International Sustainable Chemistry Collaborative Centre

Circular Economy for Renewable Energy Technologies - Photovoltaic Modules and Wind Turbine Rotor Blades

Contribution to Sustainable Development in Morocco

Implemented by:

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Abstract

Based on the Paris Agreement from 2015 future energy should come from renewables, like wind and solar power, to reduce the use of fossil fuels. We need to think about what happens to solar panels and wind turbine blades after their lifetime. What recycling options are there? What rules do we need for this kind of waste? Amongst others, these questions were discussed during workshops and trainings on renewable energy in Morocco, organized by the International Sustainable Chemistry Collaborative Centre (ISC3) from 2022 to 2023.

Over the past decades, solar and wind power have increased rapidly, and this growth is expected to continue. To meet the goals of the Paris Agreement, we need to focus on recycling of waste materials. Considering that solar panels and wind turbine blades last between 25 and 30 years. Waste can be reduced by making them last longer and by recycling their materials. In this context, research and development are important for creating long-lasting and eco-friendly designs. The industry needs incentives for recycling, regulations are crucial, in addition to deposit systems to collect old products and recycle valuable materials.

This report sets out the concepts of Sustainable Chemistry and Circular Economy. Further, renewable energy costs and the situation in Morocco are analysed. The main part of this paper focuses on technologies for solar panels and wind turbine blades, addressing the following questions:

- Which materials are used in the production?
- How long do these materials last?
- How much waste is generated?
- What are possible recycling options?
- What is the capacity of these technologies in Morocco?
- What are the best techniques for waste treatment?
- How is sustainability ensured at the end of life for these products?

The ISC3 and local experts in Morocco faced issues with policies and strategies for renewable energy technologies, looking at:

- Which role do renewables assume in Morocco's energy policy?
- What regulations exist, and what opportunities do they offer?
- What can be national strategies for end-of-life solar panels and wind turbine blades?

The local experts developed strategies for managing the life cycle of solar panels and wind turbines, aiming to:

- expand the secondary market,
- built research capacities,
- promote capacity building,
- set up a regulatory framework, including Extended Producer Responsibility (EPR),
- provide data for product passports, and
- invest in repowering to extend the life of wind farms.

Contents

ISC3 – We transform chemistry

The International Sustainable Chemistry Collaborative Centre (ISC3) fosters the transition of the chemical and related sectors to Sustainable Chemistry, promoting a circular economy in the value chain. The centre follows a multi-stakeholder approach, targeting policymakers, the public and private sector, academia and civil society. It contributes globally to international chemicals policy, develops professional and academic training measures, offers advisory services, fosters innovations, supports entrepreneurship and conducts research.

ISC3 is hosted by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) in cooperation with the Leuphana University Lüneburg as Research & Education Hub and DECHEMA Society for Chemical Engineering and Biotechnology as Innovation Hub. The centre was founded in 2017 on the initiative of the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) and the German Environment Agency (UBA).

ISC3's current Focus Topic is the nexus between chemistry and energy, raising the question of how Sustainable Chemistry (SC) can contribute to renewable energy systems and vice versa? In order to address this issue, ISC3's approach includes a stakeholder dialogue with local experts.

Global Framework on Chemicals (GFC)

In 2023, during the International Conference on Chemicals Management (ICCM5) in Bonn, Germany, governments agreed on a new "Global Framework on Chemicals (GFC) - For a Planet Free of Harm from Chemicals & Waste". It aims to reduce adverse effects from the use of chemicals and applies to all chemicals and their products from manufacture and use to the end-of-life-stage.

The GFC is a plan to guide relevant stakeholders (e.g. countries, private sector, civil society) to catalyse a transformational shift towards Sustainable Chemistry. The strategic objective "A" underlines the need for setting up a legal framework, strengthening institutional mechanisms and capacities to support safe and sustainable management of chemicals -- in addition to the application of innovative and sustainable solutions in product value chains (objective "D").

As the GFC builds on a unique multi-sectoral and multi-stakeholder approach, it provides a useful platform for stakeholders along the value chain to engage, exchange experiences, build capacities, share knowledge, and accelerate action towards its implementation. The findings of this paper and strategies identified are aligned with the strategic objective "A" and "D" of the GFC and contribute to its application.

Foreword

Dear changemaker,

Our aim with this paper is to reach stakeholders from industry, academia and regulatory institutions, specifically in countries that have just started or are currently preparing the transition to renewable energy sources. It is based on current research and a stakeholder dialogue in Morocco, which was carried out between 2022 and 2023 by ISC3. Moroccan experts analysed the local situation and developed strategies to prepare a sustainable approach for the End-of-Life (EOL) phase of renewables, such as photovoltaic modules (PV) and wind turbine rotor blades for their country.

We hope to give you valuable insights. Enjoy reading!

Bonn
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1 Executive Summary

According to the Paris Agreement from 2015, future energy supply should be based on renewable energies, such as wind and solar in order to defossilise the industry. Thinking ahead, the question arises of what will happen to the photovoltaic modules (PV) and wind turbine rotor blades after use? Which recycling option exist? Which regulations are needed for treatment of this specific waste and composite materials?

These and similar questions were dealt with in a stakeholder dialogue in Morocco initiated by the International Sustainable Chemistry Collaborative Centre (ISC3). In this context, two expert workshops on circular economy and three trainings on renewable Power-to-X were conducted between 2022 and 2023.

Considering that installed PV capacity grew at a compound annual growth rate (CAGR) of 39% over the last two decades, while wind capacity increased at a CAGR of 20% over the same period, a strong rise in renewable energy (RE) installations is expected to continue worldwide. To meet the goals of the Paris Agreement, further actions are needed. In order to sustain the foreseen growth of renewables and to reduce the environmental and societal harm, recycling must be timely addressed.

Future waste from products such as PV modules and wind turbine rotor blades (which last on average between 25 and 30 years) can be minimised through longer lifetimes and materials recycling. Other lessons learned are:

- Research and development is essential for longevity and cost-effective eco-design.
- Industry needs incentives for future recycling, wherefore regulations assume a crucial role.
- Leasing and deposit systems can aid circular economy efforts by collecting End-of-Life (EOL) products and recycling valuable materials.

In addition, further approaches and the current state of research on how to deal with photovoltaic modules and wind turbine rotor blades that have reached EOL are discussed in this whitepaper.

The theoretical concepts of Sustainable Chemistry and circular economy are presented in the second chapter. The third chapter maps the general background of climate change, costs of renewable sources, describes the current situation in Morocco and presents insights from the stakeholder dialogue organised by ISC3, which lays the basis for this report. The main part of this paper comprises chapter four and five, which focus in detail on technologies for photovoltaic modules and wind turbine rotor blades.

On technical level, the following guiding questions are addressed: Which materials are used, and what is their lifetime? Which amounts of waste are generated? What are the possibilities for recycling and reuse? What is the installed capacity of both technologies in Morocco? What Best Available Techniques (BAT) and Best Environmental Practices (BEP) exist for waste treatment? How is sustainability ensured at the EOL of photovoltaic modules and wind turbine rotor blades? BEP, including approaches for a 'design for circularity' and further opportunities, are highlighted in chapters 4.3 and 5.3.

Having started the stakeholder dialogue in Morocco, ISC3 and local experts were confronted with a variety of issues associated with policies and strategies related to renewable energy technologies. On policy level, guiding questions are:

- What role do renewable sources currently play in Morocco's energy policy?
- Which regulations already exist and what are potential opportunities?
- What are national strategies for end-of-life PV modules and wind turbine rotor blades?

Specific strategies derived from an analysis of strengths, weaknesses, opportunities and threats (SWOT), conducted by local experts are presented for PV in chapter 4.6 and for wind turbines in chapter 5.6. These strategies were developed during the ISC3 workshops in order to expand the secondary market, promote capacity building, set up a regulatory framework, foster high quality standards and invest in repowering to extent the lifetime of wind farm assets. In this context, the application of Extended Producer Responsibility (EPR) is recommended. However, it needs to be considered that established regulations do not hinder the expansion of renewable energies.

Final conclusions, concerning regulatory framework, R&D needs, producer responsibility, data for product passport and financing instruments, refer to chapter six.

2. Main Concepts

In this chapter, the concepts of Sustainable Chemistry, circular economy principles and waste treatment methods are explained. These approaches assume a vital role for the transformation of energy systems.

2.1 Sustainable Chemistry

The concept of Sustainable Chemistry addresses all three dimensions of sustainability (economic, environmental and social), according to the principles of green chemistry to decrease or entirely eradicate the use and generation of hazardous substances in the design, manufacture and utilisation of chemical products and processes.

In this context, ISC3 identified ten key characteristics of Sustainable Chemistry (SC) (see figure below), which can be applied to all stages along the production value chain, encompassing resources, manufacturing, utilisation, product end-of-life, recycling, and stakeholder services (ISC3, 2021).

In addition, Sustainable Chemistry is crucial for the transformation of education, workforce reskilling and upskilling. It guides chemistry's alignment with sustainability principles across diverse supply chains and life cycles, thus benefiting the planet. These attributes are essential for the renewable energy sector, where energy meets chemistry and lacks inherent sustainable qualities.

Therefore, Sustainable Chemistry requires a strategy to evolve from an linear economic model that uses chemical compounds, materials and processes without considering their impacts on environment, health and safety (EHS) to a circular economy. Closing the loop implies that services and functions are applied to avoid or reduce the demand for critical chemicals, improving the environmental and social performance towards sustainability.

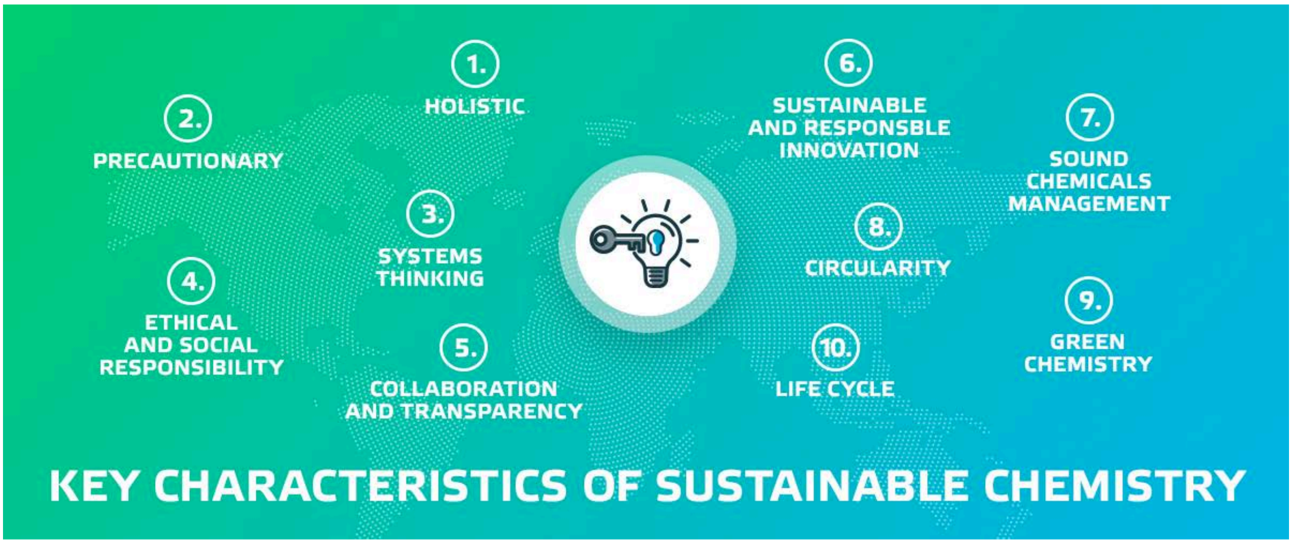


Figure 1: 10 Key Characteristics of Sustainable Chemistry

2.2 Circular Economy Principles

There are many definitions of circular economy, however, the concept is based on three main principles. 1) Minimization of waste and pollution; 2) Extension of the useful life of products and materials; 3) Regeneration of natural systems. A circular economy aims to eliminate waste and optimise resources through reduced consumption, more reuse and recycling, where waste and remaining material is transformed to close the loop.

Unlike the linear economic model, it enhances natural capital and creates the necessary conditions for the regeneration of natural systems. This approach replaces the end-of-life idea with restoration, encourages the adoption of renewable energy, eliminates toxic chemical use and strives for waste reduction through improved material design and business models (TUVSUD 2023). The following principles towards circularity according to TUVSUD 2022 and Zuin & Kümmerer 2022 can be applied to different contexts:

Nine R's for circularity

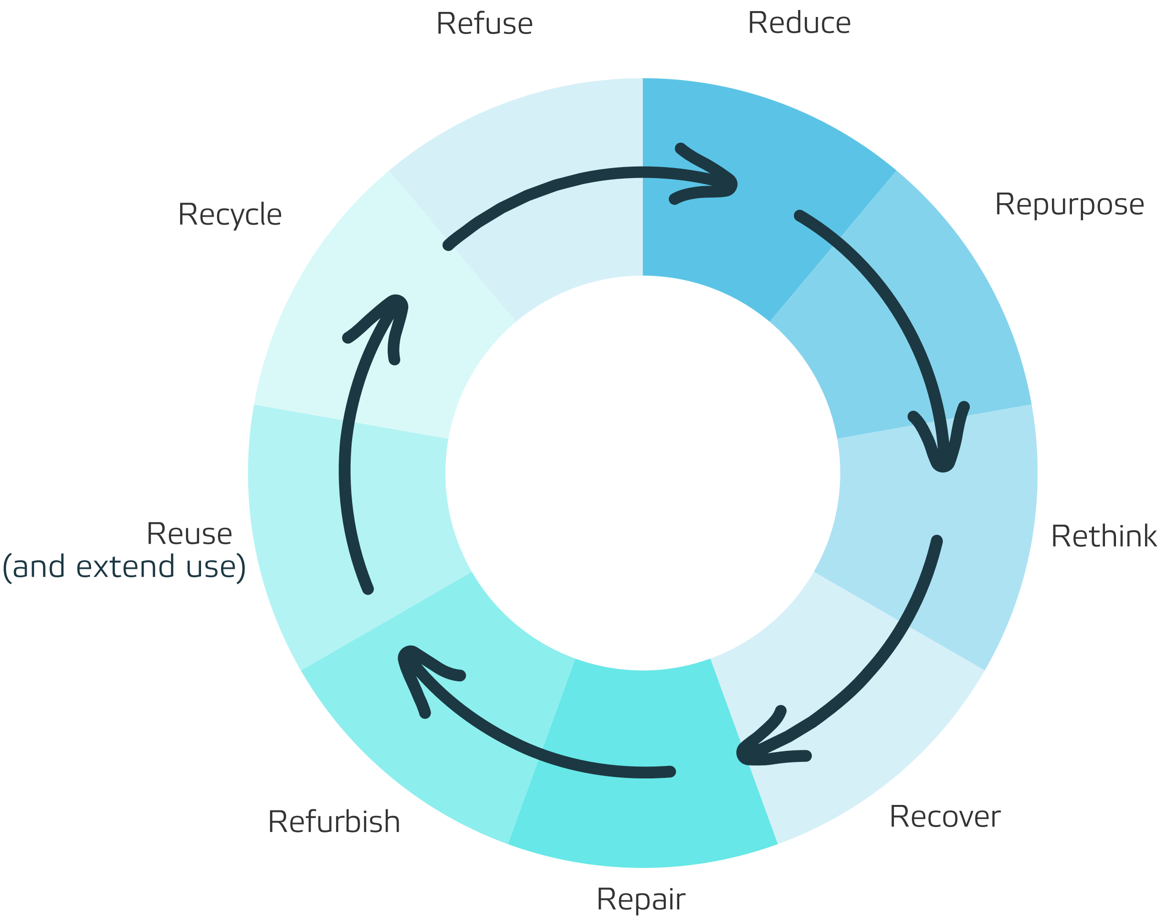


Figure 2: Nine R's for Circularity

Reduce

The avoidance of wasteful consumption and the decrease of the amount of waste generated represents the first and probably most effective step towards the production of less waste. This implies a lower consumption of energy and natural resources. It can be applied to substance flows, materials and products, encompassing factors such as size, complexity, composition, dynamics and spatial extent.

Repurpose

This means reusing an object or material for a different purpose than it was originally intended. For example, wind turbine rotor blades can be segmented and utilised for bus shelters, serve as bridge guardrails or playground equipment.

Rethink

The design of products should aim at the avoidance of waste and enable an easy disassembly after a product’s end-of-life to facilitate the reuse of valuable components.

Recover

After a product’s life cycle ends, it is essential to recover its resources for reuse in order to promote sustainability. The cradle-to-cradle strategy aims at a closed-loop system from sourcing to usage and vice versa. This requires a well-organised reverse logistics, this means that used products are collected from consumers to be returned to their manufacturers. While establishing these systems can be costlier in developed economies, the introduction of Extended Producer Responsibility (EPR) levies by governments is obliging companies to invest in these chains.

Repair

With the objective of extending a product's life cycle defective parts are replaced and maintenance work is provided. In contrast with refurbishment, the user typically does not change.

Refurbish

Rather than discarding products, this approach extends their lifespan through repair works, upgrading and reselling in secondary markets. The extension of product use does not demand a complete overhaul of the business model; it builds on existing capabilities and channels, creating additional sources of revenue. For example, computer firms refurbish and sell ‘certified used computers and laptops’. Regular inspections of wind turbine rotor blades, including microcrack treatment, noticeably prolong their operational life.

Reuse (and Extend Use)

The multiple reutilisaton of an item in its original state, the need for reprocessing materials is eliminated, whether for disposal or recycling, minimising losses. Functional products and / or materials can find a second-hand market to remain in use, preserving their value.

Recycle

As indicated below, recycling is not the most preferable treatment of waste and should only be considered if refurbishment, repair or reuse is not feasible. The following sequence should be applied in accordance with these rules: Only if the previous step cannot be performed, the next step will be taken. This means that if step 1 is not possible, it should be continued with step 2; if step 2 is not feasible, step 3 should be applied etc.

- Preserve form and size (e.g. avoid cutting wind turbine blades into pieces to keep glass fibre mats intact and reuse them).
- Retain material (during PV module recycling, avoid breaking glass and solar cells for easier reuse).
- Maintain composition (do not alter constituents during re-melting).
- Preserve molecules (polymers, additives).
- Keep building blocks (monomers).
- Retain atoms (pyrolysis).
- Conserve energy ('thermal recycling' which is in fact combustion), redirecting it for other processes and / or electricity generation when material combustion is necessary.

Refuse

Consumers should make responsible purchasing decisions. This implies to refuse environmentally harmful products; choose eco-friendly solutions with trustworthy and recognized quality labels, guaranteeing their environmental and social acceptability. This awareness, known as sufficiency, refers to the principle of not consuming more resources than absolutely necessary, which also applied to natural sciences.

2.3 Waste Treatment

As explained under 'Recycling', a sequence of treatment methods should be applied to maximise the efficient use of resources and to minimise their negative social and environmental impact. The illustration below shows the hoerarchy of waste treatment.

The most preferable waste treatment methods are indicated at the top and the least preferable measures are specified at the bottom, starting with waste reduction and prevention, reuse of materials where possible, recycling, recovering (incineration and energy), and lastly landfill disposal. The next lower step should be performed only if the previous step cannot be conducted.

Hierarchy of Waste Treatment (From Reuse to Landfill)

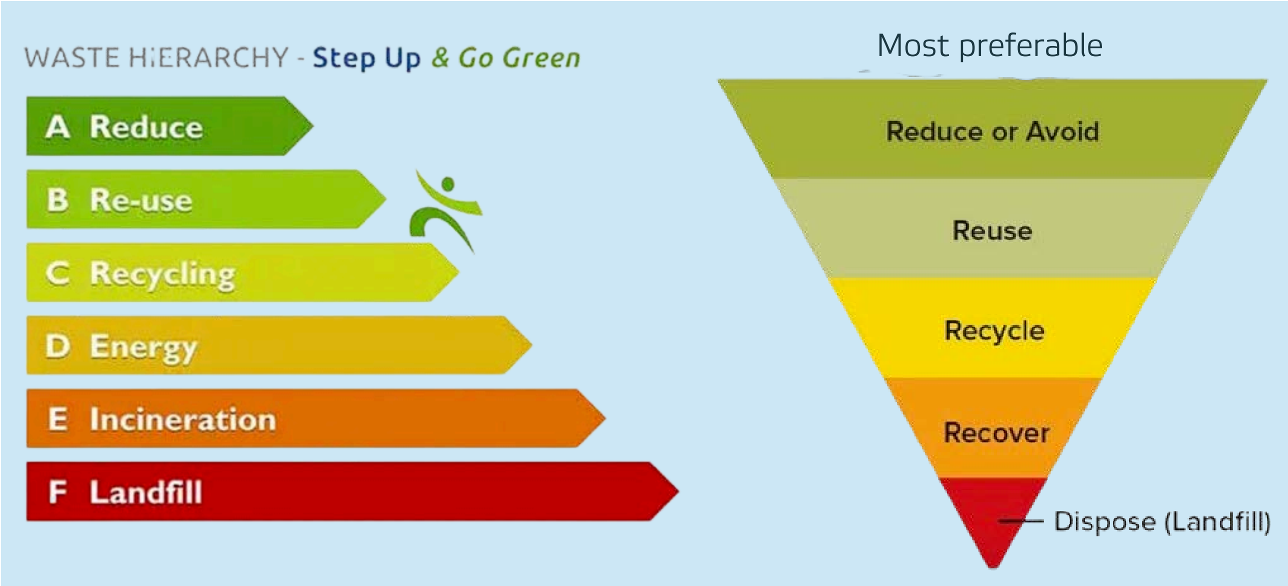


Figure 2: Waste hierarchy shown as "Lansink's Ladder" (left) and "upside down pyramid" based on Scottie Patterson (right)

2.4 Enabling the Energy Transition

Sustainable Chemistry and circular economy share the overall goal of minimising the environmental impact while maximising economic and social benefits. Energy is central to the European Union's transition towards climate neutrality by 2050, in line with the European Green Deal. The chemical industry together with cement production and the agriculture sector constitute the main emitters of greenhouse gases (GHG) (Baumert, Herzog & Pershing 2005).

Renewable energy sources will play a key role in decarbonizing our energy systems in the coming decades.

In this context, it can be differentiated between two energy transition phases:
In the first phase electricity shifts to renewables (wind, PV, biomas, hydropower, tidal, geothermal). It is fundamental to maintain the supply-demand balance, since wind and solar, as intermittent sources, require storage or short-term reserves such as hydropower, batteries or fuel cells (IRENA 2022). The second energy transition phase refers to a surplus of renewable electricity fuels, e. g. industrial heat, hydrogen, PtX and transport fuel. This broader use of renewable electricity is called ‘sector coupling’. However, it needs to be considered that extensive renewable infrastructure and storage are vital to keep this system in place in order to achieve carbon neutrality.

Energy transition can be achieved through:

Recycling critical materials such as metals, minerals, or rare earth elements, which are vital for renewable energy technologies, including solar modules, wind turbines and batteries, or further in the future electrolysers and fuel cells.

Developing innovative lower-impact methods to manufacture materials such as steel, cement, plastics or chemicals, which are integral to the construction and operation of renewable energy infrastructure.

Creating new business models and innovations that encourage the reuse and renewal of energy products and services, e. g. through leasing, sharing, refurbishing or remanufacturing.

However, adopting and expanding these concepts implies challenges but also offers opportunities. Therefore, issues such as data availability, policy alignment, stakeholder collaboration and consumer education need to be addressed on beforehand and a comprehensive system-thinking approach is vital for achieving a sustainable and reliable energy supply in the future.

3 General Background

3.1 Climate Change

Adverse effects of climate change, including extreme weather events and the current energy crisis triggered by the Russian-Ukrainian conflict have shown the strong need for reducing dependency on fossil fuels and an urgency to transform Europe's energy system. This goes in line with the Paris Agreement, limiting global warming to 1.5ºC, GHG emissions must peak before 2025 at the latest and decline 43% by 2030. An important prerequisite for this is the installation of further renewable power generation plants over the next few years.

These will mainly be based on solar (PV and CSP), onshore wind, hydropower, and offshore wind (IRENA 2022), as these renewable energy sources require low electricity generation costs at suitable locations. One key strategy to achieve climate neutrality is to replace conventional power plants and modernize grids. Here the question arises of what will happen with the renewable energy systems after its end-of-life?

3.2 Costs of Renewable Energy Sources

Over the last decade, capital spending on renewables noticeably decreased, making wind and solar the most affordable power sources (see Figure 3). The remarkably low global average levelised cost of electricity (LCOE) for onshore wind and utility-scale solar PV projects has driven a robust market shift towards these renewable energy sources.

Present LCOE figures can be even lower than shown, particularly in locations with advantageous conditions, this implies abundant wind and / or constant solar irradiation.

Nowadays, renewable electricity is the most economical choice in many areas (see Figure 3), particularly for solar PV and onshore wind systems. Between 2010 and 2020, the global weighted average LCOE for new utility-scale solar PV projects dropped by 85%, CSP by 68%, onshore wind by 56% and offshore wind by 48%. In addition, it was found out that all available solar and wind technologies fall within or below the cost of new fossil fuel plants (IRENA 2022, p. 44).

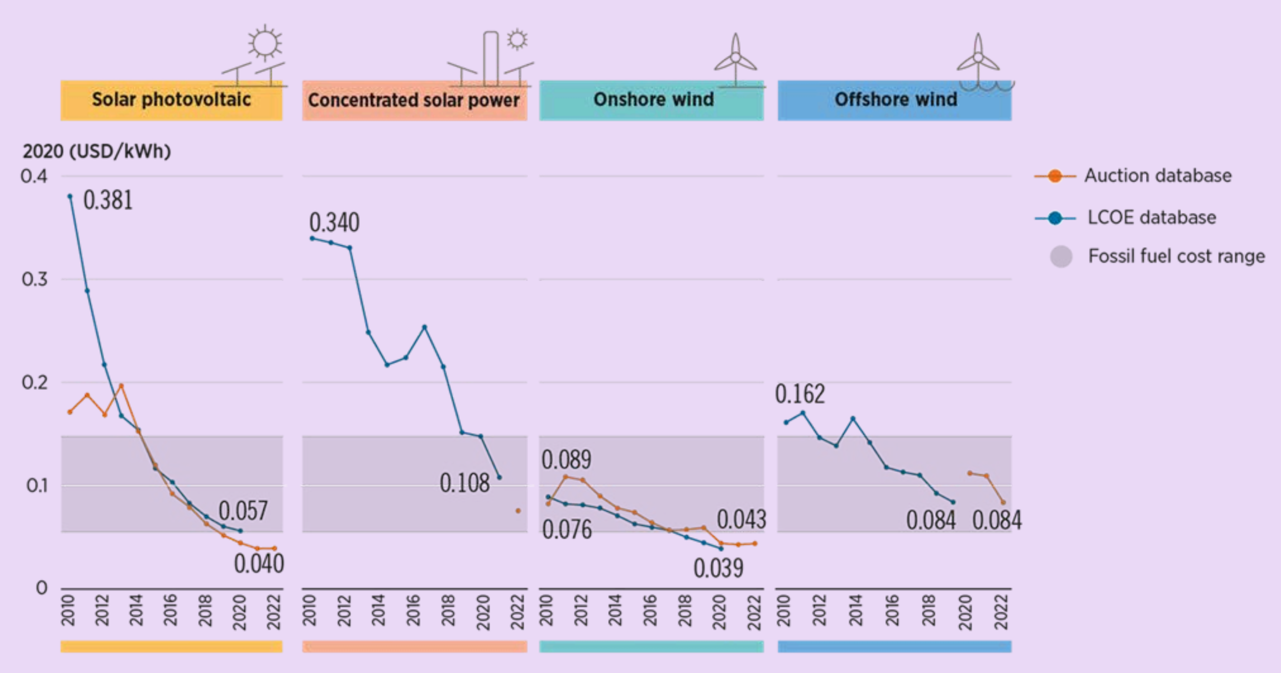


Figure 3: The global weighted average LCOE and PPA/auction prices for solar PV, CSP, onshore wind and offshore wind, 2010–2023.
Source: (IRENA 2022, p.45)

3.3 Situation in Morocco

In relation to the large-scale development of renewable energy, Morocco has set itself the strategic objective of increasing the share of green energies significantly (MWN 2022).

In the Moroccan market companies with general recycling expertise (e. g. for batteries) can be found. Although, excellent research institutes exist, circularity for waste from dismantled renewable energy systems is not on the academic agenda yet.

In January 2021, the first version of a hydrogen roadmap for Morocco was released (GH2 2023). The country has vast potential for a decarbonised energy sector based on solar and wind power facilities at low cost. Its access to European gas pipelines as well as ports in the Atlantic and in the Mediterranean Sea offer high export opportunities.

In addition, demand for technologies and knowledge in the decarbonisation of chemicals and raw materials can be identified.

Health, safety and environmental aspects are to be explored together with the potential for applying innovative recycling technologies. Materials and substances that are end products of the recycling process need to be integrated in the national value chain according to the SDGs.

Political Ambitions

Nationally Determined Contributions (NDCs) are countries' self-defined national climate pledges under the Paris Agreement, consisting of adaptation and mitigation actions. At the global level, 193 parties have issued at least a first NDC as commitment to achieve zero net emissions (UNFCCC n.d.). Many coun announced a major shift towards renewable energies. In November 2022, King Mohammed VI called for accelerating the development of renewable energies, with the aim of producing over 52% of electricity from solar and wind power in Morocco by 2030 in order to reduce its dependency on oil and gas imports (MWN 2022).

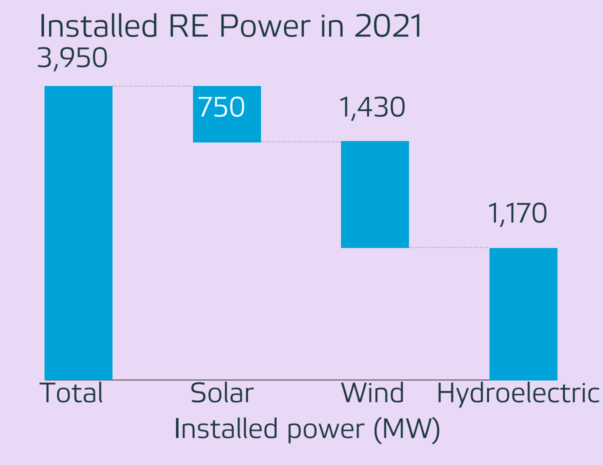


Figure 4: Installed Renewable Energy Capacity in Morocco in 2021
Source: MASEN; Chart: African Climate Solution ACS
Note: For Solar power, 540 MW Concentrated Solar Power (CSP) are included in this graph.

Regional Market

When comparing different sources of statistical data, the capacity of installed wind power systems is coherent (see Figure 4). Some deviations are to be observed in solar power data, since 540 MW Concentrated Solar Power (CSP) are installed in Morocco. In this white paper, CSP is not considered, since this technology is based on mirrors that are tracked and focus the sunlight to a (thermal) receiver. Therefore, only photovoltaic modules will be taken into consideration (IRENA 2023a).

3.4 Wind and Solar: Installed Capacities and Electricity Generation

The development of cumulative installed capacity for onshore wind and solar PV in Morocco is shown in Figure 5. It provides information on the expected amount of waste from renewable energy technologies, which will need to be treated in the future. Based on the assumption that both technologies remain in operation between 25 to 30 years.

It can be concluded that the waste rate from wind turbine blades and PV modules will be low in the coming decade. However, a strong growth rate can be observed, therefore, relevant quantities of such EOL materials will accumulate in the long term.

In 2019, the share of electrical energy generated by RE amounted to 19% according to data from IRENA. In this context, Figure 6 illustrates that wind energy contributed significantly more than PV to power generation in the respective period.

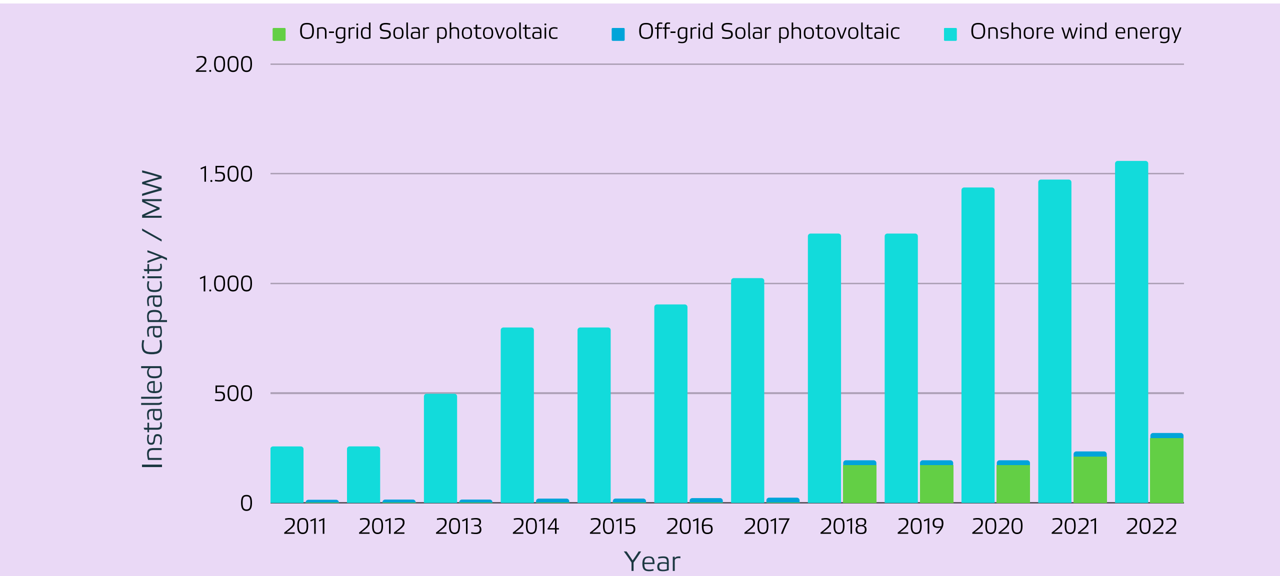


Figure 5: Installed capacity for onshore wind and on- and off-grid PV in Morocco
Source: (IRENA 2022a);Chart: PSE
The share of electrical energy generated by RE was about 19% in 2019 according to data from IRENA.

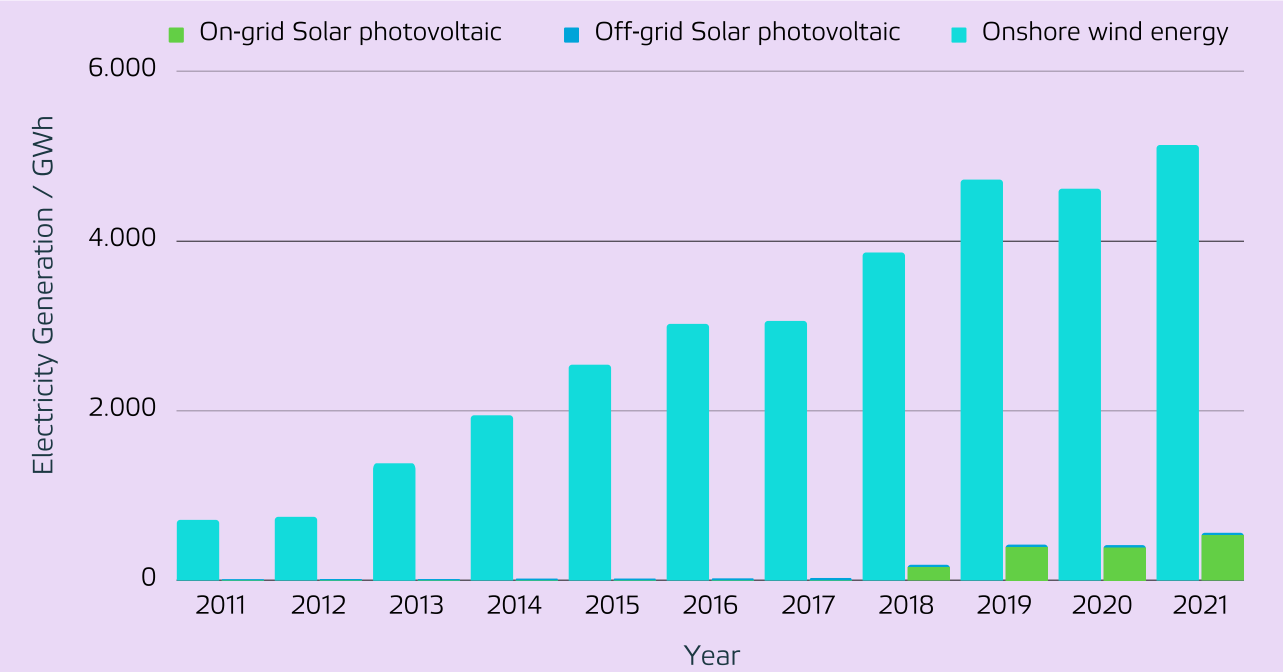


Figure 6: Electricity generated by onshore wind and on- and off-grid PV in Morocco
Source: (IRENA 2022a); Chart: PSE

3.5 ISC3 Stakeholder Dialogue with Local Experts in Morocco

Between January and May 2023, ISC3 led two stakeholder workshops in Casablanca and Rabat to discuss the circular economy approach and how it can be implemented in Morocco. The focus was on sustainability, side effects and strategies to establish an environmentally friendly development (ecodesign) and recycling.

High-ranking experts from Europe prepared inputs on the international state of the art, illustrating the most sustainable recycling and reuse processes. In additoin, ISC3 organized a panel discussion with renowned specialists from Morocco who exchanged on the state of the art and necessary steps to be taken.

On national level, few waste recovery measures exist. Therefore, economics of hazardous waste diversion and disposal needs to be determined based on data analysis in order to identify business opportunities and capitalise on potential benefits.

Morocco's RE waste regulations lack clarity and require more precise directives addressing waste types, limits and geopolitical factors.

The roundtable session discussed initially on specific national aspects, fostering cross-sectoral multidisciplinary exchange through insights from local experts. The workshops served as a platform for peer-to-peer learning, while discussions dealt with infrastructure requirements, decentral and modular solutions, circularity approaches and sustainability aspects.

Moreover, the question of how to enable an environment for CE solutions and opportunities in the country arose, promising upscaling potential for other countries in the MENA region. The results from the groupwork (SWOT analysis) can be found in chapter 4.6 and 5.6.

4 Photovoltaic Modules

From sunlight to electricity - it is recognised that clean energy can fuel the future. Especially, PV modules assume an important role in the transformation of the energy sector, based on the assumption that the energy needed to produce a PV module can be recovered in approximately one year, considering a region with strong exposure to sunshine (Frischknecht, R. (Ed.) 2022).

4.1 Materials and Waste

The following PV module technologies can be found on the international market: mono- and multi-crystalline silicon (Si), cadmium telluride (CdTe), copper indium gallium selenide (CIGS / CIS). Since most PV modules are wafer-based crystalline silicon, this paper will focus on these. In addition, CdTe modules from the US American brand "First Solar" imply their own take-back system.

In order to achieve the energy transition, enormous numbers of PV systems need to be installed to replace conventional electricity generation through combustion of fossil fuels. In the second stage of the energy transition, sectors such as domestic heating, transport or industry will also be covered by renewables.

In the future, tandem concepts such as perovskite silicon tandem PV may enter the market. However, there is no universal strategy for EOL module treatment of photovoltaic modules, due to continuous development and rapid innovation (e. g. material composition changes, wafer thickness decreases, and cell and module dimensions evolving over time) (VDMA 2022).

4.1.1 Construction of a PV Module

A solar PV module consists of a glass pane under which the solar cells are embedded in foil. Either a glass pane or a foil serves as the back protection layer (see Figure 7). The electrons flow out of the cells via thin silver wires, also called busbars, which end in contact fingers. The cells themselves are connected to each other via thin contact rails that lead into a junction box made of aluminium or plastic on the back. The module's cables branch off from the junction box. Many modules are still clamped into a frame, which is usually made of aluminium.

Bill of materials and LCA for different module technologies can be found in environmental life cycle assessment of electricity from PV systems (R. Frischknecht et al. 2020, p. 21).

More than 90% of the solar modules produced worldwide consist of solar cells made of silicon (IEA 2022, p. 13), being considered as the second most abundant element on earth after oxygen – it is found in quartz and sand.

Thin-film modules contain active layers of silicon, cadmium telluride or copper indium (di)selenide (CIS or CIGS) that are just a few microns thick.

These modules usually have no frame and have a glass back (R. Frischknecht et al. 2020, p. 17).

In many countries, exists a political will to become climate neutral by 2050. Some countries, such as Germany, have announced their intention to achieve the Paris Agreement by 2045. In this context, the expansion of solar PVs and installation of wind power contributes significantly.

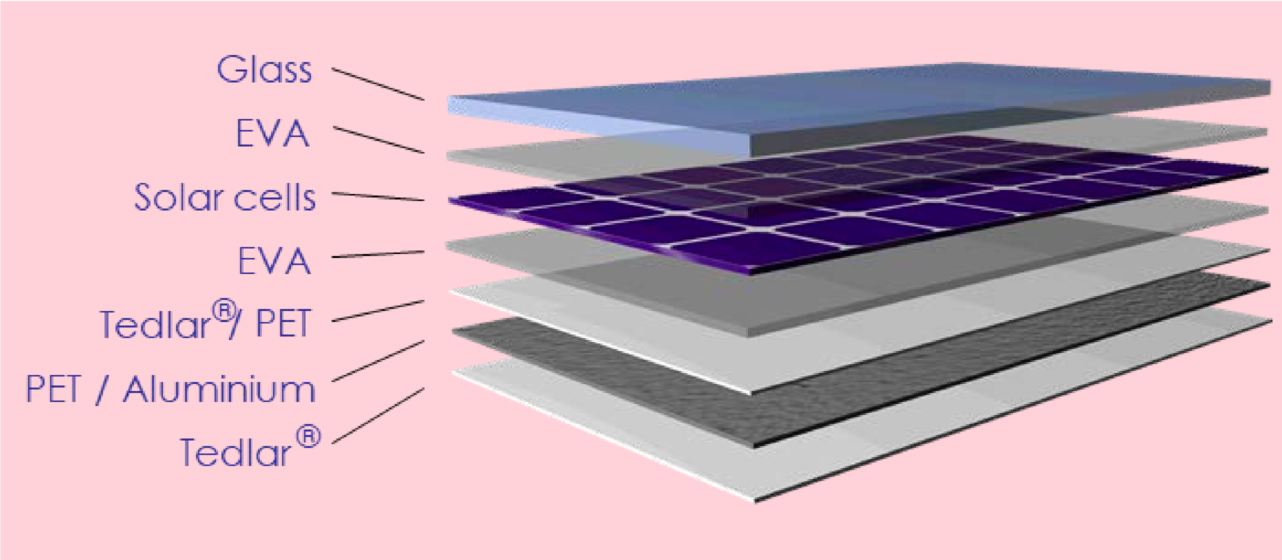


Figure 7: Layers of a standard crystalline wafer-based silicon PV module with Tedlar back sheet. Alternatively, a glass sheet can be used to seal the rear side of a PV module.
Source: Authors

The silicon wafer can be p-type or n-type. A p-type wafer is doped with boron or gallium, which has one less electron than silicon (making the cell positively charged). Nowadays, the main doping element for p-type monocrystalline silicon material is gallium, which has the advantage of significantly reducing the Light Induced Degradation (LID) of p-type material. An n-type solar cell has a phosphorus-doped wafer, which carries one more electron than silicon, making it negatively charged (VDMA 2022).

4.1.2 Amount of Waste, Hazardous Substances and Value of Recyclable Materials

Figure 8 is based on PV market numbers that were released in 2014, but are still valid. At the end of 2021, cumulative PV systems installed worldwide corresponded to 945 GW according to IEA (Masson & Kaizuka 2022, p. 9).

In most regions worldwide, solar PV and wind are considered as the cheapest sources for producing electricity from renewables, whereas grid parity has already been achieved several years ago.

In 2022, the cumulated installed PV module capacity exceeded 1,000 GW globally (IRENA 2023b, p. 25), the corresponding estimated material quantities are shown in Table 1. The sheer volumes (millions of tons) underline the need of finding a way to return these materials to the economic cycle.

It was discovered that PV modules can contain substances which are dangerous for the environment (see Figure 9). In particular, these consist in antimony within the glass (0.1 to 0.3% of weight), lead (0.01 to 0.05% of weight) in the soldered joints and fluorished plastics for the back sheet. For example, flour represents a hazardous substance which should not be released as flue gas when burning the back sheet (IEA 2018, p. 55).

	Inst. Capacity / GW	Modules / Mt	Silicon / Mt	Organic / Mt	Aluminium / Mt	Glass / Mt
Germany	≈60	≈5	>0.15	≈0.5	≈0.65	≈3.5
China	≈60	≈35	≈1	≈4	≈5	≈28
World	>1.00	≈90	≈3	≈10	≈12	≈65

Table 1: Estimated amount of material in 2022
Source: (Dold 2022, .p 10)

During normal operation of a PV system, harmful materials typically contained in PV modules are not expected to be released into the environment.

Bulk materials, such as glass and aluminium, account for more than 80% of the mass of a silicon photovoltaic cell (see left graph in Figure 9). However, about two thirds of the monetary value of a cell's materials contain silver, silicon and copper, i.e. smaller components (right graph in Figure 9).

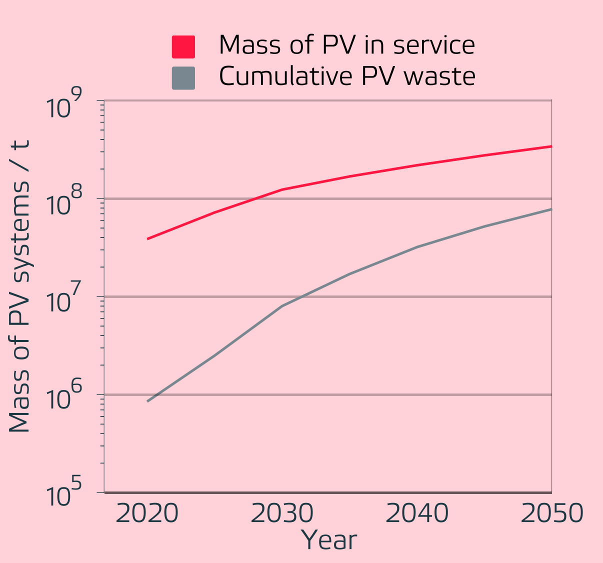


Figure 8: Global PV waste to be expected
Source: (Peplow 2022)

In the case of broken and/or damaged end-of-life modules, environmental pollution cannot be excluded as this has not been sufficiently investigated. In the EU, the costs of recycling and disposal are covered by producer levies and expected raw material profits.

Nevertheless, the financing of the decommissioning of thousands of PV ground-mounted systems is still open (Franz & Piringer 2020).

Restricted substances referred to in Article 4(1) and maximum concentration values tolerated by weight in homogeneous materials (RoHS Directive 2011) related to PV modules are: Lead (0.1 %) and cadmium (0.01 %). Based on the assumption that one EOL module weighs about 20 kg, this would correspond to 50 PV modules per ton.

The material value of one module amounts approximately to between EUR 10 and 12, if all materials are recovered (see Table 2). Therefore, one ton or 50 PV modules achieve a value of about EUR 500 (Dold 2022, p. 18).

When calculating recycling costs, the following factors need to be considered: Transport, logistics, CAPEX, OPEX and waste disposal. As a consequence, over 10,000 tons of EOL modules need to be recycled annually to make the investment in a recycling plant economically viable.

Material	Economic value per module	Price per kg (rough indication)
Aluminium	€ 4	€ 1.5/kg
Silver	€ 5	€ 500-750/kg
Silicon	€ 1	€ 1.5/kg (metallurgical silicon)
Glass	€ 0.5	€ 0.04/kg

Table 2: Material value of an EOL PV module
Source: Prof Peter Dold, Fraunhofer CSP

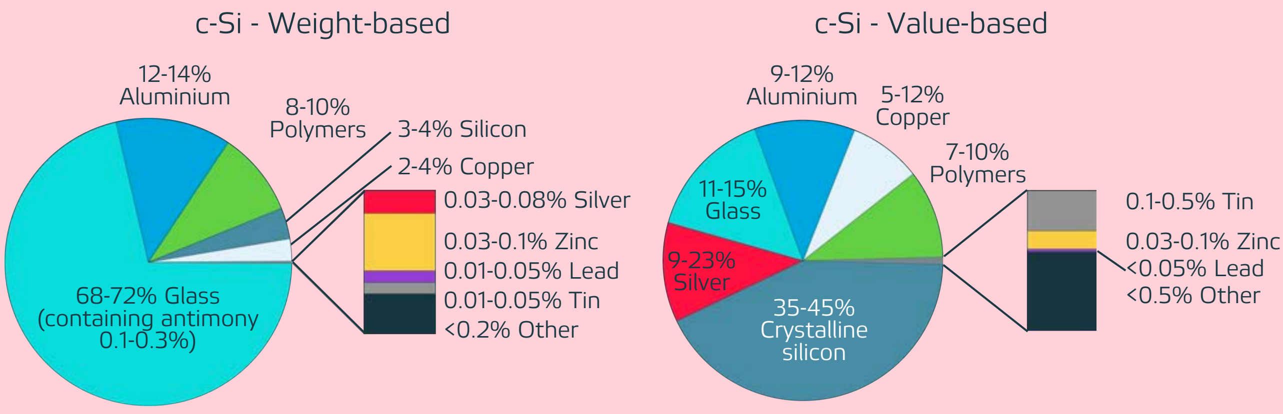


Figure 9: Material composition shares of crystalline silicon solar PV modules by weight and average values, 2021
Source: (IEA 2022)

Aluminium Frame

In the case of framed standard modules, aluminium frames account for roughly 15% of the PV module's weight. The frame provides mechanical strength and is typically between 30 and 50 mm high. It needs to withstand different weather conditions, such as strong wind, heavy rainfalls, hail and/or snow. In a typical recycling process, the aluminium frame is mechanically removed from the module so the aluminium can be returned to the material cycle (IEA 2022).

Glass

Nowadays, single-coated tempered glass with a thickness of 3.2 mm is normally used in the production process of PVs (see e.g. Borosil 2023 or Lamberts 2023). Bifacial modules are typically encapsulated with 2 mm low-iron glass on the front and on the back. Some PV module producers utilise a thinner glass of 1.6 mm, which reduces material consumption and glass weight (VDMA 2022, p. 33). Usually glass in solar modules accounts for 70 to 80% of the total mass. Although the material value of the glass corresponds to the range of 11 to 15% of the total amount (see Figure 9 left graph and Table 2).

Antimony

Antimony is a lustrous grey metalloid used in the production of low-iron high-transparency solar glass. During the recycling process, antimony may end up in the groundwater. Since antimony (Sb) is toxic to humans, similar to arsenic, efforts are being made to avoid its use or even release (Dupont et al. 2016). It is possible to produce high-transparent solar glass without using antimony and some glass manufacturers already offer such products.

Cables and Juction Box

As an indication taken from different data sheets, the cables contain copper or aluminium and plastic for the insulation. Normally, 4 mm^2 or 6 mm^2 cables of about 1 to 1.5 m in length are used for each pole. Two to six Schottky bypass diodes are integrated in the junction box (Longi 2023).

Polysilicon

About 96% of the photovoltaic modules treated by PV CYCLE in 2021 were silicon-based (PV CYCLE 2022, p. 4). The price for polysilicon fluctuates over longer periods and according to this, the recycling of this material is economically feasible or not (Bernreuter 2022). For use in semiconductors, purity is crucial in order to achieve high efficiencies.

In the past, solar cells in PV modules were usually made of p-type material and doped with boron. Recently, gallium is preferred as a dopant for p-type solar cells.

In principle, recycling of polysilicon by etching the metal contacts to remove the thin coatings is possible. However, it needs to be ensured that the material from recycled panels is treated separately after its collection: p-type for further p-type production and n-type for further n-type production of solar wafers and cells. In the past, p-type has been considered as bulk material, while nowadays, there is a shift towards n-type. This will make it difficult to reuse the p-type material in the long term, as according to a forecast (VDMA 2022, p. 11 Fig. 9) n-type will be the predominant wafer type in about five years. Another option consists in downgrading where the polysilicon is mixed with metallurgical grade silicon (mg-Si), which has a purity of 98% by weight (Luo 2017).

Solar Cell

Current encapsulation technology with EVA lamination foils and due to the fact that wafer thickness has continuously decreased over time to a level of about 170 nm make it difficult – if not impossible – to dissolve the bond without breaking the solar cells (VDMA 2022, p. 10). To reuse the solar cell, a new encapsulation design enabling easier disassembly of the module is needed. In the past, new and larger wafer sizes of up to 210 mm x 210 mm (M12 format) have entered the market, which had a significant impact on the module size (VDMA 2022, p. 12).

PV Module Reuse

According to the circularity approach, prolonging the lifetime of PV modules and its use would be optimal.

There is a second-hand market for functioning PV modules. In this context, costs for disassembly, measurement of the module yield (re-certification) to sort out defective modules, transport and reassembly at another location need to be considered. For example, 20-year-old PV panels have a significantly lower module efficiency and require more space to deliver the same power outcome than more efficient modern PV modules (Frischknecht, R. (ed.) 2022, p. 4). These are reasons against further use. However, a reuse of PV modules under non-profit-making conditions is feasible.

In summary, limitations for reuse of PV modules consist in the lack of a regional market, lower efficiency rates, shorter lifetimes and discrepancies with changing quality and safety standards (Tao et al. 2020).

4.1.3 Global Market

The historical global PV market up to 2021 and the projected market until 2030 are presented in Figure 10. In last decade, the annual installed capacity grew by 34.15% CAGR. In the course of the energy transition, a further exponential growth of PV installations is expected. As a result, large quantities of EOL panels are estimated in the medium to long term.

PV Module Lifetime

IEA-PVPS Task 12 calculates with a module lifetime of about 30 years (Frischknecht, R. (ed.) 2022, p. 2).

This means that modules produced in 2010 cannot be expected to reach their end-of-life until 2040.

However, there are always smaller quantities of modules that are damaged either in production (scrap) or during transport and / or installation. Therefore, some EOL modules already need to be treated today. For instance, natural disasters can generate prematurely damaged PV modules.

Purely auto-consumption and off-grid PV systems also exist.

However, obtaining permission is still challenging if private operators and / or small businesses are connected to the power grid and want to feed surplus PV power into the system.

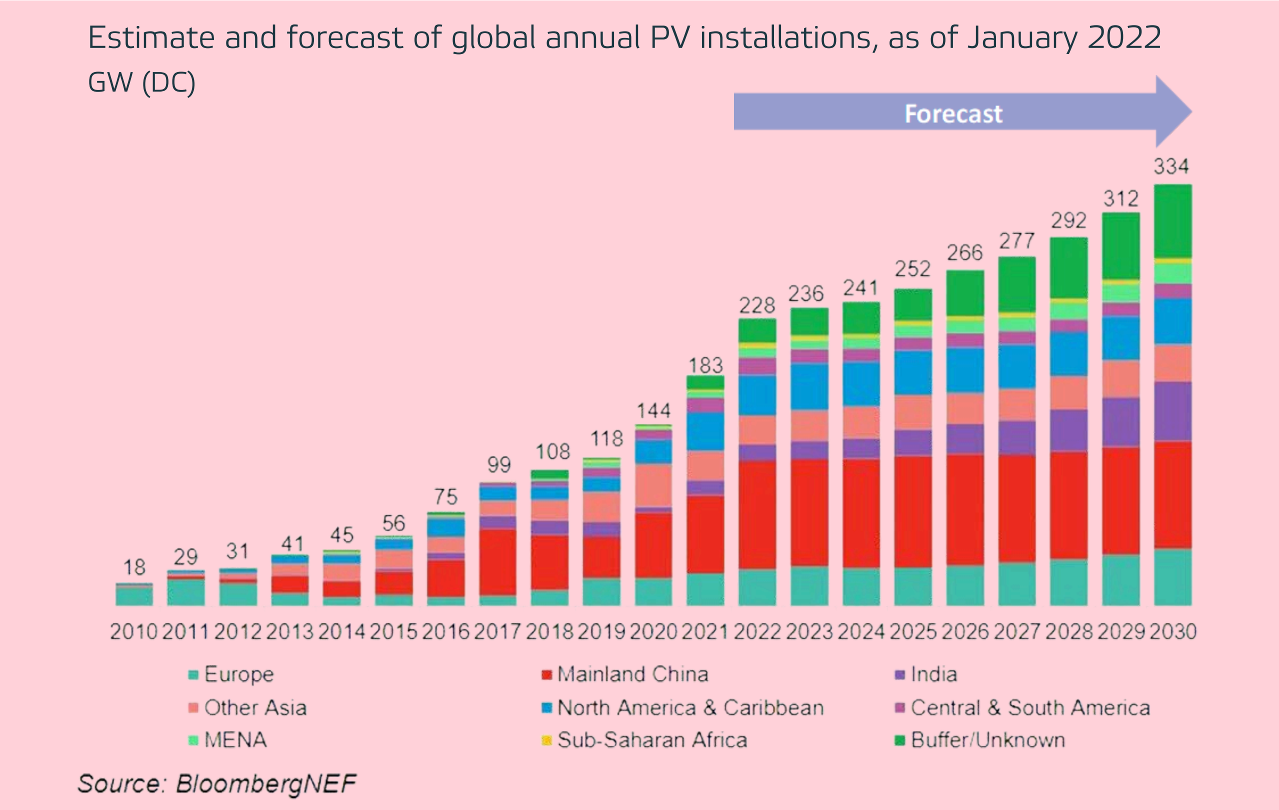


Figure 10: Estimated global PV installations (until 2021) and forecast, as of January 2022
Source: retrieved from (TaiyangNews 2022) – numbers from 2022 are forecasts.

4.1.4 Installed PV Solar Capacity in Morocco and Prospects

According to IRENA, in 2022, a total capacity of 318.2 MW PV capacity was installed in Morocco, including 23 MW off-grid installations (see Figure 4 on page 15). On the national context, few commercial Power Purchase Agreements (PPA) for medium voltage exist for utility-scale PV systems.

As a result, the current estimated amount of waste from PV modules is significantly low, but a strong increase can be expected in the future if a large number of PV systems are installed, as announced by the respective authorities.

The following questions will be addressed in the next chapter:

- Who will assume the responsibility for this waste in the future?
- Who will bear the costs for recycling?
- Which recycling possibilities exist for discarded modules?

4.2 International Best Available Techniques (BAT) for Waste Treatment

The following processes and techniques have been identified for the recycling of EOL modules. Both the international Best Available Techniques (BAT) and the Best Environmental Practices (BEP) are methods used to prevent and eliminate pollution released into the environment. In particular, these methods include the reuse of materials, thus avoiding the mining and sourcing of materials.

Mechanical Processes:

Including removal of the frame, junction box, cables, shredding, grinding, sorting (by applying laser selection or vibration), refining, etc., which have been proven as the most feasible and cost-efficient recycling solutions and are today common practice in Europe and applied by PV CYCLE, for example.

Further Methods for Recycling:

Mechanical delamination with state-of-the-art equipment, as used in the recycling business to separate first the aluminium frame and junction box and then the glass, foils, cells, etc.:

- Shredder + hammer mill
- Granulator + impact mill
- Sieve, windshifter
- Air separation table

Physical Processes:

- Various, magnetic / static fields or mass-based methods

Thermomechanical Processes:

- Pyrolysis – combustion
- Physical: heat and cold (cryogenic process)

Chemical Processes:

- Acidic etching with H2SO4-HNO3-H2O2-HCl-HF; alkaline etching; (cyanide etching) to remove the back contact, the anti-reflection coating and the emitter from the silicon solar cell

Electrolytical processes:

- Deposition of copper (lab scale)

Metallurgical processes:

- Melting of metals (Ag, Cu) and silicon (large scale); glass (lab scale)

1

It is beyond the scope of this white paper to go into all the listed techniques. The most common processes used in the PV module recycling industry today are mechanical or thermomechanical, as reported by PV CYCLE. The recycling rate is limited but in compliance with the European WEEE Directive. However, these techniques are affordable and represent a trade-off between effort and economic benefit. Further research is needed to improve the recycling rate while being economically feasible.

1. The European Commission Implementing Decision (EU) 2018/1147 of 10 August 2018 (notified under document C(2018) 5070) establishing best available techniques (BAT) conclusions for waste treatment can be found at: http://data.europa.eu/eli/dec_impl/2018/1147/oj

4.3 Best Environmental Practices (BEP)

Status Quo of PV Recycling

According to German legislation, at least 80% of the PV module weight needs to be recycled. In this process, glass, aluminium and copper cables are usually totally recycled, being considered as the heaviest components, hence complying with the regulatory requirements.

In an advanced process, metals (e. g. silver, copper, tin or lead) and silicon are recycled to be used as input for the production of new solar cells and modules (Dold 2019, p. 38).

Below key results from the project "EoL-Cycle" are presented. The first step consists in a mechanical treatment process, where the aluminium frame, the junction box and the cables are removed. Afterwards, the laminated glass is crushed in a separate process.

In the project, over 1,000 kg of silicon (including silver, lead and copper) were separated and recovered in order to optimise the process parameters. The separated glass fraction with a grain size of less than 1 mm needs to be free from plastic cargo to guarantee a meaningful material recycling.

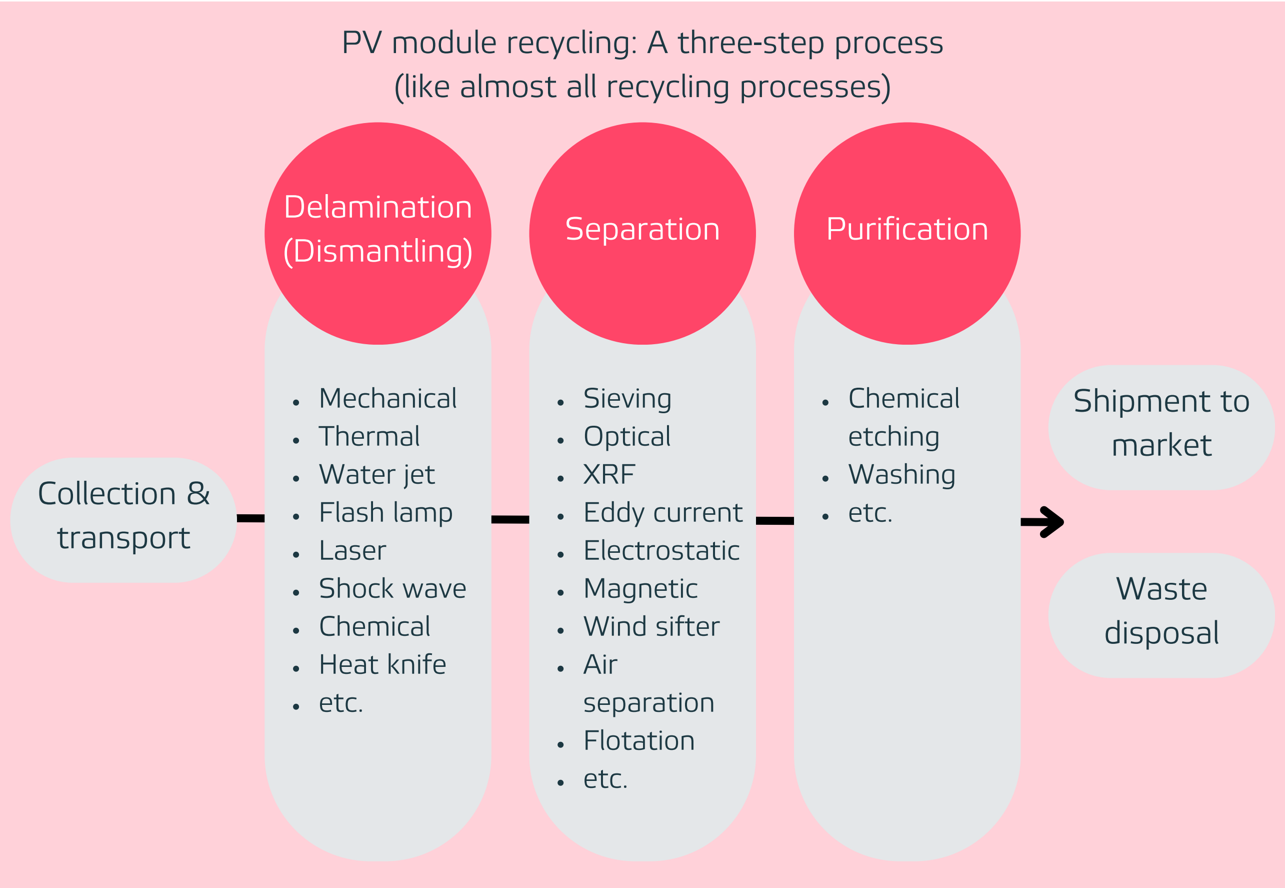


Figure 11: Recycling process chain for EOL PV modules
Diagram: Adapted from (Dold 2022)

The air separation table is consideres as the most effective method for this. Due to the fact that the separation sharpness is excellent, and depending on the size of the installation, the throughput is in the range of several hundred kilograms per hour.

For separating the foil material containing the solar cells, thermal treatment and chemical separation were identified as the most promising methods. The tested cryogenic conditions with liquid nitrogen were not effective, and strong mechanical impacts resulted in high dust exposure and significant material wear.

For the further processing of the separated cell material consisting of silicon and adhering metals (such as silver, lead, copper, etc.), the first recommended step is the magnetic separation of iron-nickel components, which are introduced in certain quantities as a result of strong mechanical effects during the crushing process. For the wet chemical dissolution of the metals lead, copper and silver, a mixture of nitric acid and hydrogen peroxide proved to be an affordable and simple method. The dissolved metal nitrates can then be easily precipitated and further processed.

The results obtained show a clear route for the economical recycling of EOL PV modules. The thermal and chemical methods yield satisfactory results, and ultimately the cost-effectiveness is highly dependent on the use of the existing infrastructure. Ensuring sufficient input material flows is crucial for economical process management to justify the necessary investment costs (Dold 2019, p. 39).

The advanced recycling process chain for end-of-life panels is illustrated in Figure 11. The advantage of this process lies in its universal application possibilities, being used for different PV module formats and technologies (e. g. mono- and multi-crystalline wafer-based solar cells).

Most of the techniques work well and can be applied in practice, the key question for implementation on a large industrial scale is how to realise high throughput at low cost (Dold 2022, p. 13).

The production boom in the solar industry has put recycling infrastructure on the back burner. For example, the US American solar panel manufacturer "First Solar" established an ongoing recycling initiative. However, it is only applicable to the provider's own products and has a maximum global capacity of two million panels per year.

At current capacity, the estimated costs for recycling corresponds to USD 20 and 30 per panel. In contrast, disposing in a landfill would cost between one and two USD. For thin-film PV technologies, separate recycling processes are required. Some companies, such as First Solar, which produce cadmium telluride PV modules, have established their own take-back systems and achieve a high recycling level.

European Regulation

In Europe, PV modules fall under the Waste from Electrical and Electronic Equipment (WEEE) Directive. According to Article 4 Product Design, the requirement to 'promote the design and production of EEE needs to be fulfilled, notably in view of facilitating reuse, dismantling and recovery of WEEE, its components and materials'. Further information can be found in Annex A.

Circular Economy and Recycling

A circular raw material economy is characterised by

- a reduction in the absolute level of consumption of natural raw materials;
- the expansion of a metal recycling infrastructure and corresponding recycling clusters;
- the further development from a waste-driven circular economy to a circular economy;
- the social and ecological dimension of the raw materials turnaround to ensure resource equity and sustainability standards in raw material supply chains;
- reliable databases so that the non-sustainable use of metals, the dissipative waste of metals is recorded, as is progress toward improved recycling and towards improved recycling and resource conservation;
- alternative business models based on service and desired functions.

As long as recycling is uneconomical, regulations need to be in place to avoid the landfill of hazardous substances such as lead and cadmium or the release of fluorinated combustion gases. In addition, producer responsibility should be extended.

Recycling Industry

PV CYCLE only applies what is known as the BATNEEC principle, which stands for “Best Available Techniques Not Entailing Excessive Costs”. In laboratory and small-scale treatment, the average recycling rate is 95% of weight. However, the procedures established in practice are still limited in volume and small industrial-scale waste treatment activities with a purely mechanical recycling process result in an average recycling rate of 70% of weight.

As installations increase, the number of solar modules reaching their EOL stage will also steadily increase. Solar modules become hazardous waste at the end of their useful life and can harm the environment if not properly recycled or disposed of. In the first 25 years of development, recycling of old modules was not an issue; however, proper disposal of solar modules at the end of their useful life is gradually becoming an important environmental issue. Therefore, proper recycling of PV waste will become increasingly important as the number of installations grows and production expands.

The use of valuable resources and the potential for waste generation in the EOL cycle of PV technologies requires efficient planning of PV recycling infrastructure. Hazardous materials, such as heavy metals, or toxic substances, such as antimony or fluorine compounds, must not be released into the environment in the process. To ensure the sustainability of large-scale PV, it is essential to develop cost-effective recycling technologies for the developing PV industry in parallel with the rapid commercialisation of these new technologies (Chowdhury & Al-Zahrani 2015).

4.4 Design for Circularity

For an optimised recycling process and the introduction of a circular economy in the PV sector, EVA encapsulation (see chapter 4.1.2) is fundamentally a problem (Schnatmann, Schoden & Schwenzfeier-Hellkamp 2022). An alternative could be the NICE encapsulation technology, a concept developed by Apollon Solar. NICE stands for New Industrial Cell Encapsulation. Further insights into the concept, which does not require EVA lamination, are provided in (Saint-Sernin 2008). With the NICE concept, only the edges of the front and rear glass surfaces are sealed, so that breaking up the module composite and thus recycling it would be much easier than with modules laminated with EVA, which are common today. However, some shortcomings in the technology – contact failures and cell breakages were reported as examples (Einhaus et al. 2005).
Improvements mainly in the crystallisation process and module assembly to reduce greenhouse gas emissions by 17% for solar modules based on mono-crystalline silicon wafer technology have been reported (Wambach 2018).

Recent Developments

There is still a lot of innovation and technological progress in PV technology. The industry strives to achieve higher cell and module efficiencies and use fewer or cheaper materials. In addition, manufacturing processes are becoming more and more automated and tailored to high throughput rates. For these reasons, high-purity silicon wafers, for example, have become ever larger and thinner. Using copper for the busbars and contact fingers instead of silver is proven to be technically feasible (Wood et al. 2015).

Latest developments in photovoltaic (PV) applications according to VDMA (2022) are:

- Monocrystalline silicon PERC with half-cut solar cells and multi-busbar is standard today
- >20% efficiency for bulk PV modules as mean value for the top ten producers (Tier 1)
- Larger wafer size were implemented by PV industry has resulted in new module formats
- Half-cut solar cells
- Shift from p-type to n-type (phosphorus as a dopant of the wafer instead of boron or gallium)
- Bifacial cells and modules
- Flexible and lightweight modules possible

The dynamic technological development causes difficulties with regard to EOL module recycling: in addition to size, wafer thickness, coatings, doping of the polysilicon, module design (bifacial instead of monofacial) as well as the substances used (future perovskite tandem cells?) change. This leads to a need for "one-size-fits-all" processes. For example, modules are always completely shattered after the aluminium frame and junction box have been removed. This has the disadvantage that a relatively high energy and material input is necessary and that it is difficult to recover materials in high purity. With regard to the circular economy principles presented in chapter 2.2, it would help to label the modules so that they could be pre-sorted according to construction type and materials or technologies used. This would make it possible to recover similar substances. The optimal path – which is unfortunately not yet technologically foreseeable – would be production in accordance with ecodesign criteria, which simplify the disassembly of EOL modules.

Moreover, the market is witnessing a surge in bifacial modules. This surge is primarily because the cell processing costs for bifacial and monofacial modules are almost identical, as noted by (Dullweber 2020). While these bifacial modules are generally encapsulated between two thin sheets of glass for enhanced durability, some maufacturers opt for polymer encapsulation to reduce weight. Such variations in encapsulation materials further complicate the recycling process. An initial selection step to segregate modules based on their encapsulation type becomes imperative. Yet, when dealing with smaller quantities of specific module types, establishing a separate recycling process might not be financially feasible.

Such technological developments are welcome if they help to reduce the use of materials (for example, less polysilicon due to thinner wafer thickness) or to increase efficiencies (as multi-busbars or back contact solar cell concepts which improve the amount of light entering the solar cell).
However, technological changes might make it more difficult to recycle the PV modules in the future, either because previous standards no longer apply – see the currently significantly larger module formats – or because the new type of material composition destroys the previous business model – for example if copper is used for contact fingers in solar cells instead of silver, the economic return of recycling decreases due to the fact that copper is worth far less than silver.

Recycling business can benefit from technological progress, but it can generate potential difficulties due to changing trends and market's needs. Hence, new fields of application were identified:

- Agrovoltaics (dual use of same piece of land for PV power generation and for farming)
- Floating PV
- Electrical vehicle-integrated PV
- Road-integrated PV
- Strong market growth for small balcony PV systems to reduce domestic electricity costs
- Combination with battery and energy management system; islanding capability to be safe for grid failure

These new application areas can easily lead to the PV modules being specially adapted to the application. In the case of electrical vehicle-integrated PV, the modules are integrated into the vehicle body. This can lead to further construction types and new material uses, which poses additional challenges for the recycling of EOL modules.

4.5 Opportunities

In current recycling mechanisms, glass and aluminium are recovered, wheras silver, silicon and polymer back sheets not. With regard to the use of alternative thermoplastic encapsulants or other ecodesign approaches the module lifetime should not be negatively affected.

An alternative or complementary approach to recyclable design is to use minimal amounts of scarce or harmful materials to simplify components (e.g. the junction box). The basic idea consists in that if a material is not available or does not need to be recovered, then the need for separation and reprocessing, similar to the cost of recycling and the environmental impact of the module, is reduced.

Potential for Job Creation

A study from the Dii Desert Energy initiative estimated that each investment of EUR 1 billion in solar PV installations will create 1,000 jobs. In Morocco, employment promotion for 15,000 and 23,000 people is expected in construction, machinery, metals and business services (Dii 2013, p. 19). According to IRENA, global job creation in the field of solar PV is estimated at 4.3 million (IRENA and ILO 2021). In 2022, a total capacity of 318.2 MW PV was installed in Morocco (see Figure 4). Several gigawatts can potentially be installed in Morocco, which will generate many jobs, reduce dependence on energy imports and make a significant contribution to achieving national climate targets.

4.6 Industrial Strategies for PV Module Recycling in Morocco

The following strategic recommendations for PV module recycling were developed from the perspective of industry and associations in Morocco at a workshop on 31 January 2023 in Casablanca. Attendees from industry and associations, NGOs and academia identified strengths, weaknesses, opportunities and threats (SWOT) in the national context and derived respective strategies from the analysis.

SWOT Analysis for PV Module Recycling

Strengths

- Affordable and qualified labour
- Existing (small) module assembly firms
- Time to craft framework for recycling
- R&D for ecology (IRESEN, MASEN) available

Weaknesses

- No existing recycling facilities
- No quality check during import process
- Missing regulations
- Lack of traceability and understanding of existing fleet makeup
- Missing installation standards and inspection/certification protocols

Opportunities

- New jobs and business value creation
- Reuse through recertification (establish testing centres, relabel modules and provide new warranty)
- Creation of Extended Producer Responsibility (filter suppliers through willingness to be involved in recycling)
- R&D in universities and specialised independent engineering firms (either ecodesign of modules or improved recycling technologies)

Threats

- No existing legal framework
- Many players/installers in the market, but not governed
- Being the recipient of European/American used/discarded panels that are not tested or certified

The following strategies were defined based on the SWOT analysis obtained from world café groupwork. Therefore, strengths should be expanded, weaknesses made up for and opportunities safeguarded. For possible treats, an avoidance strategy should be developed.

Strategies from SWOT Analysis

Expand • R&D to better train workforces and to develop design for recycling • R&D for advanced PV module recycling technology • Fostering of start-ups engaged in module reuse or recycling	Catch up • Establish/enable presence of certification/audit/testing firms overseeing product quality and supporting governmental authorities • Enable import of EOL modules (for example from other countries in Africa to obtain a critical mass for recycling facilities (> 10.000 tons/p.a. = 0.5 mill. modules per year are needed to make module recycling business profitable) • Collaborate with European countries to acquire best practices • Foster circular economy mindset @purchase (funding for reused products or recycled materials)
Safeguard • Encourage workforce to stay and support the local development	Avoid • Importing non-certified/-tested /-audited products

4.7 General Conclusion for PV Modules

It is essential that components are cleanly separated. For example, in the ReModul project Fraunhofer CSP demonstrated the technical feasibility of recycling almost 100% of silicon and producing new solar cells and modules from it. However, scalability and cost-effectiveness are crucial aspects, and current "Best Available Techniques Not Entailing Excessive Costs" (BATNEEC) principle is applied in practical recycling in Europe with about 70% of waste (weight) being recycled for silicon wafer-based PV modules.

Fostering circular economy approaches in the solar panel industry accounts for a significant step towards sustainable energy production and progress in achieving the goals of the EU Green Deal, contributing to the SDGs. A fully comprehensive recycling of PV panels with suitable (chemical) processes is required in order to reduce negative impacts from mining, e. g. metals such as silver.

The release of hazardous substances such as lead, cadmium, antimony or flourinated molecules needs to be avoided in order to protect people's health and the environment. Once waste volumes are significant, recycling and reuse of such metals are likely to become economically viable, and economies of scale will also benefit PV module recycling facilities (El-Khawad, Bartkowiak & Kümmerer 2022). As long as they are not, regulations or incentives need to be in place to avoid the landfill of such resources. Innovative technical, economical and societal solutions, including design, politics, regulations and new business models, need to be in place to improve EOL treatment of PV modules towards a circular economy.
Rapid innovations in cell and module design make it difficult to define a recycling strategy that will presumably still work in a few decades. Mandatory product labelling, for example with a permanently affixed QR code on the back of a PV module or on the junction box, could indicate whether the wafer is p- or n-doped and with which element (boron or gallium, for example, for p-type). The properties of the glass (e.g. antimony content) and the materials used for the lamination and backside foils, the silver or copper content of the contacts, etc. could also be documented in this way so that subsequent recycling is simplified by ensuring pre-sorting by material thanks to the provision of this automatically readable data.

Common Rules

These principles provide guidance for a sustainable transformation of the renewable energies sector:

1. Prolongation of product lifetime to reduce the amount of waste.
2. A product register (database) and product labelling (passport) can help to sort and separate materials in the recycling process.
3. To establish a profitable recycling business, a critical mass of EOL products is needed.
4. Collection and transport can be supported by business models, e.g. deposit systems.
5. Research and demonstration projects are required for innovative design to facilitate dismantling of such composite products after EOL (ecodesign approach).
6. Ecodesign: PV modules and wind rotor blades produced today will need recycling at the earliest after 30 years. There is therefore hardly any motivation in industry to proceed in this direction, meaning that regulations need to be in place to stimulate recycling.
7. Nowadays, recycling of EOL PV is mostly not a business case. Regulations are required to assign responsibilities among all involed parties and determine rules for treatment of waste materials. A legal framework is necessary to get political commitment.

5. Wind Turbine Rotor Blades

5.1 Materials and Waste

A typical wind turbine consists of a foundation, a tower, a housing (nacelle) and a rotor with three blades. A wind turbine is composed of an estimated 25,000 components (Razdan and Garrett, 2015). In term of weight, for example, to build a 100 MW onshore wind farm with 4.2 MW wind turbines, net required materials can be more than 67,850 tons of foundations, towers, nacelles, rotors with blades, cables, switchgears and transformers (Mendoza et al. 2022). Rotor blades account for only a fraction of the weight of a wind turbine but for nearly a quarter of the manufacturing costs: high manufacturing costs are a major issue because the blades are subject to a constant development process. This means that not only old, disused rotor blades present a recycling challenge but also the production waste, which comprises complex materials such as:

- Reinforcement fibres
- A polymer matrix (consisting of thermosets such as epoxies, polyesters, vinyl esters, polyurethanes, and thermoplastics containing bisphenol A)
- Sandwich cores (e.g. balsa wood)
- Surface coatings (e.g. polyethylene and polyurethane)
- Metals (such as copper wiring and steel bolts or lead shot as counterweight)

Not only old, disused rotor blades, but also the production waste present a recycling challenge.

Essentially, a rotor blade consists of two half shells (a top and a bottom shell), which are sandwiched together at the front and rear edge with resin adhesive (Figure 12).

In terms of weight, fibre composites constitute the largest share, amounting to at least 70%. Carbon Fibre-Reinforced Polymer (CFRP) is used increasingly in newer and larger wind turbines.

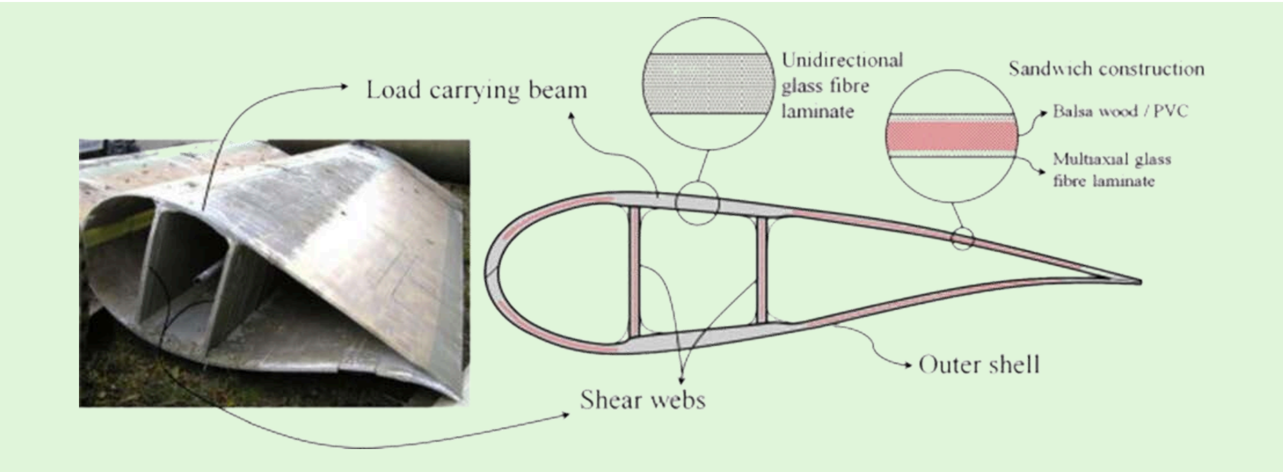


Figure 12: Wind turbine blade structure and material
Picture source (adapted): (Beauson et al. 2016)

The materials can be divided into three fractions:

1. Fibre composites and their constituents (glass and carbon fibres, epoxy and vinyl resins)
2. Metals (iron, copper, aluminium, lead) and other materials (such as electrical or electronic components)
3. Foam, balsa wood, paint, coatings, etc.

5.1.1 Amount of Waste, Hazardous Substances and Value of Recyclable Materials

Composites with a weight of 2.5 million tons were in use in the wind energy sector globally in 2020 (RechargeNews 2020). According to (Liu & Barlow 2017), there will be 43 million tons of blade waste worldwide by 2050, with China responsible for 40% of the waste, Europe 25%, the United States 16% and the rest of the world 19%.

There are concerns about the environmental impact of chemicals used in wind turbine blades. Hazardous materials used in wind rotor blades are plastics and adhesives such as epoxies, polyesters, vinyl esters, polyurethanes and thermoplastics and further softeners such as bisphenol A (BPA). The potential health impacts of BPA exposure from wind turbine blades are still being studied and are not yet fully understood. Nevertheless softeners with BPA can release solvent vapours that are hazardous to health. Bisphenol A could be leached out into the groundwater in landfills (Smith 2023). This is particularly significant, as BPA is one of the main constituents of turbine blades.

Bisphenol A is a chemical produced in large quantities for use primarily in the production of polycarbonate plastics and epoxy resins (Smith 2023). In 2023, the European Food Safety Authority (EFSA) established a tolerable daily intake (TDI) of 0.2 nanograms (0.2 billionths of a gram) per kilogram of body weight per day because bisphenol A can be carcinogenic, lead to infertility or cause other serious damage to health (EFSA 2023).
The research on the potential emissions of BPA from manufacturing, using and disposing of epoxy resins was conducted by Beratungsgesellschaft für integrierte Problemlösungen (BIPRO) on behalf of the Epoxy Resin Committee (EPOXY-EUROPE.EU 2015a).

Most epoxy resins found in the energy sector are used in wind turbines, particularly in composites and adhesives needed to produce rotor blades and other structural elements (EPOXY-EUROPE.EU 2015b).

Lead, which is used as a balancing mass in rotor blades, is a heavy metal and could contaminate the combustion residues and fumes if the EOL rotor blades are processed at high temperatures.

Carbon Fibre-Reinforced Polymer (CFRP) is used in wind turbine rotor blades as a lightweight material to increase the stability of the blade by improving its strength and rigidity, especially when structural integrity and resistance to mechanical fatigue are critical. CFRP waste in incineration or cement kilns should be avoided because it clogs the flue gas filtering system.

Sulphur hexafluoride (SF6) is used in the wind turbine's electrical gas-insulated switchgear as an interruption agent and an insulator preventing electric arcs. SF6 has a global warming potential (GWP) of about 23,000 times that of carbon dioxide (CO2) over a 100-year period (Widger & Haddad 2018).

Vattenfall data indicate that Europe's 100,000 wind turbines have leaked approximately 900 kg of SF6 over six years, equalling 3,525 tons of CO2 annually. This figure refers to emissions during reclamation and recycling processes.

At a turbine's end-of-life, SF6 is recovered from switchgears and reused. Comparatively, in 2017 wind energy prevented 255 million tonnes of CO2 emissions in Europe by producing 336 TWh of electricity, replacing fossil fuels.

Thus, the SF6 leakage represents only about 0.001% of the emissions offset by wind energy each year (WindEurope 2019).

Neodymium, a critical raw material (CRM) used in the magnets of the wind turbine generator, should be reused or recycled due to its rarity. Recycling neodymium from wind turbines is technically feasible and expected in future processes.

This recycling is more efficient and ecofriendly compared to primary extraction from mining. Since only a few elements of the rare earth group are used, their separation and recovery are easier when recycling neodymium from the magnets of wind turbines. Although suitable recycling methods exist at laboratory and pilot scales, large-scale industrial application awaits the availability of substantial waste quantities.

The value of end-of-life rotor blades depends on the type of material used, the method of decommissioning and the options for reuse or recycling. Some possible values are as follows (Beauson & Brøndsted 2016):

Reuse: Some end-of-life rotor blades can be reused after being decommissioned, either as whole blades or as parts, for applications such as bridges, playgrounds, furniture, or art installations which are downcycling. In this way, their service life is extended and their environmental impact reduced.

Recycling: Some end-of-life rotor blades can be recycled, either mechanically or chemically, to recover materials such as glass fibres, resins or metals. These materials can be used for new products such as cement, asphalt, insulation or composites. In this way, resource efficiency is improved and waste generation minimised.

Energy recovery: Some end-of-life rotor blades can be incinerated to produce produce heat or electricity, either alone or mixed with other waste streams. In this way, the energy content of the blades is utilised and landfill avoided.

These are some examples of the value of end-of-life rotor blades. However, there are also challenges and barriers to implementing these solutions, such as technical, economic, environmental, social and legislative aspects which will be described further in the next paragraphs. Therefore, a holistic approach is needed to optimise the end-of-life management of rotor blades.

5.1.2 Global Market

The global wind power capacity reached about 840 GW in 2021, of which 93% were onshore systems and 7% offshore systems.

Depending on maintenance and repair, a lifetime of 20 years and more can be expected (WindEurope 2020b).

From the perspective of waste management, rare earth elements in the permanent magnets of generators, composites used for rotor blades in wind turbines and metals offer potential for recycling and at the same time pose technical and environmental challenges.

80-90% of the mass of the blades is made from composites, in which 60-70% of the mass is glass-reinforced plastic (GRP) (Jacoby, 2022).

Because of its high strength, flexibility and processing ease, it is popular in the shipbuilding and automotive industries, as well as being used in the production of rotor blades for wind turbines. But, until now, the possibilities for its recycling have been limited. Dumping GRP waste in landfill sites has been prohibited in Germany since 2005, and incineration is only permitted to a limited extent (Frank J. Kroll).

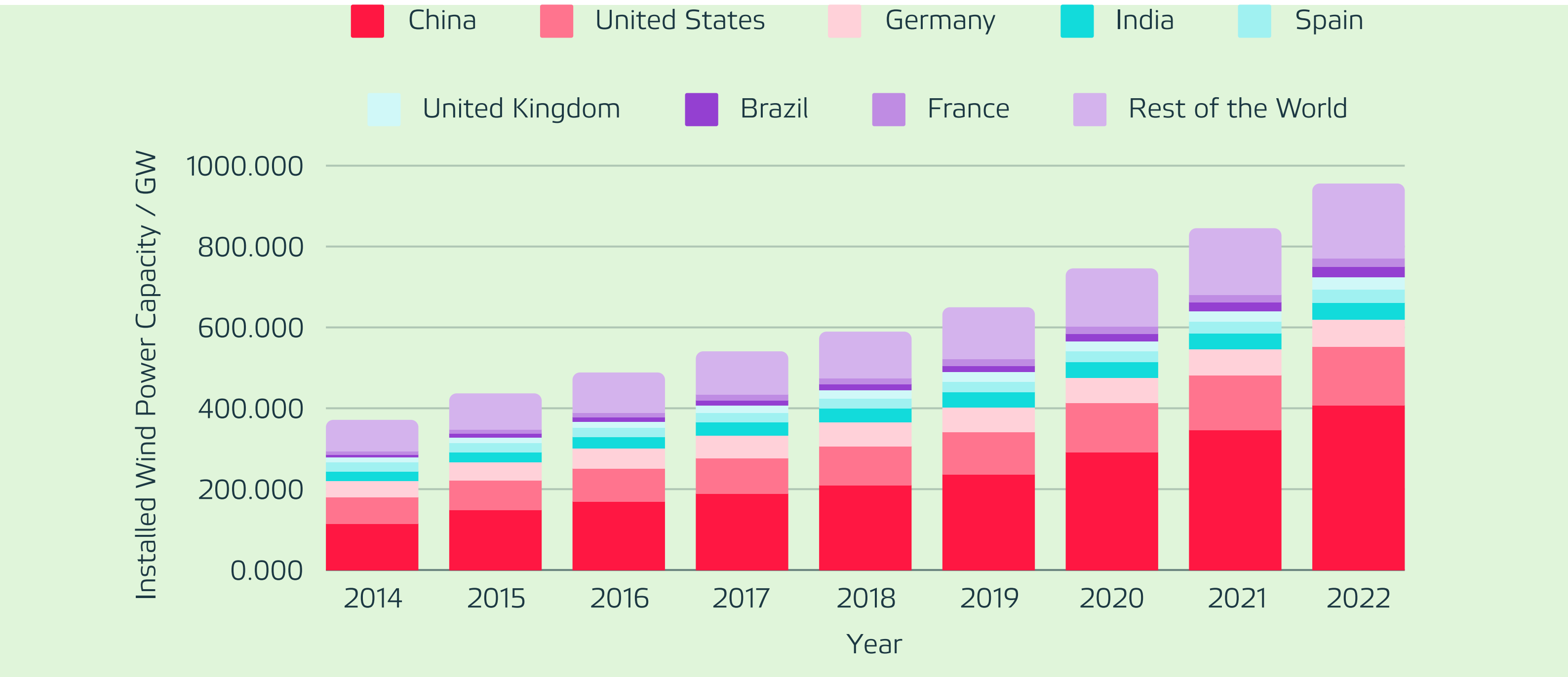


Figure 13: Global installed wind power capacity by country
Data source: WWEA 2023, Chart: PSE Projects

Even the recyclability of the whole wind turbine is estimated at about 85-95% thanks to the metal content in its parts. In fact, the recycling rates for steel, copper and aluminium are about 44%, 45% and 60% respectively (Mendoza et al. 2022).

The recycling rate for electronic components is about 50%; 100% of fibreglass, paints/adhesives are landfilled (Alsaleh & Sattler 2019).

5.1.3 Wind Energy Capacity in Morocco

According to IRENA, a total capacity of 1,556 MW onshore wind energy capacity was installed in Morocco in 2022 (see Figure 4). No offshore wind installations have been reported so far.

Siemens Gamesa had a regional office and a large-scale blade factory in Morocco.

Five years after going into operation, the factory had to close in the winter of 2022 due to declining orders.

5.2 International Best Available Techniques (BAT) for Waste Treatment

The European Waste Framework Directive (2008/98/EC) establishes fundamental principles for waste management. It promotes increased recycling efforts and draws attention to the dwindling availability of landfill space for waste disposal (WindEurope 2020, p. 20). Table 3 presents innovative material research topics for wind turbine rotor blades and the intended effects.

	AREAS OF MATERIAL RESEARCH	EFFECT
Processing Design	Process modelling optimisation and control of the curing processes of the composites	Increased lifetime, higher conversion efficiency
	Automated manufacturing processes for consistent material qualities and more robust techniques	
Process	Cost- and energy-saving manufacturing of carbon fibre-reinforced composites. Cheaper recovery of carbon fibre than of glass fibre	Longer blades, increased conversion efficiency
	Innovative resin/fibre combinations with improved ductility and fatigue resistance	Increased lifetime
	New infusible thermoplastic resins processed by in-mould polymerisation with better mechanical properties	Cost reduction
	Strengthening nano components and coatings by respecting HSE requirements. No complex recycling methods	Increased lifetime, improved recyclability
	Hybrid reinforcements with high performance glass, carbon and nano fibres	Longer blades, increased conversion efficiency
Materials	Durable coating materials for erosion-resistance e.g. gel coats, paint systems and tapes, resealable and self-healing coatings	
	Bioresins from available biowaste for more performance	Non-fossil raw materials, reduced carbon footprint
	New thermoset 3R resins for better re-processability, repairability and recyclability	Increased lifetime, improved recyclability

Table 3: Innovative areas in material research for wind turbine blades
Source: (WindEurope 2020, p. 13)

5.3 Best Environmental Practices (BEP)

From an environmental point of view, prolonging the lifetime of the rotor blades would be a favourable option for reducing the amount of waste or at least for postponing the need to recycle it into the future. If the lifetime of a part is increased by x percent, the current volume of waste is decreased to 1/(1+x). For example, increasing lifetime by 20% would result in a decrease of the current volume of waste to 1/1.2 (which is 83.33 %) of the amount without prolonging the lifetime. This means that by prolonging the lifetime of wind turbine rotor blades by 20%, the current amount of waste would decrease by about 16.7%.

Prevention

The wind industry aims to sustainably manage waste by first preventing blade waste through reduction and substitution strategies during design.

This includes the following (WindEurope 2020a, p. 21):

- Reducing the mass of blades to minimise recycling material
- Lowering blade failure rates and extending their lifespan. This is achieved through robust testing and certification, using updated standards like DNVGL-ST-0376 and the forthcoming IEC 61400-5.
- Designing blades for easy upgrading to newer versions, such as segmented or modular blades, which, however, are not yet standard.

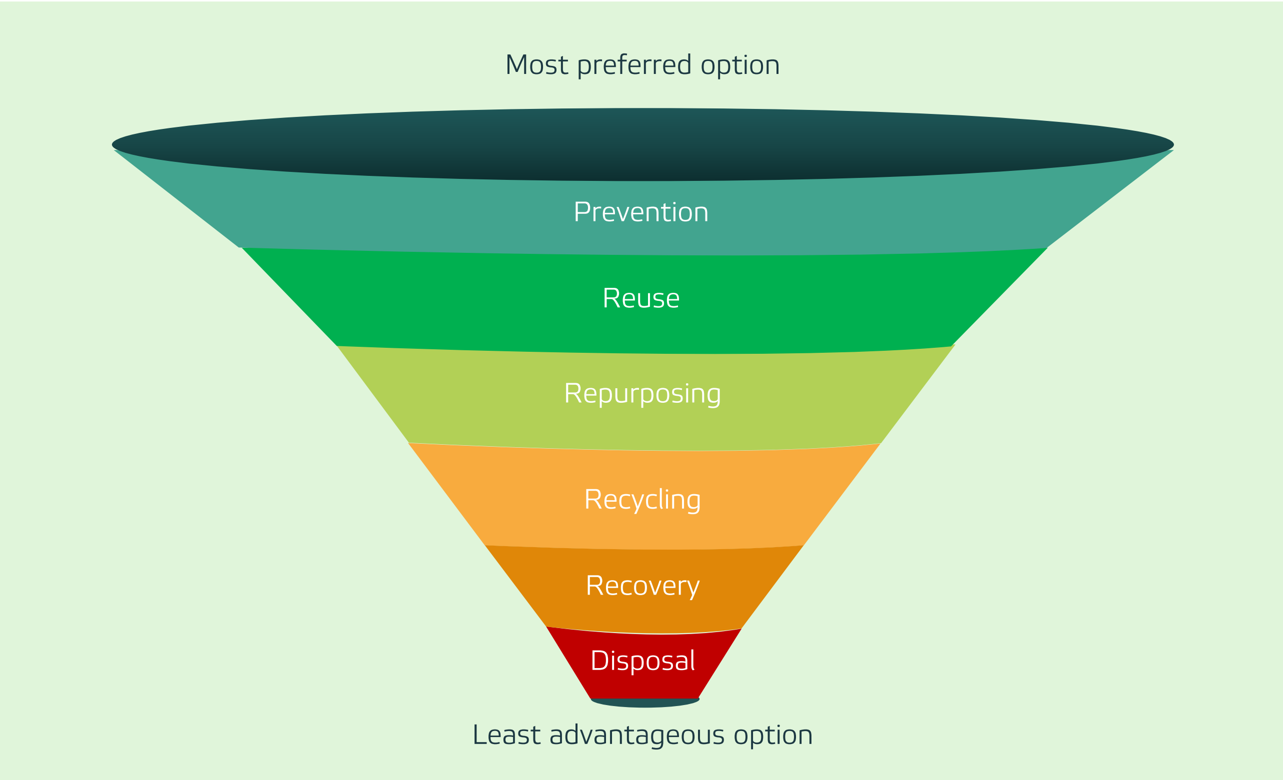


Figure 14: Hierarchy for sustainable blade waste management
Source: ETIPWind

Two strategies exist for this: first, preventing damage, for example by reducing the load on the blade, and second, maintenance and repair, that is periodic inspection of the rotor blades and repairing cracks or small damage. Figure 15 outlines these two strategies.

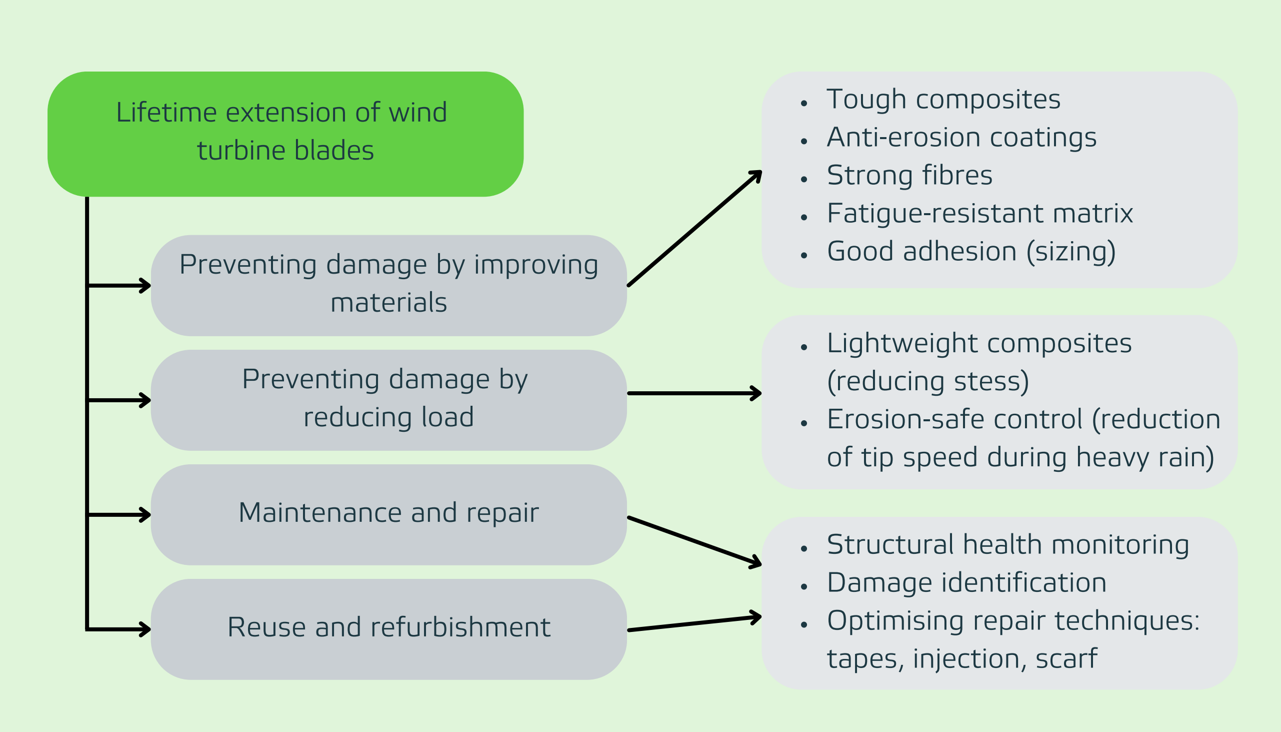


Figure 15: Lifetime extension of wind turbine rotor blades
Adapted from: (Mishnaevsky 2021, p. 3)

Reuse

Before considering waste treatment, the goal is to use and reuse the blade as much as possible. Regular maintenance and repair are crucial to achieving the blade's design lifetime. To extend its lifetime, its remaining useful life (through fatigue load analysis using SCADA data or similar) should be assessed in conjunction with site inspections and review of maintenance history. The outcome could involve repairs and reinforcements. DNV-GL and the IEC have developed standards for extending the lifetime of wind turbines. Additionally, various European and North American firms sell refurbished turbines and components.

Repurposing

The next phase in waste management is repurposing, which involves using parts of the blade for a different, typically lower value, application. Examples include:

- Repurposing blades for playgrounds or street furniture
- Using specific structural parts for building structures such as bicycle shelters, bridges, walkways, or for architectural reuse

However, the existing repurposing examples are mostly demonstration projects and unlikely to be a large-scale solution for anticipated future waste volumes (WindEurope 2020, p. 21).

Legislative frameworks

The legislative framework to foster an environment for circular economy (CE) opportunities and applications plays a crucial role for wind energy to be developed, applied and controlled. In particular, the waste from wind turbines, which will be generated at the end of their lifetime, must be managed sustainably. There are a number of laws and support schemes for wind energy promotion, as seen in the EU (González & Lacal-Arántegui 2016), such as the Renewable Energy Directive 2009/28/EC, support schemes (such as feed-in tariffs, feed-in premiums, quota system and tradable green certificate, tax incentives or exemption, investment grants, etc.).

Some other legislative frameworks can be used for different CE strategies through regulatory/planning instruments (e.g. waste management regulations, waste management plans, Best Available Techniques, Extended Producer Responsibility schemes, procurement procedures in favour of recycled products), economic instruments (e.g. landfill tax, take-back systems, reverse logistics, financial incentives), voluntary instruments (e.g. public-private partnerships for recycling technologies, waste separation with informal waste picker cooperatives) and informational instruments (e.g. guidelines for waste recycling, product labels and certificates, information campaigns).

Product design requirements

Obliging wind turbine operators to continue using the rotor blades after wind turbine decommissioning would only be considered if the rotor blades could continue to be used for the relevant period and if a market for such used rotor blades were to exist or could be established. This should be dealt with on a case-by-case basis and not be the subject of an abstract/general obligation.
However, according to Section 24 (1) of the German Circular Economy Act (Kreislaufwirtschaftsgesetz – KrWG), the authorities might rule that (UBA 2022a, p. 59):

- Only rotor blades designed in such a way as to facilitate their multiple use may be put on the market. This might mean a design that allows the disassembly of the rotor blades or an effective separation of rotor blade parts containing fibres.
- Full consideration must be given to dismantling, reuse and recycling in the design and production of rotor blades.
- The use of hazardous substances must be avoided.

5.4 Design for Circularity

One way to design wind turbine rotor blades so that they can be recycled more easily is to use recyclable composites that can be separated into their original materials at the end of their lifetime. For example, Siemens Gamesa has launched the world's first recyclable wind turbine blade, called RecyclableBlade, which uses a thermoplastic resin that can be heated and remoulded into new applications. This novel resin has a unique chemical structure that simplifies its separation from other elements at the end of the wind turbine rotor blade's lifetime. Unlike other recycling methods, this gentler process preserves the materials' qualities. After separation, these materials can be repurposed for new uses (Menendez-Vila, M. 2021).

Another example is the RECREATE project, which aims to develop reusable fibre composite structures for wind turbine rotor blades, using a reversible bonding technique that allows[1] easy disassembly (Recreatecomposites 2023).

Another way to design wind turbine rotor blades for easier recycling is to use biobased materials that can be composted or biodegraded. For example, the German Environment Agency (UBA) has published a report on the sustainable use and waste processing of rotor blades, which includes examples of biobased composites made from natural fibres and resins (UBA 2022b).

Recent developments

The average size and power capacity of wind turbines have increased over time, from 0.05 MW and 15 m diameter in 1985 to 3-4 MW and 150 m diameter onshore and 8-12 MW and 220 m diameter offshore in 2020. The length of the rotor blades depends on the size of the turbine, but can reach up to 170 metres.

1. Further information is available on the project website https://www.recreatecomposites.eu/

5.5 Opportunities

Under the CE approach, and considering the context of Morocco, where most wind turbines are imported from other countries, the CE opportunities and applications can be categorised in several groups:

Circular Business Models (CBMs)

CBMs are an important part of CE, such as new thinking towards resources and waste, collaboration and innovation. Mendoza et al. (2021) listed some potential CBMs for wind turbines, with industrial business cases as examples. Some relevant to the context are: collection, take-back and reprocessing (magnet recycling as one example), community-owned wind parks, reuse (new lease of life for ageing wind turbines (PES 2015), repurposing (wind blades for urban furniture, playgrounds, bus shelters) or recycling. Other options are lifetime extension, repowering and decommissioning of the site (Ziegler et al. 2018, pp. 1261–1271).

While various technologies for recycling blades exist, and an increasing number of companies offer composite recycling services, most solutions are not yet widely available or cost-competitive.
Some recycling technologies for wind blades are:

- Solvolysis (using reactive solvents to break down chemical bonds in thermoset resins)
- Pyrolysis (thermal decomposition of materials at elevated temperatures, often in an inert atmosphere)
- Downcycling: input for cement industry or road construction, insulation

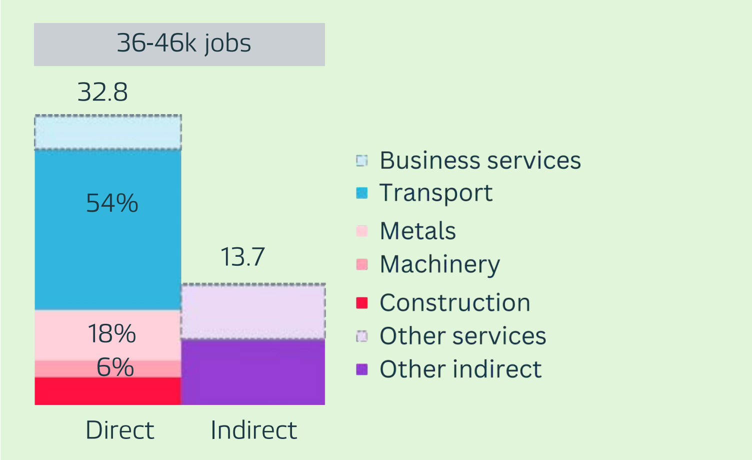


Figure 16: Job effects per EUR 1bn investment for wind technology power plant construction.
Potential for Morocco.
Dotted lines due to uncertainty.
Source: IfW / Dii (Dii 2013, p. 19)

Potential for job creation

Investment in wind energy contributes to job creation. Wind energy itself does not create a lot of direct jobs (except in the construction of wind power plants), but it creates more indirect ones in the production of components and related training and teaching services (AfDB 2016). Like other renewable energy sectors, related sectors such as energy efficiency in buildings contribute significantly to job creation. Figure 16 presents job effects per EUR 1 billion investment for wind power plant construction with potential for Morocco.

5.6 Industrial Strategies for Wind Turbine Rotor Blade recycling in Morocco

The following strategic recommendations for wind turbine rotor blade recycling were developed from the perspective of industry and associations in Morocco at a workshop in January 2023 in Casablanca.

Wind turbine rotor blade recycling - SWOT

Strengths

- Well concentrated in Morocco, many actors involved
- Low-cost labour for reuse/recycling of blades
- Qualified workforce (IFMEREE, OFPPT)
- Reuse mindset
- Developed steel recycling industry

Weaknesses

- Lack of field experience
- Insufficient volumes of waste to establish a recycling industry
- Incomplete regulatory framework
- Difficult to transport
- High cost for recycling
- No existing facilities

Opportunities

- Regional hub for repowering[1]
- Have requirements in terms of availability of blades that can be used as biodegradable materials

Threats

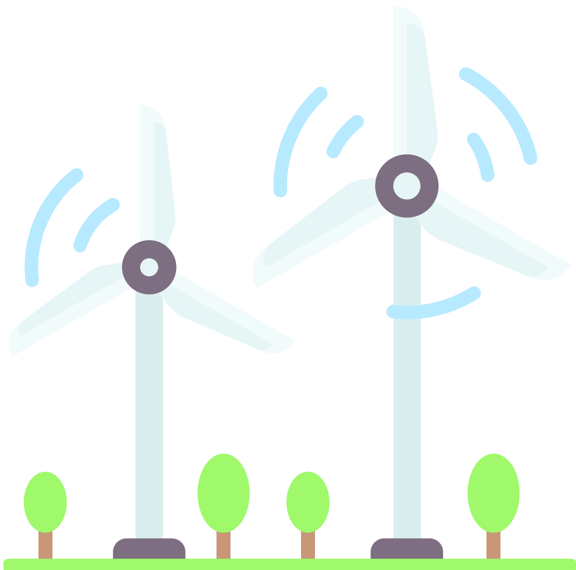
- New tech impacts existing recycling plants; for example, soluble resin design would significantly change the dismantling process of wind turbine rotor blades
- Health impacts of working with fibreglass

1. Repowering a wind farm means replacing the old turbines by more powerful and efficient models that use the latest technology. The previously installed systems can be refurbished and reused – possibly in other markets.

The following strategies were derived from the SWOT analysis above in World Café groupwork.

Strategies derived from SWOT

Expand	Catch up
• Export know-how (Europe and America) • Develop secondary market for repowered blades • Capacity building	• Set up a regulatory framework • Require a minimum quality standard for future installations / blades
Safeguard	**Avoid**
• Repowering needs to be actioned • Quality control	• Investment in a full recycling plant due to the risk of stranded assets in the event of a significant change in technology (instead invest in smaller installations to cut the blades so that they can be transported more easily) • EHS[1] risks and problems – for example from respirable dust that can be generated during the crushing of wind turbine rotor blades • Landfills



1. EHS = Environment, Health, Safety

5.7 General Conclusion for Wind Turbine Rotor Blades

Extension of blade lifetime, maintenance, repair and refurbishment are the most reliable approaches for reducing composite wastes.

There are a number of good and promising solutions for recyclable composite materials for the next generation of wind turbines. Soluble resins are being investigated that will facilitate the dismantling of end-of-life rotor blades. These solutions are now on Technology Readiness Level (TRL) 3 to 6 and will come on the market in 2027 or after.

A technical and organisational plan for handling waste from wind power systems in the future is needed. Developing standards is recommended to ensure quality and a viable strategy for recycling rotor blades without harm. This involves a comprehensive concept for the maintenance, repair, dismantling and processing of rotor blades (UBA 2022).

Learning from German experience, UBA recommends some organisational improvements for high-quality rotor blade recycling that include:

- Enhancing information for wind turbine operators and disposal companies
- Defining disposal provisions for rotor blade waste
- Upgrading monitoring of waste disposal
- Introducing take-back requirements for turbine manufacturers if proper disposal infrastructure is lacking

Quantifying rotor blade waste is complex and uncertain due to data challenges. Operators and disposal companies lack essential disposal information, necessitating improved data sheets e.g. a cradle-to-cradle passport in the market register, rotor blade labelling and manufacturer information.

Mandatory data in the market register should include:

- Rotor blade weight, material and design
- Turbine and blade data
- CFRP and GFRP labelling, fibre characteristics, balancing weights and recycling options

Avoiding waste issues includes not using CFRP waste in incineration or cement kilns and preventing contamination of other waste streams. Guidelines and thresholds for hazardous substances such as lead, bisphenol A and SF6 should be established.

A national guideline for Morocco might include:

1. Environmentally friendly dismantling (soil and water protection, etc.)
2. Criteria to prevent storing blades as 'sham spare parts'
3. Steps to examine economic feasibility of reuse
4. Prevention of dust emission during segmentation
5. On-site fraction separation

Take-back obligations might be needed if disposal facilities are insufficient. Extended Producer Responsibility (EPR) could involve turbine manufacturers and distributors. EPR principles should not exempt operators from financial responsibility (UBA 2022a, p. 58f).

6. Conclusion

Morocco aims to increase renewable energy to over 50% of its electricity mix by 2030 by leveraging abundant wind and solar resources of the MENA region. This shift reduces oil and gas dependence, thus aligning the country with climate goals.

In ISC3-guided workshops, Moroccan experts analysed sustainability issues arising with the disposal of renewables and give recommendations. These include improved waste monitoring, manufacturer take-back rules for PV modules, and wind turbine rotor blades recycling standards. A comprehensive national plan for maintaining, repairing, dismantling and processing PV modules and rotor blades is considered essential. While 100% recycling would be ideal, it may not be justified due to the costs, the energy and resources required for the recycling process. Thus, a pragmatic approach is suggested in this paper, focusing on current best practices and emerging trends.

The workshop participants derived strategies from a SWOT analysis and 'World Café' groupwork that focused on regulations, R&D, Extended Producer Responsibility, organisation, statistical data and financing:

Regulatory Framework

Morocco's waste management, guided by Law 2800, shows commitment to sustainability. Despite initial progress, outdated and complex regulations need improvement. The WEEE Directive and the RoHS Directive in the European Union regulate electronic waste and recycling quotas and provide a threshold for critical materials. They could serve as best practices for Morocco, since they are some of the strictest regulations for protecting human health and avoiding pollution.

Emphasising waste separation, strengthening capacity building and sharing information are key to enabling the economic feasibility of recycling initiatives. To support, a public, regularly updated regulation database is being developed for easy accessibility of regional, state and national legislation.

Different stakeholders from private associations are already involved in the creation of a regulatory ecosystem for more holistic waste management.

Research and Development

Morocco is in the early stage of addressing waste management. The country has a solid foundation with some large-scale installations. Despite challenges such as a lack of recycling infrastructure and limited knowledge of specialised recycling, there are political will and resources.

As an example: The World Bank supports renewables programmes while international success stories inspire progress. Plans include pilot projects, recycling training, stakeholder awareness raising, initiating industrial partnerships and attracting investors. Additionally, efforts are underway to establish a symbiotic ecosystem linking the research community and industry, promoting government-private partnerships, training of trainers and encouraging specialisation in recycling. Collaboration between different stakeholders such as academia, authorities and industry, is crucial for identifying further R&D requirements and facilitating knowledge transfer.

Clear Responsibility

Extended Producer Responsibility (EPR) can be assigned to wind power plant operators, ensuring funds for rotor blade end-of-life treatment. For PV modules, often produced in Asia, a collection system like PV CYCLE is suitable for organising EOL recycling.
Given locally limited waste volumes, cross-country collaboration for organising collection, recycling and general circular economy practices appears to be the best approach.

Statistical Data and Product Passport

Asking questions that are relevant for EOL is essential: Does the rotor blade contain carbon fibres or lead? Is the PV module made with p-type or n-type silicon solar cells? A product passport or precise labelling will aid sorting and deciding for proper recycling. Statistical data on product types in various regions are valuable for EOL determination, waste assessment and future waste estimation. A 'master market data register' helps in the management of wind and PV power plants and grid control.

Financing

Morocco's funding for a circular economy is gaining traction through diverse strategies. Grants and investment mechanisms offer access to finance and security. Despite data gaps, financial studies and plans are guiding investments. Support extends to innovative projects and start-ups. Tax incentives bolster this sector.

A strategic approach focuses on recycling facilities and technological solutions. Ecotax and land acquisition funding are being explored as supporting mechanisms. These steps signal a promising future for Morocco's circular economy financing.

Concluding the report, the following opportunities should be highlighted:

- Growing waste streams from PV modules and wind turbine rotor blades represent a future environmental challenge, but are also unprecedented resource to create and pursue new economic avenues.
- End-of-life management could become a significant component of the respective value chain and can spawn new industries, supporting considerable value creation.
- Re-powering of PV or wind systems could lead to a second-hand market in which the old systems could be reused after being checked and repaired.
- Waste treatment is economically feasible if a critical mass of waste is available. International collaboration is required to apply Best Available Techniques and ensure a high recycling rate – in particular to circulate rare materials and extract hazardous chemicals.

Further Reading

Going into detail on all aspects of recycling composite materials such as PV modules and wind turbine rotor blades would have been beyond the scope of this white paper. A more comprehensive overview can be found in the following publications and the references underneath. We would like to thank for their contributions to this report: Dr Dorota Bartkowiak (El-Khawad, Bartkowiak & Kümmerer 2022) for her input on improving the EOL management of PV modules and Dr Leon Mischnaevsky (Mishnaevsky 2021) for his input on the sustainable EOL management of wind turbine rotor blades.

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Annex A: Regulatory Framework

European WEEE Directive and RoHS Directive

The European Union has the world's strictest legal frameworks for waste treatment. There is the WEEE Directive – Directive 2012/19/EU on waste electrical and electronic equipment (WEEE) - and the RoHS Directive – Directive 2011/65/EU on the restriction of the use of certain hazardous substances in electrical and electronic equipment (EEE). Both directives can be a blueprint for other countries.

WEEE Directive 2012/19/EU

- The basic principle of the directive is the Extended Producer Responsibility – manufacturers bear the responsibility for the waste management of their products throughout their entire life cycle.
- The WEEE Directive contains the following cornerstones:
    - Producers of electrical and electronic equipment must ensure the treatment and recovery of WEEE collected or taken back.
    - Producers, when they put a new appliance on the market, guarantee the financing of its subsequent environmentally sound disposal.
    - Distributors take back WEEE from private households under certain conditions.
    - The collection and recycling/recovery targets set out in the Directive are met.

RoHS Directive – Directive 2011/65/EU

- RoHS Directive – 2011/65/EU on the restriction of the use of certain hazardous substances in electrical and electronic equipment (EEE).
- Dangerous substances (Annex II of the Directive) include lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB), polybrominated diphenyl ethers (PBDE), di(2-ethylhexyl) phthalate (DEHP), butyl benzyl phthalate (BBP), dibutyl phthalate (DBP), diisobutyl phthalate (DIBP).
- The limit value is 0.1% in each case, and 0.01% for cadmium.

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Annex C: Glossary

CAGR	The Compound Annual Growth Rate (CAGR) is the annualised average rate of revenue growth between two given years, assuming growth takes place at an exponentially compounded rate.
CAPEX	An acronym for capital expenditures CAPEX refers to capital expenditure on longer-term fixed assets, such as machinery, buildings, but also original equipment, spare parts, computer systems, etc. CAPEX is an important characteristic value of the balance sheet. CAPEX costs increase the assets on the balance sheet, which are depreciated over the long term.
CFRP	An acronym for Carbon Fibre-Reinforced Polymer.
CO2	The chemical formula for carbon dioxide.
Ecodesign	Ecodesign is the design or redesign of products, services, processes or systems to avoid or repair damage to the environment, society and the economy. It involves considering environmental aspects at all stages of the product development process, striving for products which make the lowest possible environmental impact throughout the product life cycle.
EESG	Economic, Environmental, Social and Governance factors to consider in sustainable development.
EHS	An acronym for Environment, Health, Safety.
EOL	An acronym for End of Life. Product End of Life (EOL), is when a product is retired from the market. Retirement can involve completely pulling the product from the market without replacing it or, in many cases, replacing it with a new version.
EPR	Extended Producer Responsibility. The OECD defines EPR as an environmental policy.
EVA	An acronym for Ethylene Vinyl Acetate used as the standard material to laminate PV modules.
IFMEREE	Institut de Formation des Energies Renouvelables et Efficacité Energétique.
GFRP	An acronym for Glass Fibre-Reinforced Polymer.
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit (German Agency for international cooperation).
IRENA	International Renewable Energy Agency located in Abu Dhabi.
IRESEN	Research Institute for Solar Energy and New Energies headquartered in Rabat, Morocco.
ISC3	International Sustainable Chemistry Collaborative Centre headquartered in Bonn, Germany.
LCOE	The levelised cost of electricity (LCOE) is a measure of the average net present cost of electricity generation for a generator over its lifetime.
MASEN	Moroccan Agency for Sustainable Energy. headquartered in Rabat, Morocco.
NDCs	An acronym for Nationally Determined Contributions. They reflect each country's climate goals and contribute to the Paris Agreement objectives.

OFPPT	A public vocational training organisation in Morocco.
OPEX	An acronym for Operational Expenditures. OPEX refers to the ongoing expenses for functioning business operations. OPEX therefore includes the costs of raw materials, supplies, personnel, leasing, energy, etc. They are accounted for in full.
PERC	Passivated Emitter Rear Contact (PERC) solar cells consist of the addition of an extra layer to the rear side of a solar cell. This dielectric passive layer reflects unabsorbed light back to the solar cell for a second absorption attempt, increasing solar cell efficiency.
PtX	PtX is an abbreviation for power-to-X, which is a term that refers to the conversion of electricity from renewable sources, such as solar or wind, into other forms of energy or materials, such as hydrogen, methane, ammonia, or synthetic fuels.
PV	An acronym for Photovoltaics. A process for the direct conversion of light energy into electrical energy using semiconductor material.
RoHS Directive	Restriction of Hazardous Substances in Electrical and Electronic Equipment. EU rules restricting the use of hazardous substances in electrical and electronic equipment to protect the environment and public health.
SDGs	United Nations Sustainable Development Goals.
WEEE Directive	Waste from Electrical and Electronic Equipment. EU rules on treating waste electrical and electronic equipment, to contribute to sustainable production and consumption.

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