline for preparing PV modules for reuse was published in 2022 by the Horizon 2020 EU-funded project CIRCUSOL. The guideline was built upon the initial proposal outlined in a May 2020 study on reused PV modules commissioned by PV CYCLE and delivered by Imec and Bifa Umweltinstitut.[55] It outlines an initial attempt to define the steps required for the application of several testing methods to determine what constitutes a functional PV module, ensuring sufficient quality and safety while maintaining cost-effectiveness. This document was the baseline of a qualification and triage framework for PV reuse within the TRUST-PV[56] research project (see details in the following section) and is currently being used by the International Electrotechnical Commission's Technical Committee 82 (IEC TC 82), which is in the process of drafting a Technical Report "IEC TR 63525 ED1 Reuse of PV modules and circular economy".

55 PV CYCLE (2020): Study of re-used PV modules.
56 https://trust-pv.eu/

The findings are anticipated in early 2025 and should become the basis for the Committee to decide if a Standard or Technical Specification is required.

Initiatives towards PV reuse are also taking place at a Member State level. In France, Soren contributes up to 5% of the WEEE contribution fee in subsidising reuse operators, helping them resell certified second-life modules at a competitive price. Currently, the PRO is also developing a set of technical criteria for PV reuse that could be used at a European and national level, and which are compatible with EU norm 50614:2020, which sets out the requirements for preparing WEEE products for reuse. In Germany, the Standardisation Commission for Electrical, Electronic & Information Technologies (DKE) is currently drafting guidelines for correctly preparing second-hand PV modules for reuse.

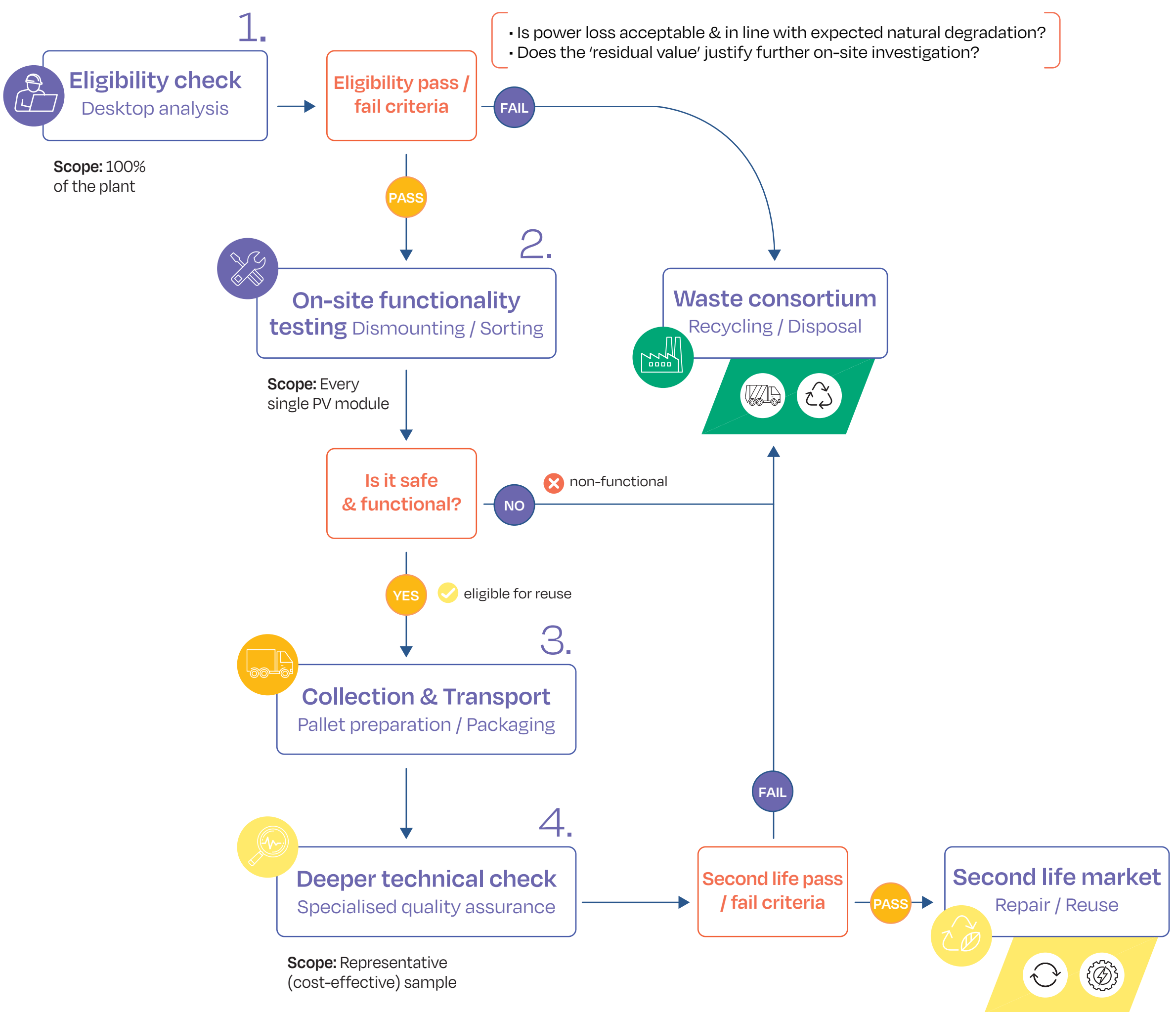
Approaches and best practices

PV MODULE REUSE

To qualify for reuse, PV modules should undergo functionality testing procedures that are technically feasible, cost-effective, and adapted to the second-hand market, giving priority to safety, and secondarily to performance and reliability. To be prepared for reuse, PV module functionality should be tested on-site according to specific technical criteria (e.g. IEC 61215). On the contrary, replicating the same qualification procedures for new PV modules should be avoided as it would be prohibitively expensive and technically challenging.

The suggested tests and steps to prepare PV modules for reuse are illustrated in Figure 10 and described below.

FIGURE 10 PROCEDURES FOR PREPARATION FOR REUSE



Source: BayWa r.e.

As a first step, the **eligibility check (1)** includes an analysis based on electrical and weather variables and O&M historical data to calculate and estimate the performance loss of the entire plant or sections of it (at transformer, inverter, or string level). This assessment is intended to be conducted in the office to determine whether additional checks on-site should be performed. Additionally, known failures should be evaluated based on annual or monthly reports and punch lists provided by the O&M service provider and/or asset manager, such as IR thermographic and I-V curve measurement campaigns that are typically conducted contractually at least once a year. Consequently, O&M service providers that follow high-quality monitoring practices in accordance with international standards and which have quality assurance evidence, should be able to avoid costly diagnoses. This assessment should leverage all existing documentation that outlines the history of the plant, not limited to O&M data alone. This approach will help reduce additional costs.

Secondly, the **on-site functionality testing (2)** step is intended to be carried out by site technicians shortly before and/or while decommissioning solar PV panels (e.g. during revamping or repowering activities). It includes dismounting, sorting, and on-site temporary storage. Functionality testing should be done for every single module, including but not limited to dedicated visual inspection, insulation resistance test at string box level or panel level, if feasible, and possibly low-cost infrared thermography with a hand-held device or smartphone. This step should benefit from the fact that field technicians are already on-site executing module substitutions for O&M activities. Once the modules are dismounted and the functionality testing is completed, sorting into two main categories is possible: non- functional and eligible for reuse.

After sorting modules into the two different categories, **the collection and transportation (3)** step follows. This step is carried out through proper pallet preparation and packaging to avoid further damage and ensure that the shipment is not confused with e-waste. It is suggested that a differentiated packaging procedure is put in place for functional and non- functional modules. To minimise additional packing costs during revamping activities, it is recommended to reuse the pallets and cardboard of the new batches of modules that are being installed.

Lastly, a **deeper technical check (4)** provides definitive and accurate evidence on the health status of modules that have been described as eligible for reuse in previous steps. Specialised quality assurance procedures (see Figure 11) should be applied to a representative sample to ensure that costs are kept at a manageable level. Based on this evaluation, the final value and price of PV modules can be set and agreed with the final client.

FIGURE 11 SPECIALISED QUALITY ASSURANCE PROCEDURES FOR MODULES DESTINED FOR REUSE

Visual inspection	IR thermography	STC measurements	EL imaging	Insulation testing
• Visual inspection is a non-destructive assessment, which provides information regarding optical appearance of PV modules. It can be used as a contactless method for diagnosing some thermal and electrical failures in PV modules.	• Infrared (IR) imaging is a non-destructive measurement technique, which provides fast, real-time, and two-dimensional distribution of characteristic features of PV modules. It can be used as a contactless method for diagnosing some thermal and electrical failures in PV modules.	• Measurements of PV array I-V characteristics under actual on-site conditions and their extrapolation to Acceptance Test Conditions (ATC, i.e., STC) can provide data on power rating and verification of installed array power and performance relative to design specification.	• EL is an optical procedure for a qualitative assessment of module failures. EL is particularly suitable for the detection and tracking of crack related issues, which can occur for example during module transportation.	• The insulation test measures currents between the electrically conductive parts in the modules and cables to ground. These residual currents must not exceed certain limit values in order to protect people, environment and the system itself.
1. IEC 61215	2. IEC TS 62446-3:2017	3. IEC 61215 & IEC 609044	4. IEC 60904-1-13	5. IEC 61215

Source: PI Berlin.

Having applied the steps mentioned above in a real case study, within the TRUST-PV project, some key takeaways should be highlighted:

1. On-site dry insulation testing might not be conclusive for reuse purposes, and it is recommended to perform wet insulation tests only when there are safety concerns as it is time-consuming. Broken modules with clearly compromised electric insulation can yield positive insulation results without the presence of water;
2. Sampling is feasible, but a criterion for the maximum variation in module power might be necessary. A final basic visual inspection of each PV module is required.

For more details of proposed eligible pass/fail criteria and examples of the steps 1 to 4 described above, please check SolarPower Europe's End-of-Life Management: Best Practice Guidelines.[57]

PV MODULE REPAIR

PV modules can fail due to natural aging or external damage, such as storms, hail, or electrical surges. While internal defects, like snail tracks and delamination are generally irreparable, external damage, including broken glass, microcracks, faulty bypass diodes, and burnt junction boxes can typically be repaired. Repairing PV modules is becoming increasingly important within the circular economy with a focus on components, such as frames, backsheets, and bypass diodes. However, the repair industry faces challenges due to the lack of standardised re-certification protocols, making warranty claims unreliable. Numerous standardisation activities on reuse, described in the previous section, will provide help in this regard.

Although recycling is currently the primary strategy for handling decommissioned PV modules, it is expected that a significant portion of future solar PV waste will result from premature failures, mainly due to manufacturing defects or damage during transportation. Studies suggest that up to two-thirds of these modules could be repaired or refurbished, redirecting around 50% of waste from recycling. The industry remains largely informal, with repairs mainly carried out by independent companies, lacking support from original manufacturers, and facing significant testing costs. Projects, such as CIRCUSOL, TRUST-PV, and SUPERNOVA aim to establish better standards for testing and certifying repaired modules to support the growing refurbishment market. Additionally, more efforts are required to assess the economic viability of reuse and identify the most optimal business models.

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57 SolarPower Europe (2023): End-of-Life Management: Best Practice Guidelines.

BUSINESS MODELS FOR SECOND-LIFE SOLAR PV PRODUCTS

Circular business models can enable resource efficiency, lifetime extension, and reuse of products, and have the potential to capture the residual value from by-products or 'waste'. However, circular business models covering the reuse of PV modules lack visibility. B2B and B2C reuse models in the solar PV sector are noticed in some European countries, where, for example, second-hand traders act as facilitators through online market platforms. Traders might also be involved in repair and relabelling activities.

Examples of circular business models focused on reuse include:

- **B2B models:** Turnkey solutions (service-centred approach) for C&I rooftops, carports, leasing, charging stations for e-mobility, and public lighting (road, bus stops), etc.
- **B2C models:** Trading of decommissioned PV components for household rooftops (product-centred approach) through an e-commerce platform for installers, leasing, and others.
- **Donation models:** Donation of decommissioned PV components for charity institutions in underdeveloped regions for off-grid applications (irrigation, lighting, clinics, and schools).
- **Sustainability-driven customers:** Sale to customers that view sustainability as a top priority in their purchasing decisions, such as social entrepreneurship organisations, public procurement bodies, and others.

INVERTER REUSE

Reusing solar PV inverters is crucial for sustainable energy management. Extending the service life of inverters can be achieved through refurbishment and the second-hand market. Refurbishing older or defective inverters involves replacing defective parts and thoroughly testing the device to ensure it is fully functional. Establishing a robust infrastructure for purchasing and selling used inverters can further extend their lifespan and reduce the need for new products. Reusing inverters conserves valuable materials and energy, and second-hand inverters are often less expensive compared to newer ones, lowering the overall solar PV system costs.

The refurbishment process begins with an assessment and diagnosis, including visual inspections and functional testing to identify and replace damaged components. Cleaning, updating firmware, and rigorous testing ensure that refurbished inverters meet original performance standards. Quality assurance measures guarantee the reliability of second-hand inverters, and educating customers on their benefits builds market trust.

Promoting eco-friendly refurbishment processes minimises environmental impact. Offering warranties and ongoing technical support enhances customer confidence. Developing a second-hand market requires robust infrastructure and partnerships with component suppliers and recycling centres, while participating in industry networks ensures that practitioners remain updated on best practices and technological advancements.

However, implementing reuse strategies poses challenges. Companies may need to develop new business models, reorganise processes, and invest in new technologies and training. Setting up infrastructure for reuse and refurbishment can be costly, requiring specialised equipment and skilled personnel. Additionally, market demand for reused inverters is uncertain, as customers may have concerns about the reliability and lifespan of used equipment. Ensuring the availability and approval of old inverters is also an important factor to consider.

In conclusion, by embracing reuse strategies and overcoming challenges, companies can contribute to environmental sustainability, reduce costs, and meet the growing demand for renewable energy solutions. Close collaboration amongst stakeholders is essential to promote the reuse of solar PV inverters and foster a more sustainable future.

INVERTER REPAIR

Repairing inverters involves a systematic approach and several key strategies to promote ease of repair and maximise benefits. Firstly, promoting modular design is essential, allowing for the easy replacement of individual components without necessitating the replacement of the entire device. This design approach, coupled with the commitment to maintaining a steady supply of spare parts, ensures that repairs can be carried out efficiently as needed.

Furthermore, repair processes encompass on-site repairs, which significantly reduce the need for transporting inverters and associated costs. Equipping technicians with adequate training and instructions enables them to address common faults and defects directly on-site, enhancing repair efficiency. Manufacturers play a crucial role in this by providing comprehensive training and detailed repair instructions to ensure effective repairs by technicians and installers.

Repairing inverters instead of replacing them offers various benefits, including the significant reduction of e-waste, and economic advantages as repairs are typically more cost-effective than purchasing new devices, thereby lowering the operating costs of solar PV systems.

Implementing repair strategies presents several challenges. The initial investment required to establish and maintain an effective repair infrastructure can be substantial, encompassing expenses related to training, tools, and spare parts. Moreover, logistical challenges may arise, particularly in organising and conducting on-site repairs, especially in remote or inaccessible areas.

Despite these challenges, promoting ease of repair in solar PV inverters through modular design, spare parts availability, and comprehensive repair processes is crucial for maximising the benefits of repair over replacement. By addressing these challenges and implementing effective repair strategies, companies can contribute to environmental sustainability, reduce operating costs, and prolong the lifespan of PV systems.

REUSE OF MOUNTING STRUCTURES

The reuse of mounting structures can contribute to reducing the carbon footprint of solar PV systems. However, there are several challenges that prevent the uptake of this practice. In particular, regarding steel mounting structures, the reuse of the posts is rarely taken into consideration, as they tend to deform when driven into the ground, making them difficult to reuse. Without a solution to prevent deforming, reusing these components is unlikely to become a viable option.

In regard to the upper parts of the mounting structures, the conditions differ as these components can be easily disassembled and reused. When produced with a thick and strongly bonded layer of zinc, galvanised mounting structures can last several decades, increasing the likelihood for their reuse. However, disassembling the upper parts for reuse is a lengthy procedure and leads to higher costs than the decommissioning for recycling. Hence, this activity is uncommon, unless the asset owner is particularly focused on sustainability.

When reuse of mounting structures is sought, it should be first assessed whether the new modules weigh equal to, or less than the older ones. It should then be verified if the mounting structures pass statistical tests (load and sail capacity tests), and finally assessed if they can house the design of the new modules. Additionally, the thickness of the galvanised coating should be evaluated to determine their anticipated lifespan and whether the structures can be reused.

After several decades of use, mounting structures may be re-galvanised before being put back into service. In this case it is necessary to initially assess if re-galvanising is feasible. Steel products that have been batch galvanised according to EN ISO 1461 can be repeatedly reused or re-galvanised – a practice that also applies to mounting structures. Mounting structures that have been batch galvanised also require very little or no maintenance.

Fronius Repair Centre International. © Fronius

Case studies

Inverter repair centre

'Repair over disposal' is a principle deeply embedded in Fronius' practices. This commitment is evident in the development of innovative service concepts across all areas, ensuring products can be repaired rapidly and to a high standard. This foundation is ingrained in the early stages of the product development. Fronius offers repair options for its inverters. The GEN24 Plus inverter model, for example, enables the exchange of various components, such as the fan, the data communication unit (both located on-site), 4 varistors on the power stage set, as well as the replacement of the complete power stage set (both located at the Fronius International Repair Centre). These repairs reduce the need to replace the entire inverter, conserving new raw materials and extending the life service of the product.

For devices beyond repair, Fronius dismantles and separates the components, and hands them over to waste disposal companies for recycling.

SOL-EXTEND project

A significant challenge in solar PV reuse is effectively identifying defects and determining the feasibility of repairs for aging modules. In collaboration with the French research institute **CEA-INES**, **ENGIE**, and other partners, the SOL-EXTEND project addresses this challenge by focusing on the repair and reuse of PV modules.

The project aims to establish a comprehensive maintenance process that bridges the gap between defect identification in modules and their recycling. This approach offers the opportunity for on-site repairs, enabling the reintegration of functional modules back into the power plant. This method serves as a complementary solution to repowering or replacing modules with custom-made options, which can be prohibitively expensive.

Furthermore, SOL-EXTEND effectively mitigates the issue of 'sprawl' in power plants, an issue where aging modules are not replaced due to their incompatibility with newer modules of varying sizes and power outputs. By extending the lifespan of existing modules through repair, this management strategy not only enhances operational efficiency but also reduces the carbon impact associated with module manufacturing and disposal. Overall, SOL-EXTEND represents a forward-thinking approach to sustainability in the solar PV sector that maximises the value of existing assets.

RENEW project

Both technical and economic design of the PV second-hand market are key for a wider uptake of PV module reuse in the future. The RENEW research project, carried out by **ZSW** and other project partners, and funded by the German Federal Ministry for Economic Affairs and Climate Protection (BMWK), focuses on both aspects by developing a reliable and comprehensive qualification process for used modules to test their functionality and safety for further use. In this context, a spatially resolved insulation testing replaces the previous insulation testing methods in order to identify insulation faults on used modules much more reliably. The modules that show a defect during initial qualification should be repaired, if possible. These repair methods should be qualified through laboratory tests and accelerated ageing tests. The acknowledged significant issues with defective polyamide-based backsheets, resulting in the early failure of around 10 GW of PV modules, put the focus on repair solutions for defective backsheets. The project explores additional aspects, such as the implementation and application of these methods, as well as the associated processes and the reuse of PV modules on-site. The aim of the project is to reliably evaluate the quality of used PV modules through a new insulation testing method and to implement repair methods for modules that fail prematurely. This objective seeks to maximise the amount of PV that is in operation until the end of its service life, initiating a sustainable circular economy in the solar PV industry.

Case studies

SOLMATE project

Reusing PV modules conserves valuable materials and offers new economic opportunities, particularly when new business models are developed. EU-funded project SOLMATE aims at facilitating a secure, affordable, and sustainable energy transition, particularly by advancing clean energy technologies, like solar PV modules and EV batteries. These technologies, which are crucial for the energy transition, rely heavily on critical raw materials, which poses challenges as the demand for metals grows.

To address these challenges, the project consortium, including **CEA-INES**, **ENGIE**, **Soren**, **Tecnalia**, and other partners, is dedicated to establishing a circular economy for second-life PV modules and EV batteries, ensuring that products at the end of their life are reused or recycled, in line with the Waste Framework Directive. The project focuses on repurposing retired batteries and PV modules, extending their lifespan, and, when repurposing is not feasible, ensuring proper resource recovery through recycling.

SOLMATE also seeks to develop decentralised energy systems that are reliable and cost-effective, with applications in emerging markets, such as Agri-PV and low-income communities. Over four years, the project addresses various challenges, including low-cost automatic dismantling, testing, and certification protocols. It introduces a three-stage approach: technology development, testing and validation, and demonstrating low-cost energy systems. SOLMATE contributes to creating a sustainable supply chain and promoting circular business models for clean energy technologies.

TRUST-PV project

TRUST-PV addressed key challenges in the solar sector, such as managing solar PV waste, re-using PV modules, and fostering a second-hand PV market in Europe. To tackle these issues, the project consortium led by EURAC and consisting of partners, such as **BayWa r.e.**, **3E**, **Above**, **Enel Green Power**, **Huawei**,**PVCase**, **TÜV Rheinland**, and **SolarPower Europe** focused on improving solar system performance through innovative technologies, like advanced aerial inspections, enhanced forecasting services, and artificial intelligence. This project, which ended in August 2024, highlighted the essential role of operation and maintenance service providers in extending component lifetimes that supports a more sustainable solar sector. Activities within TRUST-PV included evaluating business models for PV module reuse in Italy and adapting a methodology to reuse PV modules in a 12-year-old PV plant case study.

SUPERNOVA project

Building on the successes of TRUST-PV, SUPERNOVA responds to the growing need for expanded reuse methodologies beyond PV modules to maximise resource efficiency in the solar industry and enhance circular economy practices across the entire PV lifecycle. Led by **EURAC**, the project consortium includes **BayWa r.e.**, **CEA**, **Tecnalia**, **Statkraft**, **3E**,**Above**, **CSEM**, **PVCase**, and **SolarPower Europe**.

Case studies

PV module reuse and recycling centre

In 2022, the company ReTechPV Portugal, a member of **APREN**, acquired a former PV module factory in the city of Setubal, close to Lisbon, that belonged to Eurener Portugal. It then promoted and licensed the facilities for refurbishment and recycling of PV modules. According to the company's data, 90% of all faulty PV modules would be repairable through ReTechPV solutions, that work mostly with Tier 1 producers, offering a 10-year warrantee for the repaired products (235 W and 230 W). Backsheet degradation represents 70% of module faults. Others include broken glass, insulation, delamination, snail trails, soiling, broken cells, poor string connection, potential induced degradation, backsheet chalking, hot spots, multijunction box, micro-fissures, holes, and scratches. Unfortunately, ReTechPV, which had been present in Germany, Spain, Bulgaria, USA and Portugal, concluded their activities in Portugal in 2023, due to the lack of funds and support.

Marketplace for surplus and second-life products

Although it is widely agreed that solar PV panels have a long and useful life, which can reach up to 25 years, there is a growing trend towards their premature decommissioning as part of the technological conversion of solar power plants. With the appropriate technical supervision, around half of these PV modules can be reused in less demanding applications, given that they continue to have approximately 80% of their initial conversion capacity.

To incentivise this practice, Electrão, a member of **APREN** has launched the platform "Onde Doar" that aims to promote the donation of electrical equipment, batteries, furniture, textiles, and other products, which are mostly new but also 'used in good condition'. In this instance, the producers of this type of goods can inform about the surplus of their production and gift it to credible social or environmental institutions – an example of responsible and effective action for the prevention of additional waste production.

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3.3 Waste management and recycling

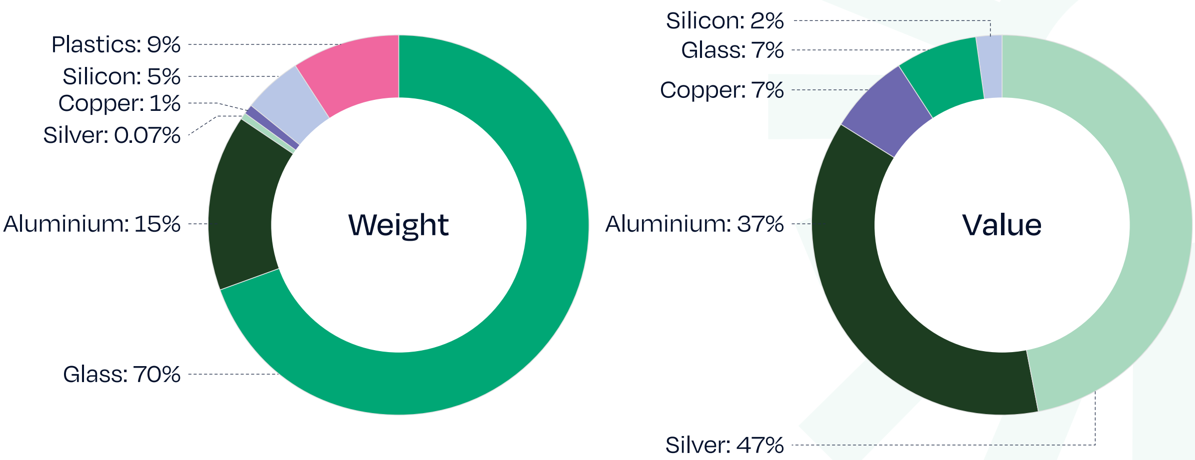
© BayWa r.e.

Context and background

As introduced in Chapter 3.1, the rapidly expanding solar industry faces the long-term challenge of handling very large volumes of solar PV waste, once the currently operating solar PV systems eventually reach the end of their operating lifetimes. In the EU, it is estimated that 14.3–18.5 million tonnes of PV waste will be generated by 2050[58], although these forecasts are based on conservative assumptions on projected solar PV installed capacities. The United Nations Institute for Training and Research (UNITAR) assessed the status of solar PV waste in 2022, finding that 0.6 million tonnes of PV waste is generated globally, with only 17% documented as collected and recycled.[59]

Despite the challenges in assessing future solar PV waste streams, which depend on several factors, it is clear that these growing waste streams also provide remarkable economic opportunities. Crystalline silicon PV modules, which are mainly composed of glass, aluminium, and plastics, also contain a small fraction of high valuable raw materials, such as silver, copper, and silicon (see Fig. 12). Notably, there is a stark difference between

FIGURE 12 WEIGHT AND VALUE OF MATERIALS OF PV MODULES



Source: Solar Materials.

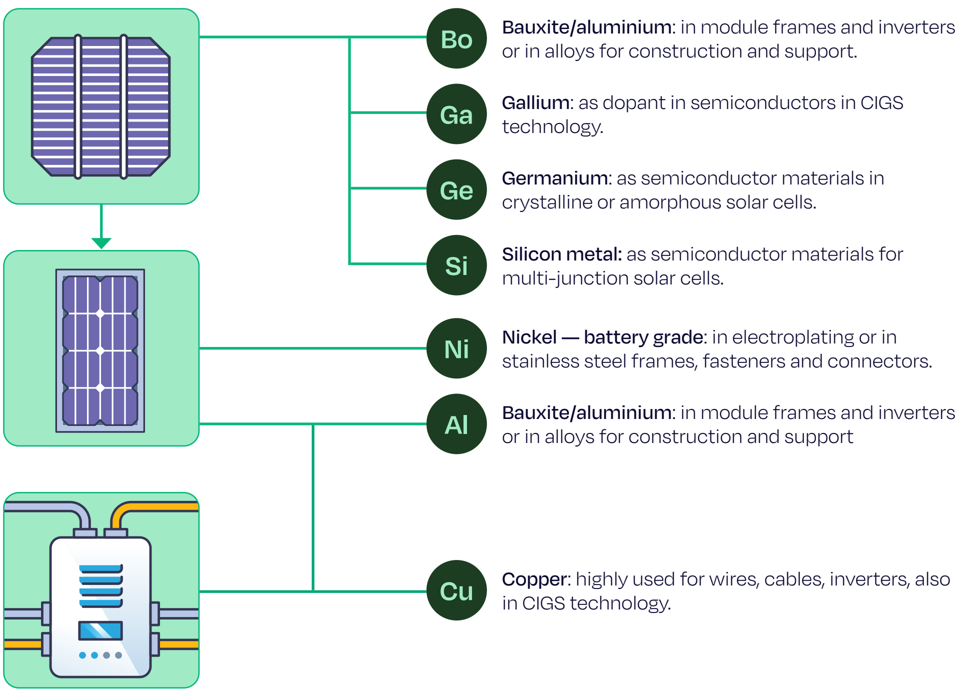
58 Kastanaki et al. (2022): Energy decarbonisation in the European Union: Assessment of photovoltaic waste recycling potential.
59 UNITAR (2024): The global e-waste monitor 2024.

the material breakdown by weight and by value. Some assessments indicate that glass, which constitutes 70% of the module's weight, only contributes to 7% of its value. By contrast, silver makes up less than 0.1% of weight, but it captures 47% of the material value. IRENA is projecting the global value of solar PV recovered materials globally to be 8.8 billion USD[60], while other studies provide a much higher estimate, projecting 22 to 27 billion USD of profit for Europe only.

The advantage of solar recycling goes beyond the mere economic value of the recycled materials. Crystaline silicon modules, a PV technology with the largest market share in the EU, use materials, such as silicon metal, antimony, and copper, which are all listed as Critical Raw Materials (CRMs) in the EU (Fig. 13). Under the **Critical Raw Materials Act**[61] (CRMA), the European Commission highlighted the importance of ensuring access to a secure and sustainable supply of CRMs, setting benchmarks for domestic capacities, including recycling.

The EU aims to meet three key benchmarks under the CRMA, focused on selected Strategic Raw Materials (SMRs) – a sub-category of critical raw materials: extracting at least 10% of the SRMs the EU consumes annually, supplying the processing capacity of at least 40% of the EU annual consumption of SRMs, and recovering at least 25% of SRMs from recycled products, while significantly boosting the amount of strategic raw materials recovered from waste. SRMs present in solar PV products are illustrated in Fig. 13.

FIGURE 13 RAW MATERIALS USED IN SOLAR PV TECHNOLOGIES



Source: JRC, European Commission, SolarPower Europe.

60 IRENA (2023): World Energy Transitions Outlook 2023: 1.5°C Pathways.

61 European Union (2024): Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1724 and (EU) 2019/1020.

In this context, solar PV recycling becomes an important activity for EU strategic autonomy, as well as a source of materials for the EU solar industrial ecosystem.

To harness the economic and strategic potential of solar PV waste, EU countries need to follow the Waste Framework Directive and the WEEE Directive. Across the EU, companies which place solar PV modules on the market fall under the scope of the Extended Producer Responsibility and, therefore, must take responsibility for their waste management, including separate collection, sorting, and treatment operations. This rule has been in place since 2014 under the WEEE Directive. For inverters, these responsibilities have been required since 2005 as part of the first WEEE Directive. Companies can either manage these obligations individually or by joining a Producer Responsibility Organisation (PRO).

All EU countries have transposed the recast of the WEEE Directive into their national law. Since 2019, the minimum annual collection rate is set to 65% of the average weight of the electric and electronic equipment placed on the market within the three preceding years in the concerned Member State, or 85% of WEEE generated within the Member State's territory. Moreover, 80% of the collected waste needs to be prepared for reuse and recycling. Given that the waste from electrical and electronic equipment regulated by a Directive is only binding to each Member State, and only the WEEE law of each Member State is binding towards the companies, there is a significant variety of implementation at a national level in each Member State, as described in Box 5.

An evaluation of the WEEE Directive has started in 2023 and is planned to be completed by 2026. The assessment may potentially lead to a revision of the categorisation of the solar PV modules, which are currently listed under the 'large equipment' category. The revised legislation may enable a separate category with specific collection and recycling targets for PV modules. It can be expected in the future, as the Commission is planning a new Circular Economy Act, with the aim to foster the market demand of secondary raw materials.

BOX 5 WEEE DIRECTIVE IMPLEMENTATION INTO NATIONAL LEGISLATION

The Extended Producer Responsibility on waste of electrical and electronic equipment is covered by a Directive and therefore, it solely defines the minimum requirements for the Member States, which subsequently transpose these requirements into national legislation. Therefore, the WEEE Directive has been transposed into national legislation in various ways.

In **France**, all solar PV modules are classified as household equipment. Extended producer responsibility for solar PV modules is organised by the PRO entity Soren. PV modules have been transposed into the scope of national WEEE regulations by Decree 2014-928. France classifies all solar PV modules as household equipment, since the products are manufactured for dual use. The collection system is fully financed by a visible contribution fee, which is paid by the producers each time a new equipment enters the French market for the first time. The contribution fee is strictly proportional to the volume put on the market. Collection of end-of-life modules is, therefore, free of charge to the waste owner, regardless of the brand, technology, or age of the equipment. The solar PV modules that entered the market before the introduction of the WEEE Directive for PV modules are also covered. Collection is done either through a collection point for volumes less than 40 modules, or directly on-site for volumes over 40 modules. Moreover, new non-price criteria which will enter into force in January 2025 offer a discount to the WEEE contribution fees for compliant manufacturers. These criteria include a carbon footprint threshold, rate of recycled content, reduced use of critical raw materials, and limits of potentially toxic material content.

In **Belgium**, all solar PV modules are also classified as household equipment. Extended producer responsibility for PV modules is organised by the PRO, PV CYCLE Belgium. PV modules have been transposed into the scope of regional WEEE laws in the Flemish, Brussels, and Walloon Region. The collection and waste treatment are fully financed by a visible contribution fee, paid by the producers when they put a PV module for the first time on the territory of Belgium. The contribution fee is strictly proportional to the volume placed on the market. Collection of end-of-life modules is, therefore, free of charge to the waste owner, regardless of the brand, technology, or age of the equipment. The solar PV modules that entered the market before the introduction of the WEEE Directive for PV modules are also covered. Collection is done either through a collection point for volumes less than 40 modules, or directly on-site for volumes over 40 modules. The PRO is obliged to set aside provisions which take into consideration the operational costs over a defined period, in case the PRO no longer exists, or if the producers no longer exist or stop selling PV modules within the Belgian territory. A representative of the public regional waste administration is present in the Board of Directors of PV CYCLE Belgium as an observer.

In **Italy**, the Coordination Centre WEEE (CDC RAEE) classifies solar WEEE into two types. PV modules placed in systems with a nominal capacity of less than 10 kW are classified as household solar electrical and electronic equipment (EEE). Producers are responsible for financing the delivery of household PV modules to municipal collection centres, as well as proper treatment, recovery, and disposal of the modules. These responsibilities apply if the installation of the solar PV plant was before 12 April 2014. As a result, household rooftop owners can bring their PV modules from installations under 10 kW to these public collection points free of charge.

Solar EEE generated by systems with a nominal capacity higher than 10 kW is classified as professional solar EEE. For PV modules installed before 12 April 2014, plant owners are responsible for financing their waste management of these modules, while producers are responsible after this date. The solar PV waste must be directed to an approved treatment facility.

Furthermore, for solar PV plants that receive incentives from the Italian Conti Energia, the Gestore dei Servizi Energetici (GSE) deducts a certain amount (10 EUR) per module from this incentive to cover the costs of the proper disposal of solar WEEE. For both residential and professional WEEE, the amount withheld by the GSE is identical, but with different timings for payment.[62]

In **Germany**, all PV modules are classified as household equipment. Extended producer responsibility for electrical and electronic equipment, including for solar PV modules, is through the E-waste law (ElektroG) directed to the individual producer. Producer Responsibility Organisations do not exist, and a visible fee is not viable. Collection of end-of-life modules is free of charge for the waste owner, regardless of the brand, technology, or age of the equipment, as long as the waste owner returns the PV modules to the public municipal collection points and the quantity is similar to a household volume. The Foundation EAR assigns the responsibility to each individual producer to handle, at their own cost, the delivery of empty receptacles and the collection and treatment of full receptacles of PV modules at approximately 1,500 public collection points. The collection and treatment of volumes originating from commercial, industrial, and large-scale solar PV power plants is borne by the producer, unless there is a prior agreement with the solar PV waste owner. In general, the financing approach is a 'Pay-As-You-Throw' (PAYT) model. Germany is the only country in the EU where a Financial Guarantee is required, covering the risk of the producer going bankrupt.

In **Portugal**, the PRO Electrão is licensed to organise and manage the Integrated System for the Management of Waste of Electrical and Electronic Equipment (SIGREEE), which also covers solar PV modules. In this context, on behalf of the participating producers and importers, Electrão has developed structured solutions for the collection, reuse, and recycling of solar PV waste. Recycling in Portugal is usually operated in generalist WEEE facilities. Electrão is collecting approximately 200 tonnes of PV modules annually, which are sent for treatment in two facilities selected and monitored by the PRO, achieving a recycling rate of approximately 90% (glass, aluminium, and copper).

For the case of inverters, there is a state-specific regulation in place, but typically these products are classified and handled as 'household electronics' or 'consumer electronics' by electronic waste companies, and a financial contribution must be paid by the inverter manufacturer to a national system to ensure proper management of the inverter at the end-of-life stage.

62 GSE (2023): Istruzioni operative per la gestione e lo smaltimento dei pannelli fotovoltaici incentivati.

Compared to some electronic products, **PV modules** have a potential to be **highly recyclable**, with current technical recycling rates of 90% or beyond. As showcased in Fig. 12, the weight of a crystalline silicon-based PV module – the majority of PV modules currently in the market – is broken down into about 70% glass, 15% aluminium, 9% polymers, 5% silicon, and 1% copper. The remaining materials inside the solar PV cells, including the metallisation paste, are only a small fraction, making up less than 1%. For the other solar PV technologies, the weight composition can be very different, but in general terms, the majority of the weight is attributed to the glass, the polymers, and the aluminium of the frame – except for frameless modules.[63]

In most cases, the waste treatment operations start with a collection and sorting process, which includes operations such as reception, bulking, sorting, and transferring to recovery or disposal centres. Sorting is a common step in waste treatment activities, performed to ensure that the waste input is suitable for subsequent treatment processes, to enhance recovery and recycling rates, and to improve the quality and purity of outputs for further use.

During the typical recycling process, the junction box, cables, and aluminium frame are initially mechanically-separated either manually or using an automated process. These components can be recycled following standard well-established routes for the copper in the cables and for the aluminium, while the plastic in the junction box can be recycled or typically incinerated.

For the rest of the solar PV module, recycling technologies are usually based on mechanical shredding, while its components, including glass, aluminium (in case the frame was not previously removed), and solar cells residue are usually isolated using a sorting process, such as Eddy current separator, optical sorter, sieving, and others.

To reach higher purity of secondary raw materials, shredding and milling technologies, combined with sorting processes, can achieve higher-purity and quality of the output fractions.

For high-value recycling routes, delamination technologies are usually based on mechanical, thermal, optical, or electrical process, allowing improved separation and fraction purity. Delamination methods include using hot-knife machinery, peeling off the PV modules by layers, physical-chemical treatment, and pyrolysis, while additional options are currently explored.

In the second phase, the sorted or extracted or recovered materials are further processed by mono-material treatment technology which shall result in material or product recycling or recovery or other recovery operations.

Regarding glass applications, glass could be cleaned and reused intact, but it is usually used as feedstock for packaging, foam, or potentially flat glass industries, depending on impurity levels. The third step in the high-purity recycling approach is the metal extraction to recover silicon, silver, aluminium, indium, copper, or other elements, depending on the solar PV cell type. It is typically based on chemical dissolution of the metals by leaching, followed by electrowinning, precipitation, or replacement processes. These procedures may not yet be profitable given the current market price of the recovered secondary products, but the recycling process is expected to become profitable in the near future.

In Europe, several companies develop innovative waste treatment techniques and set up dedicated solar PV module waste treatment and recycling lines. These activities help recover high-quality and high-value materials, which make up only a small percentage of a PV module's weight and strive to obtain glass of high-purity. In France, for example, the first industrial delamination line is in operation, chemically recovering silver and silicon. Across Europe, several recycling lines for PV are currently operating with capacity ranging from 4,000 to 50,000 tonnes. Plenty of these activities are explored in more detail in the case studies section.

The **recycling process for inverters** reflects their material composition. Metals, such as aluminium and copper, are used in the housing and internal wiring. The electronics inside include various semiconductors, diodes, and capacitors made from silicon, gallium, and germanium. Additionally, plastics and polymers are used for insulation and housing parts. Printed circuit boards (PCBs) are also present, containing small amounts of precious metals, like silver and gold.

63 IEA (2022): Special Report on Solar PV Global Supply Chains.

The recycling process for solar PV inverters involves manual disassembly, mechanical processing, material separation, and recovery and refining. During disassembly, easily-detachable components, like the housing, wiring, and other large parts, are separated. In the mechanical processing, remaining parts, such as transformers, are shredded to break down the inverters into smaller pieces. Lastly, using methods, including magnetic, eddy current, and density-based separation, materials are separated to metals, plastics, and other materials. During this step, iron, for example, is recovered using magnetic separation. Valuable materials, including copper, aluminium, and precious metals, are extracted and undergo various refining processes. Copper, for example, is melted down in copper smelters and refined into new, pure copper suitable for industrial use. Organic substances are usually incinerated, while individual components are generally not reused.

Despite the benefits of inverter recycling, there are several challenges. The diverse and intricate composition of inverters makes the recycling process technically challenging and resource intensive. Economic viability is an additional issue, as current market prices for secondary materials often do not justify the costs of the recycling process, making it economically unfeasible without subsidies or incentives. Moreover, existing recycling technologies may not efficiently recover all valuable materials, leading to potential losses and inefficiencies.

Since **mounting structures** represent a significant portion of the components of solar PV systems and can considerably improve both their output and sustainability performance, not only should they be manufactured with robust, durable, and reusable materials, but it is also essential to make them fully recyclable. The mounting structures and trackers are mainly made of galvanised steel. The structure can be dismantled, with the steel redirected to standard steel recycling routes, if reuse is not feasible. In the EU, 90% of steel is currently recycled.[64]

During recycling, steel and zinc are recycled together without any loss of properties in the electric arc furnace steel production process.[65] It is important to minimise the presence of other metallic elements in the coatings as these elements may not be as easily recycled during the steel recycling process. During the steel recycling process, the zinc that remains from the coating is volatilised and collected in the dust that is subsequently recycled in specialist facilities and returns in primary refined zinc production. As a result of this process, zinc recycling rates are estimated at 98% in Europe.[66]

64 Steel Construction Institute: The recycling and reuse survey.
65 EGGA (2021): Galvanized Steel and Sustainable Construction: Solutions for a Circular Economy.
66 Ibid.

Approaches and best practices

In Europe, several startups and established waste treatment companies are setting up facilities to handle the increasing volume of solar PV module waste. They understand the forecasted steep increase of the PV waste stream not as a problem to be handled, but as an opportunity to recover valuable materials. There are three approaches currently leading the way for solar PV recycling.

RECOVERING HIGH-PURITY GLASS

In solar PV manufacturing, two types of glass are typically used: float glass and patterned glass. For float glass, advanced thermomechanical processes can be used to recover high-quality glass from end-of-life solar PV modules without relying on harmful chemicals. The high quality of the glass qualifies it for premium applications, such as packaging or production of new float glass. This ensures that nearly all of the glass material is reintegrated into the production cycle, maximising its economic value and reducing the environmental impact. As for patterned glass, information on the use of substances, such as antimony, ensures proper allocation of the waste streams in the recycling process.

RECOVERING SRM, CRM AND HIGH-VALUE MATERIALS

Innovative delamination and separation technologies have been developed to separate the multi-layer sandwich and isolate solar cells from glass and organic materials to recover raw materials, such as silicon metal, silver, copper, and gallium from solar PV modules. These processes achieve recovery rates of over 98%, allowing the recovered materials to be used in new solar PV modules or other high-tech industries. In several cases, the purity of recovered silver reaches 99%, and purified silicon is returned to solar-grade quality. This high-efficiency recovery significantly reduces reliance on virgin materials and supports a more circular solar PV value chain.

DEVELOPING SUSTAINABLE BUSINESS MODELS

New recycling technologies are being integrated into business models that demonstrate both economic viability and environmental sustainability. By focusing on the recovery of critical raw materials, strategic raw materials, and high-value materials, recycling operations can lower material supply costs, improve the supply of raw materials in Europe, and generate new revenue streams. Additionally, research projects are actively exploring new markets for these secondary raw materials. This approach ensures that the recycling process is profitable, while contributing to the circular economy in the solar PV sector, making the business case fit for large-scale adoption.

Advanced PV module recycling

SOLAR MATERIALS, based in Magdeburg, Germany, specialises in the recycling of raw materials from PV modules using a patented thermomechanical process. This method enables the recovery of all materials without the use of environmentally harmful chemicals, and with reduced energy consumption. Key materials, such as silver and silicon, are recovered during the process, while the high quality of the recycled glass qualifies it for premium applications, including packaging and production of float glass.

Through this process, SOLAR MATERIALS recovers 98% of raw materials from PV modules and is certified as an electronic waste treatment facility for PV modules. Currently, the recycling capacity in Magdeburg is 3,000 tonnes, or 150,000 modules, per year.

To accommodate increasing demand, SOLAR MATERIALS is expanding its operations, with an industrial recycling plant set to be completed by spring 2025, increasing the Magdeburg facility's capacity to over 10,000 tonnes annually. Plans for a recycling plant beyond Germany are in development, with commissioning expected in 2026.

PHOTORAMA project

PHOTORAMA

The majority of solar PV recycling is currently conducted in facilities that recycle various products, while recycling lines dedicated to solar PV are rare. The PHOTORAMA project, funded by the EU's Horizon 2020 programme, is focused on developing advanced recycling technologies for PV modules, particularly targeting c-Si and CI(G)S technologies.

This initiative, involving **CEA-INES**, **Enel Green Power**, **Soren**, **ENEA**, and other eight project partners, aims to recover valuable materials, like glass, silicon, silver, copper, aluminium, indium, gallium, and other metals from end-of-life PV modules through a multi-step integrated process, involving automated mechanical disassembly of external components, separation of the multi-layer sandwich layers by delamination, and environmentally-friendly metal recovery processes. The pilot line, integrating up to six technologies, offers a flexible model for high-value recycling. It can handle a wide range of module types and sizes, adapting to diverse designs, frame seals, backrail frames, junction box locations, and types of module: glass/foil, glass/glass, all c-Si technologies (including SHJ/In recovery), as well as thin films CIS/CIGS, with compatibility for CdTe as well. Key technologies include mechanical delamination techniques, such as water jet and diamond wire cutting, and optical delamination using flashlights for CI(G)S structures, which successfully produces clean glass sheets and glass or plastic panes, facilitating easier reuse or recycling. For metal recovery, the project uses environmentally friendly or biodegradable solvents, such as Deep Eutectic Solvent (DES) and Methane Sulfonic Acid (MSA), which are directly recycled in a closed-loop process. This is followed by electrowinning to recover high-purity metals. The project's circular model aims to reintegrate these secondary raw materials into cross-sectoral value chains, driving market adoption of sustainable recycling technologies.

PHOTORAMA's recycling pilot line, targeting a technology readiness level of 7 out of 9, is projected to handle 1,200 tonnes of solar PV waste annually, with plans for further scale-up to an industrial level. The pilot line will be fully operational and open for public demonstration in April 2025 at LuxChemTech in Germany. The project's innovations, including the use of recovered materials in new PV products or other industries, represent a significant step forward in sustainable waste management and high-value recycling. The project has been recognised for its innovative approach, winning the 2024 European Sustainable Energy Award in the Innovation category.

Case studies

EVERPV project

Delamination is the stage of the recycling process that determines the purity of recovered materials. As a result, the newest research focuses on innovative delamination technologies. EVERPV is a three-year Horizon Europe-funded project, led by **CEA**, and involving partners, such as **SolarPower Europe**, **CSEM**, **ENEA**, **Mylar**, **Soren**, and **Tecnalia**, focused on optimising two innovative delamination technologies. One of them involves grinding end-of-life PV modules from the back, while the other one uses infrared heating to separate the module layers. These advanced techniques will enable the efficient recovery and reuse of valuable materials, such as silver, glass, and polymers from PV modules, making the recycling process more effective.

The goals of the project include optimising these delamination processes and benchmarking them against other technologies to determine the most suitable and scalable with pilot lines. This optimisation will also aim at ensuring the high-purity recovery of silver, polymers, and glass. The project will also demonstrate the reusability of these materials and will highlight the way in which recovered materials can be reintegrated into the solar value chain and other industries.

Moreover, emerging recycling technologies and opportunities for reusing recovered materials are introducing new business models and expanding markets in the solar recycling sector, thereby supporting sustainable job creation across Europe. By encouraging the circular use of resources, EVERPV contributes to reducing dependency on primary raw materials and strengthening the domestic sourcing of raw materials within the European Union, while supporting regional sustainability goals.

RESiLEX project

Developing technologies and practices to recover high-purity materials from PV modules is key for their further reuse in new solar PV or in other industries. The RESiLEX project, funded by Horizon Europe, and involving partners, such as **SolarPower Europe** and **CSEM**, advances recycling technologies to reduce the EU's dependence on critical raw materials, particularly silicon, in PV module production and other key sectors. A core objective of the project is to enhance the sustainability of the silicon value chain by developing innovative methods for recycling and reusing silicon from end-of-life PV modules and other applications, including Li-ion batteries. RESiLEX also targets the recovery of valuable materials - including cobalt and antimony - from mining waste and aims to create a sustainable, carbon-free process for silicon production in solar applications.

New separating techniques that help recover silicon from the shredded glass-silicon mixture are under investigation. The GeMMe laboratory (University of Liège) also performed assessments to purify recovered silicon from solar PV modules, by leaching the contaminants like aluminium and iron, off the pieces of silicon cells recovered, and demonstrated the possibility to obtain a silicon purity above 99.5%.

By improving recycling processes and promoting the reuse of silicon, the project seeks to reduce the EU's reliance on imported materials and strengthen the circular economy in critical industries.

In addition to recycling activities, the project will also explore the use of recovered silicon to create high-efficiency silicon-carbon composite anodes for Li-ion batteries, replacing graphene. Finally, RESiLEX will conduct a multi-faceted impact assessment of its innovations and provide EU policy recommendations based on these advancements, helping to shape the future of Europe's silicon value chain.

RETRIEVE project

RETRIEVE is an EU-funded project focusing on the high-purity recovery challenge, with the objective of recovering over 99% of silver and purifying silicon to solar-grade quality. The consortium involved in RETRIEVE, including **RPIA**, **Fraunhofer CSP**, **Iberdrola**, **Total Energies**, and **FORSCHUNGSZENTRUM JULICH**, combines organisations across the solar PV value chain with cutting-edge recycling technologies to upcycle components from end-of-life PV modules, improving material quality to meet industry standards for reuse. RETRIEVE aims to develop and demonstrate cost-effective recycling technologies that can process diverse solar module components, including silicon and silver, but also glass, heavy metals, and polymers.

The project envisions a closed-loop system where recycled glass and silicon are reintegrated into new PV module production, turning waste into valuable raw materials. In addition to developing high-throughput technologies for dismantling PV modules and upcycling over 95% of materials to meet industry standards, RETRIEVE also focuses on innovative methods for valorising plastic components through syngas production, integrating carbon capture and toxin removal. The project aims to forecast future solar PV waste streams, evaluate market potential, and lower the financial burden of material recovery, making the recycling process more profitable and opening new commercialisation opportunities. RETRIEVE's mission, reflected in its full name, 'Reintegration of Photovoltaic Panel Waste Back into Manufacturing as High-Value Products,' underscores its commitment to boosting circularity in the solar PV sector by reintroducing valuable materials from discarded PV modules into the production chain.

High-value recycling of cadmium telluride modules

Once **First Solar's** PV modules reach the end of their useful life, high-value recycling helps recover materials so they can re-enter the solar supply chain to enable sustainable growth. First Solar has a longstanding leadership position in solar PV recycling, having established the industry's first global recycling programme in 2005, and recycled nearly 400,000 metric tonnes of PV modules by the end of 2023. While the majority of solar PV recycling processes focus solely on recovering high-mass fraction materials, such as glass and frames, First Solar's high-value recycling process takes it a step further by achieving closed-loop semiconductor recovery and providing high-quality secondary resources for new PV modules, glass, rubber, and aluminium products. First Solar operates scalable, high-value solar PV recycling facilities in Germany, the United States (Ohio and Alabama), Vietnam, Malaysia, and India. In 2023, First Solar's recycling facilities achieved a global average material recovery rate of approximately 95%. The remaining 5% consists of glass fines created during the mechanical crushing process, which cannot be used in secondary raw materials and are handled using other responsible waste treatment techniques. One kilogram of First Solar's semiconductor material can be recycled 41 times over, which translates into a use time of more than 1,200 years. First Solar aims to be able to feed all our recycled materials back into the solar supply chain, as is already done with their semiconductor material, which is used in new First Solar modules.

SolarPower Europe

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