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International Report on the Recycling of Wind and Photovoltaic Equipment Industries

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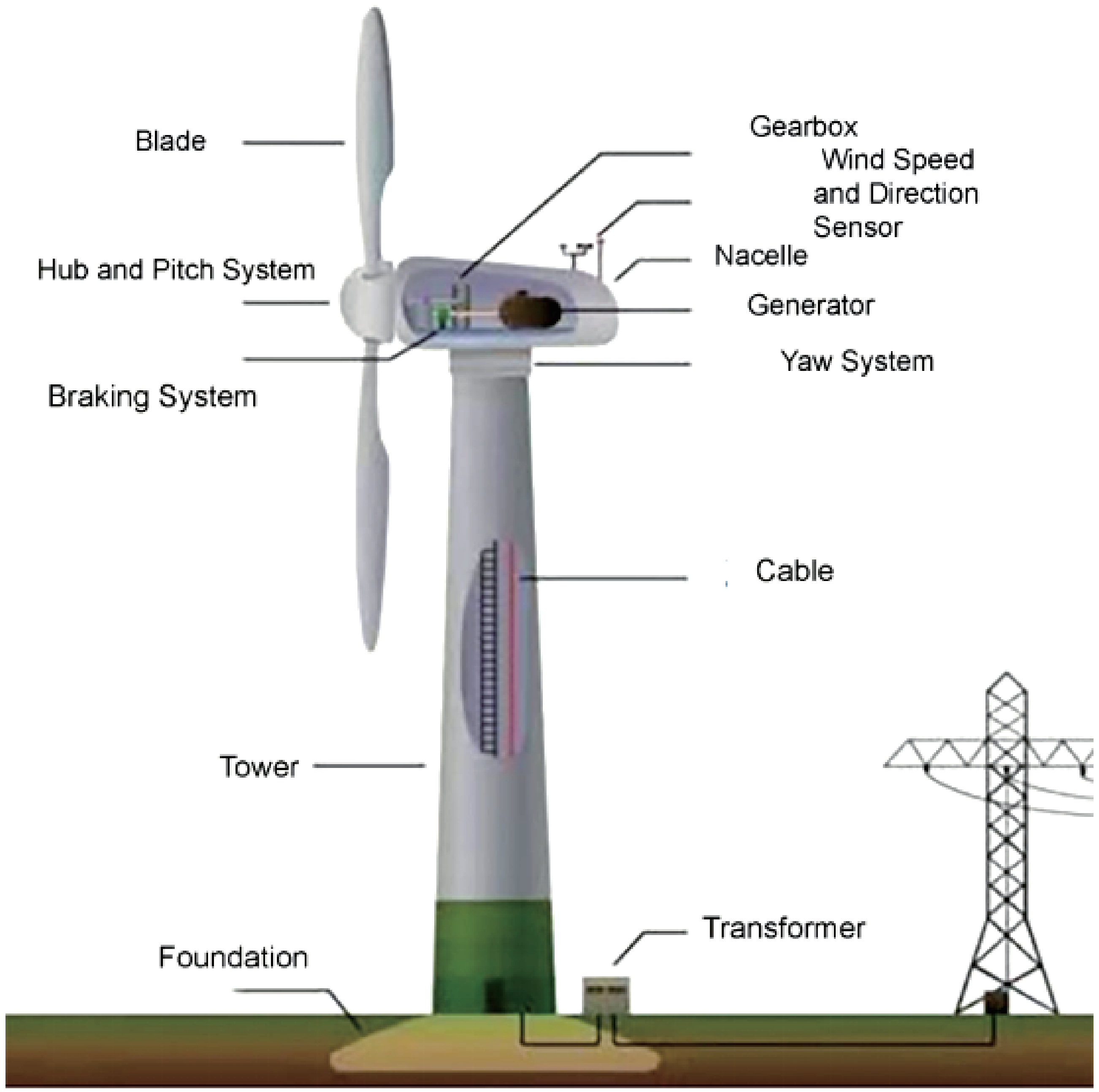
Wind Power Section

Photovoltaic Section

Chapter 1
Overview of the International Wind Power Equipment Recycling Industry

1.1 Development of the Wind Power Industry



Wind energy is one of the earliest energy sources utilized by humans and has become a mature, low-carbon technology playing a crucial role in meeting global electricity demand. Wind power generation converts the kinetic energy of wind into electrical energy. Wind turbines primarily consist of foundations, towers, blades, nacelles, generators, large mechanical components (such as gearboxes, main shafts, and bearings), and electrical control systems.

The global wind power industry originated in Denmark in the late 19th century. However, it was not until the 1973 oil crisis that wind power regained attention, leading to widespread development and deployment globally. In the 1990s, Denmark pioneered offshore wind turbine installations, creating a new domain for offshore wind energy. In 2015, the annual newly installed capacity of renewable energy generation worldwide surpassed that of conventional energy for the first time, marking a structural shift in global power system construction.

Since 2001, the development of global wind power can be broadly divided into the following stages:

Time Period	Phase	Development Overview
Phase 1 (2001-2009)	Global Wind Power High-Growth Period	The compound annual growth rate (CAGR) of newly installed wind power capacity reached 22%. The offshore wind market began to emerge, with countries such as the Netherlands, the UK, Germany, and Belgium exploring offshore projects. However, due to limited technological expertise and high levelized costs of energy (LCOE), newly installed offshore wind capacity accounted for only about 1% of total new installations.
Phase 2 (2010-2015)	Global Wind Power Adjustment Period	The growth rate of installed capacity slowed, with the CAGR of newly installed capacity dropping to 10%. European countries sustained their focus on offshore wind development, and China entered the offshore wind market. The share of newly installed offshore wind capacity increased to around 3%.
Phase 3 (2016-Present)	Offshore Wind Power Development Period	Wind power technology advancement accelerated, with noticeable reductions in LCOE. The CAGR of newly installed capacity stabilized at 8%. Europe achieved significant offshore wind technology improvements, and China experienced rapid offshore wind market growth, with offshore capacity rising from 5% to 23% of total new installations. By the end of 2023, global newly installed wind power capacity reached a record-breaking 116.6 GW, and cumulative capacity surpassed 1,021 GW, marking a major milestone for the industry.

The wind power industry has transitioned from its initial stages to a period of rapid development. Starting with small-scale experimental wind farms, it has evolved into large-scale commercial operations. Significant advancements have been made in technological innovation, equipment manufacturing, and market development. With vast resource potential, mature technology, and renewability, wind energy has gained increasing global attention as a critical tool for reducing greenhouse gas emissions and addressing climate change. Recognized as one of the greenest and most economically sustainable forms of electricity generation, wind energy has been developed extensively worldwide.

1.2 Wind Power Equipment Recycling Industry

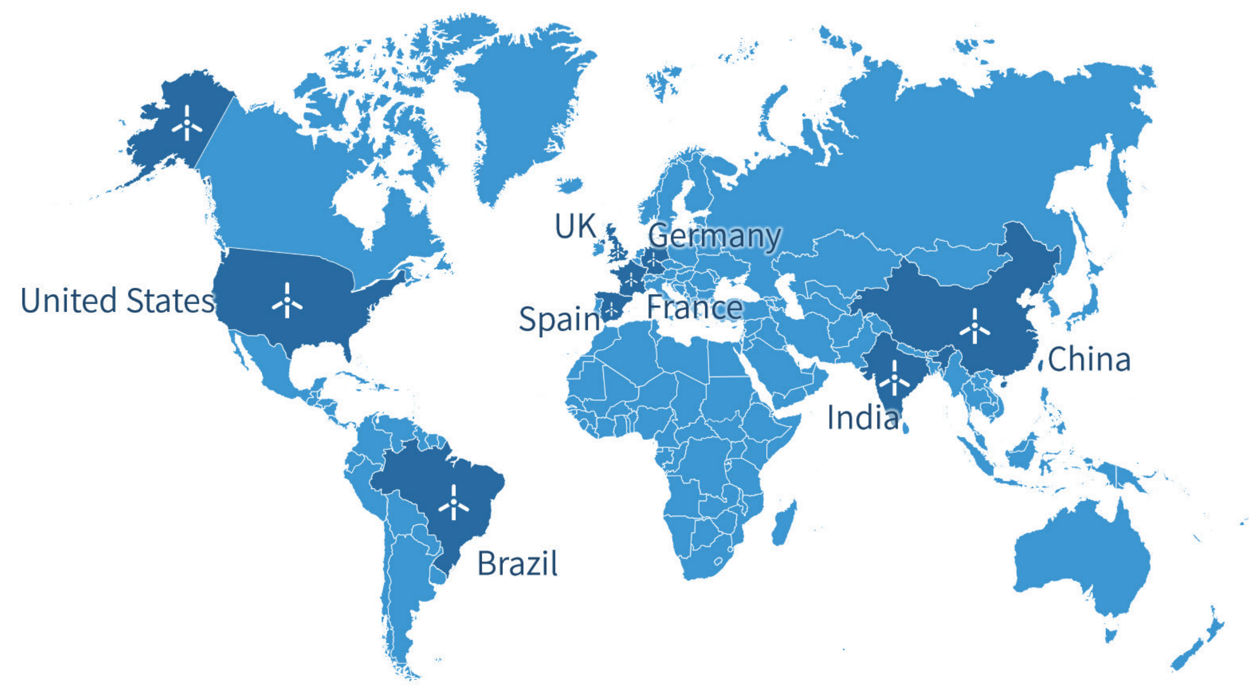
The world faces increasingly severe challenges in climate, environment, and resource management, with environmental concerns drawing heightened global attention. Balancing economic development with environmental protection and achieving sustainable development has become a global consensus. Initially, wind power equipment ushered in the trend of "green, low-carbon renewable energy." However, with the accelerated upgrading of the industry and the replacement of equipment, a significant wave of wind power equipment decommissioning is imminent. Decommissioned wind power equipment contains materials such as steel, copper, aluminum, and fiberglass that can be recycled. Each megawatt (MW) of decommissioned wind power equipment can yield 100–240 tons of recyclable materials, including steel, copper, aluminum, and fiberglass. This reduces the extraction of virgin resources, thereby lowering carbon emissions. Furthermore, it helps decrease dependence on fossil fuels, contributing to additional carbon emission reductions.

Component	Main Recyclable Materials	Material Weight (tons)	Carbon Emission Reduction (tons)
Tower and Nacelle	Copper	4.35	25.23
	Neodymium Magnet	1	52.41
	Aluminum	2.6	20.67
	Steel	170	453.9
Blade	Glass Fiber	11.55	11.55
	Resin and Adhesive	6.3	37.23
Total			**601.19***

Table 1-1: Carbon Emission Reductions Achieved Through Wind Power Equipment Recycling
When a wind turbine is fully recycled, approximately 600 tons of carbon dioxide emissions can be avoided (data from Greenpeace).

This estimate is based on the carbon emissions generated during the production process of a 1.5 MW wind turbine under current technological conditions. The total carbon emissions reduced by recycling turbine materials will vary with advancements in technology and optimization of turbine structures. It is important to note that the recycling process itself generates varying levels of carbon emissions depending on the recycling methods used. This calculation does not account for emissions produced during the disposal and recycling phases.

Maximizing the residual value of decommissioned wind power equipment and achieving green processing throughout its lifecycle has become a critical challenge for the global wind power industry. **This report will provide an overview of the wind power equipment recycling industries in countries such as China, the United States, Germany, Spain, India, the United Kingdom, France, and Brazil.**



1.2.1 Industry Foundations

The global wind power equipment recycling industry is gradually being established and refined. Its development is driven by multiple factors, including the global energy transition, technological advancements, policy support, and market demand.

Firstly, European countries entered the wind power market early, experiencing an installation boom in the 1990s. While the typical design lifespan of wind turbines is approximately 20 years, actual replacement times in Europe vary widely, ranging from 9 to 27 years due to differing operational conditions. Beginning in 2018, large-scale dismantling of wind power facilities commenced in Europe and North America. According to WindEurope, by 2025, approximately 25,000 tons of wind turbine blades will reach the end of their lifecycle annually. Furthermore, Europe plans to prohibit the landfill disposal of decommissioned turbine blades by 2025, posing significant challenges for recycling technologies.

Secondly, early wind turbine technology was relatively underdeveloped, leading to equipment with lower performance and quality. Aging turbines frequently experience failures, including severe incidents such as collapses or blade breakage. In addition, electricity generation capacity often declines over time, and older turbines may no longer meet grid requirements. Maintenance and repair costs increase substantially, significantly reducing economic viability. In some cases, turbines are decommissioned prematurely. This situation has also resulted in the emergence of "orphan turbines" as some manufacturers exited the market, leaving unsupported equipment.

Thirdly, wind power equipment models are evolving rapidly. Early-generation turbines typically had smaller capacities and were often installed in areas with abundant wind resources. However, these older turbines now face limitations due to outdated technology, leading to resource underutilization. Larger-capacity turbines can better harness the potential of wind farms and contribute more effectively to achieving carbon neutrality goals. As a result, many early-generation turbines are being decommissioned prematurely, even before reaching their designed lifespan.

Fourthly, innovation in technology and operational models is driving the wind power equipment recycling industry. Efforts are being made to advance technology, reduce costs, and improve efficiency. These innovations include green design principles, precision dismantling techniques, and advanced materials recycling and reuse technologies, all of which aim to enhance the sustainability and economic viability of wind power equipment recycling.

1.2.2 Policy Support and Guidance from Various Countries

Many onshore wind farms in Europe and North America have been in operation for over 20 years, making them the first large-scale group of wind farms to approach decommissioning globally. As the decommission wave of wind power equipment approaches, the recycling and reuse industry for decommissioned turbines remains in its infancy and lacks a systematic framework. In the early stages of turbine decommission, with relatively small volumes, decommissioned components—particularly blades—were often disposed of through landfill or incineration. This approach was commonly used by businesses in countries such as the UK and those within the EU. While current international recycling methods can recover up to 90% of wind turbine materials, the remaining portion presents challenges due to its complexity and the difficulty of recycling certain components. A multifaceted approach is required to manage decommissioned wind power equipment effectively. Establishing scientifically sound and rational industrial policies is a critical prerequisite for fostering a healthy recycling industry. Responding to global sustainability goals and the demand for a circular economy, the EU, China, the United States, South Korea, and other nations have introduced relevant policies to address the challenges of recycling decommissioned wind turbines.

European Union

As a pioneer in the global wind power industry, Europe is not only one of the largest wind energy markets but has also made significant strides in developing policies and practices for wind power waste recycling. While European countries have established numerous regulations for solid waste recycling, specific policies targeting the recycling and disposal of wind turbines remain relatively limited. In 2009, the European Environment Agency (EEA) introduced the Ecodesign Directive, emphasizing the importance of incorporating recycling and resource efficiency considerations during the design phase. This directive aims to optimize the design of wind turbine blades, photovoltaic panels, and other equipment, ensuring efficient resource use and minimizing waste throughout the product lifecycle. In March 2018, the European Commission adopted the European Plastics Strategy, the EU's first comprehensive plan addressing plastic products. This strategy laid the groundwork for recycling the extensive composite materials used in wind turbines. In December 2019, the new European Commission unveiled the European Green Deal, which targets achieving carbon neutrality by 2050 and envisions a modern, competitive economy decoupled from resource consumption. On March 11, 2020, the EU introduced a revised Circular Economy Action Plan, embedding circular economy principles throughout the product lifecycle—encompassing design, production, consumption, repair, recycling, and reuse. This plan aims to increase the use of recyclable materials and positions the EU as a global leader in circular economy practices. One of its primary goals is to significantly reduce overall waste by 2030 and cut the volume of non-recyclable municipal waste by half.

WindEurope has advocated for a ban on landfilling decommissioned wind turbine blades in major EU and UK wind markets by 2025. WindEurope also urges governments to encourage the use of recyclable and reusable materials while providing policy support for advancing related technologies. Countries like Germany, the Netherlands, Austria, and Finland have responded proactively, introducing restrictions that explicitly prohibit landfill disposal of wind turbine blades and other composite materials.

China

China's wind power industry started relatively late, but the early wind farms that began operation are now entering the latter stages of their lifecycle. A large-scale "decommission wave" for wind power equipment is imminent, with the peak expected during the 15th Five-Year Plan period. To address this, the National Development and Reform Commission (NDRC) of China, in collaboration with relevant departments, issued the "Guiding Opinions on Promoting the Recycling of Retired Wind and Photovoltaic Equipment" (Document No. [2023]1030). This policy aims to advance the recycling and sustainable use of wind and photovoltaic (PV) equipment.

Figure 1-1: Guiding Opinions on Promoting the Recycling of Decommissioned Wind and PV Equipment

The goal is that by 2025, a comprehensive responsibility mechanism will be established for managing the decommission of equipment from centralized wind farms and photovoltaic power stations. Relevant standards and regulations will be further refined, and significant breakthroughs in key resource recycling technologies are expected to be achieved. By 2030, a fully mature end-to-end recycling system for wind and photovoltaic equipment will be in place. The recycling model will be more robust, aligning recycling capacities effectively with the scale of decommission, while standards and regulations will be further optimized to ensure sustainability and efficiency.

United States

Over the next 30 years, the total volume of decommissioned wind turbine blades in the United States is projected to exceed 2.1 million tons. This has prompted the government and industry to seek more sustainable solutions. Through policy guidance and incentives, the U.S. government is actively promoting the recycling of wind power equipment. For example, the Department of Energy (DOE) has collaborated with businesses to explore incorporating discarded turbine blades into cement production. This innovative approach enables recycling while reducing carbon dioxide emissions during cement manufacturing by up to 27%. Additionally, the U.S. government encourages companies to use environmentally friendly materials and technologies in wind power equipment manufacturing, ensuring that these components are easier to recycle and repurpose at the end of their lifecycle.

Germany

Germany has been a leading advocate and practitioner of extended producer responsibility (EPR) legislation. The 1986 Act on Avoidance and Proper Disposal of Waste first established the principle of EPR, mandating that producers are responsible for the recycling and reuse of waste from specific products. This was further expanded by the 1996 Circular Economy and Waste Act, which extended producer responsibility to the entire lifecycle of products, requiring producers to develop recyclable new products. Over time, Germany institutionalized EPR across various industries, including end-of-life vehicles and construction waste, creating a systematic framework. Due to the composition of wind turbine blades, which include organic materials such as resin and fiberglass, landfill disposal is not a viable option.

To address these challenges, Germany established the RDRWind e.V. (Industrial Association for Wind Turbine Modification, Dismantling, and Recycling). This organization focuses on creating binding standards for the sustainable dismantling and recycling of wind turbines. It published the DIN SPEC 4866 Standard, which outlines processes for the sustainable dismantling, disassembly, recycling, and recovery of wind turbine components.

Spain

Spain has enacted its first Energy Transition Law, setting ambitious goals to reduce greenhouse gas emissions by 23% by 2030, achieve a 42% share of renewable energy in final energy consumption, and ensure that 74% of electricity generation comes from renewable sources. In addition, the Spanish Council of Ministers approved the Roadmap for Offshore Wind and Marine Energy Development, which aims to achieve 3 GW of installed offshore wind capacity by 2030. This roadmap integrates the concept of the circular economy into the offshore wind supply chain, with a particular focus on recyclable design to enhance sustainability and resource efficiency in the sector.

India

The Indian government prioritizes the green transition and sustainable development of the wind power industry, setting ambitious renewable energy goals. By 2030, India aims to achieve 450 GW of installed renewable energy capacity, with 40% of its electricity generated from non-fossil fuel sources, including a total wind power capacity of 140 GW. At the 2021 COP26 conference in Glasgow, India further enhanced its 2030 targets, committing to meeting 50% of its national energy demand with renewable sources and announcing its intention to achieve carbon neutrality by 2070.

United Kingdom

The UK government has pledged to achieve carbon neutrality by 2050, with the wind power sector playing a pivotal role in this transition. To support this effort, the government issued the National Policy Statement for Renewable Energy Infrastructure (EN-3), which outlines planning and policy frameworks for renewable energy infrastructure, including wind power equipment. Additionally, the UK government encourages businesses to adopt localized supply chains and increase the domestic content of wind power projects. This approach aims to foster the growth of a domestic wind power recycling industry, strengthening the sustainability and economic impact of the sector.

France

On June 22, 2020, France introduced the Wind Turbine Installation Act, mandating that 90% of decommissioned turbine blades be reused or recycled by July 2022, and 95% by January 2024. This reflects the French government's strong policy support and guidance for the circular use of wind power equipment. France has also submitted the final version of its 2030 National Energy and Climate Plan (NECP) to the European Commission. The plan aims to achieve 33% renewable energy in the national energy mix by 2030, with wind energy playing a key role. By 2028, France plans to achieve 34.7 GW of onshore wind capacity and expand offshore wind capacity to 8.75 GW.

Chapter 2
Current Status and Development Trends in the Wind Power Equipment Recycling Industry

2.1 Installed Capacity and Cumulative Scale of the Wind Power Industry in 2023

Global New Installations

In 2023, the global wind power industry achieved remarkable growth in newly installed capacity. According to the Global Wind Energy Council (GWEC), new wind power installations worldwide reached 116.6 GW, representing a 50% year-on-year increase and setting a historical record. This significant expansion was driven by sustained global investments in renewable energy and continuous advancements in wind power technology. Both onshore and offshore wind sectors contributed to this growth. Onshore wind installations reached 105.8 GW, reflecting a 54% year-on-year increase and surpassing the 100 GW milestone for the first time. Offshore wind installations, with 10.8 GW of new capacity added, grew by 24% year-on-year and also showed a steady upward trend.

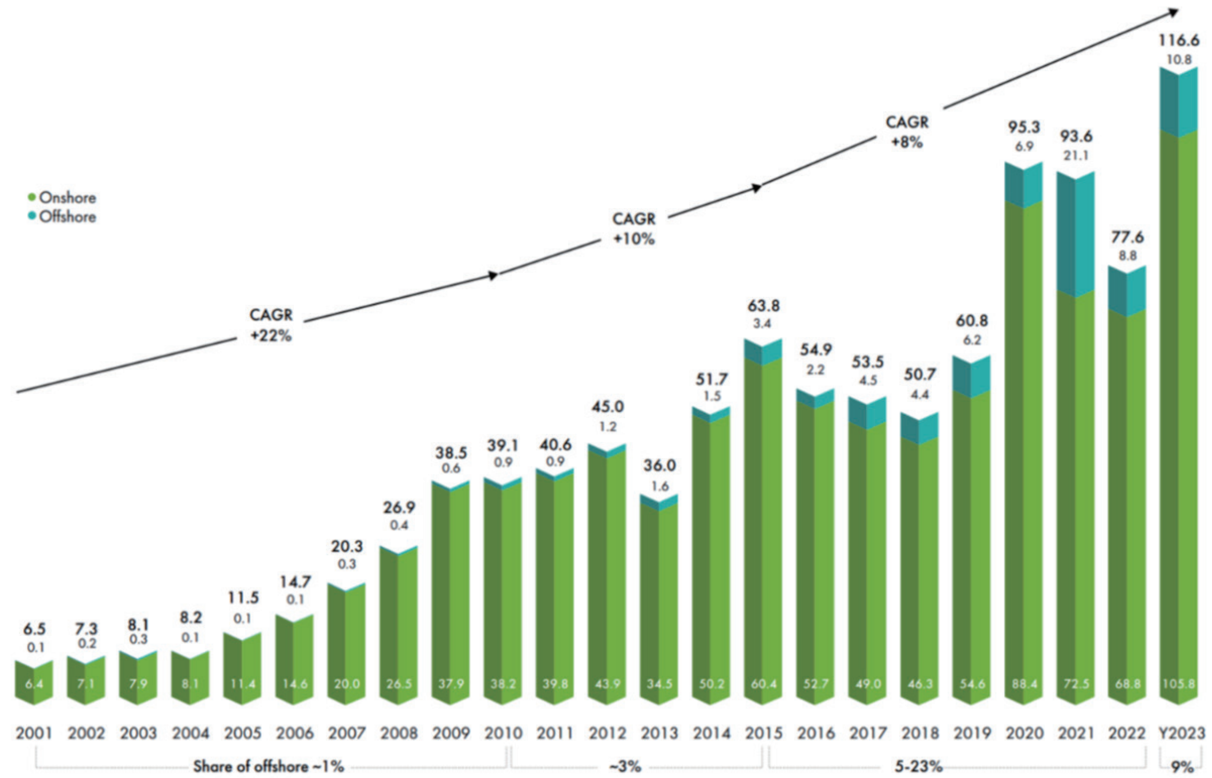


Figure 2-1: Global New Wind Power Installations (GWEC, 2024)

Driven by significant new installations in China and India, the Asia-Pacific region solidified its position as the largest wind power market globally, accounting for 71% of the global market share in 2023, a 15% year-on-year increase compared to 2022.

As the second-largest market, Europe added 18.3 GW of new wind power capacity in 2023, with EU countries contributing 16.2 GW, most of which (79%) was onshore wind. However, Europe's global market share decreased by 9% year-on-year in 2023.

North America retained its position as the third-largest market, but its market share fell by 5% due to a drop in U.S. onshore wind installations, which reached their lowest level since 2014.

Latin America remained the fourth-largest market, holding 5% of the global share in 2023, with Brazil achieving a record high. Additionally, Africa and the Middle East accounted for 0.9% of the global market share.

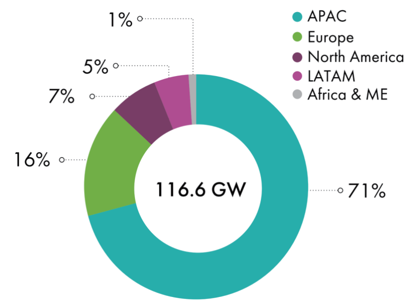


Figure 2-2: New Wind Power Installations by Region in 2023 (GWEC, 2024)

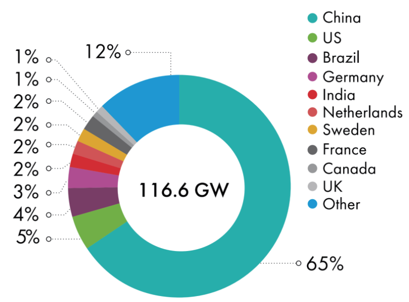


Figure 2-3: New Capacity and Market Share of the Top Five Markets in 2023 (GWEC, 2024)

In 2023, the top five countries for global new wind power installations were China, the United States, Brazil, Germany, and India. Compared to 2022, the only change was India replacing Sweden in the fifth position. By 2023, the top five markets accounted for 80% of global new installations, a 9% increase from the previous year. This growth was primarily driven by China's 16% increase in its global market share compared to 2022.

Global Cumulative Capacity

In 2023, the European wind power industry also demonstrated steady growth. According to data released by the Global Wind Energy Council, by the end of 2023, the cumulative global wind power capacity reached 1,021 GW, reflecting a 13% year-on-year increase and marking a historic milestone of surpassing 1,000 GW. This achievement highlights the substantial progress made by the global wind power industry over the past few decades and underscores its growing importance in the global energy mix.

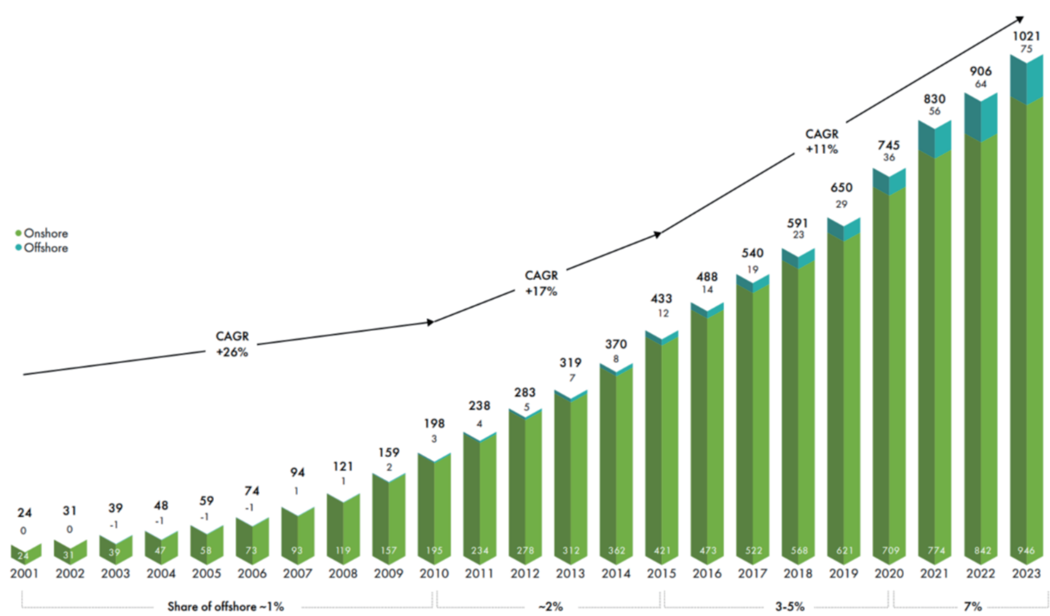


Figure 2-4: Cumulative Global Wind Power Capacity (GWEC, 2024)

By the end of 2023, the top five markets for cumulative wind power capacity remained unchanged: China, the United States, Germany, India, and Spain. Together, these countries accounted for 72% of the world's total wind power capacity, maintaining the same percentage as the previous year.

China

In terms of regional distribution, China is the world's largest wind power market. Since 2010, China has consistently ranked first globally in cumulative wind power capacity for 14 consecutive years. According to data from the National Energy Administration, as of the end of June 2023, China's installed renewable energy capacity surpassed 1,300 GW, historically exceeding coal-fired power capacity. In 2023, China's new wind power installations reached 75.9 GW. By the end of December 2023, the country's cumulative wind power capacity stood at approximately 440 GW, representing a year-on-year growth of 20.7%.

Year	2008	2009	2010	2011	2012	2013	2014	2015
New Installations (MW)	/	9180.1	13990	17630.9	15370	16088.7	27747.3	32970
Cumulative Capacity (MW)	8420	17600.2	31073	47000	62370.2	75480	95810	129341
Year	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
New Installations (MW)	1930	1503	2059	2574	7167	4757	3763	7590
Cumulative Capacity (MW)	148641	163671	184260	210050.2	281530.6	328482	365440.4	441340.8

Table 2-1: Annual Overview of China's Wind Power Installation Data

Note: Data sourced from the National Energy Administration of China.

United States

In 2023, the United States saw significant growth in wind power installations. According to data released by Guofu Consulting, the total cumulative wind power capacity across the U.S. reached nearly 147.5 GW, capable of supplying electricity to approximately 45 million American households. New installations included nearly 6,500 MW of utility-scale onshore wind power capacity. The offshore wind project pipeline grew by 53% compared to the previous year, reaching 80,523 MW (approximately 8.05 GW). Currently, nearly 6 GW of offshore wind projects are under construction, with an additional 3 GW having signed power purchase agreements and preparing for construction.

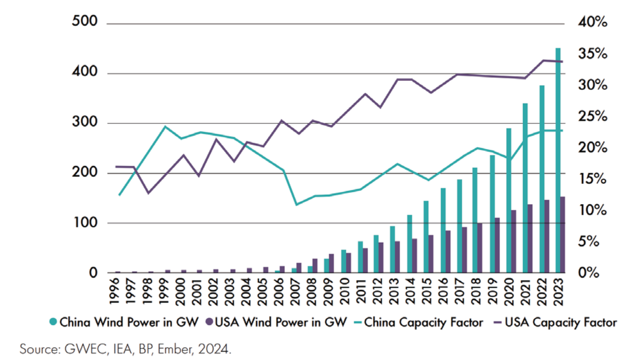


Figure 2-5: Wind Power Capacity and Capacity Factors of China and the United States (GWEC, 2024)

Germany

In 2023, Germany's onshore wind power capacity achieved a net increase of 4 GW, bringing the total onshore installed capacity to 60.9 GW by the end of the year. Offshore wind farms added 329 MW of new capacity, with less than 0.3 GW of total offshore installations becoming operational during the year. Germany's total offshore wind power capacity in the Baltic Sea and North Sea reached approximately 8.5 GW.

Spain

Wind energy is the largest renewable energy source in Spain. In 2023, wind power capacity increased by 2.4%, reaching 30,883 MW, while the combined installed capacity of wind and solar power reached 62 GW. The Spanish government approved the Roadmap for Offshore Wind and Marine Energy Development, setting targets to achieve 3 GW of offshore wind capacity and 60 MW of marine energy (wave and tidal power) capacity by 2030.

India

The Indian wind power market has entered a phase of rapid growth. By the end of 2023, China's wind turbine exports to India had reached a cumulative capacity of 882.3 MW. India ranked fifth globally for new wind power installations in 2023, replacing Sweden, and secured the fourth position in cumulative wind power capacity worldwide. Between 2023 and 2027, India is expected to add 30.9 GW of new installations, with a compound annual growth rate (CAGR) of 23%.

United Kingdom

In 2023, the United Kingdom added 833 MW of offshore wind capacity. Of this, 820 MW came from the unfinished portion of the 1.1 GW Seagreen project, while 13 MW was part of the 1.2 GW Dogger Bank (Phase A) project. The UK government has advanced its target for achieving 100% zero-carbon electricity to 2035, actively promoting the development and adoption of clean energy technologies. According to its plans, by 2030, the UK's offshore wind capacity is projected to increase by approximately 29 GW, bringing the total installed capacity to over 43 GW. As of 2023, the UK's total wind power capacity reached 30 GW, reflecting a year-on-year growth of 5.1% and accounting for 3.0% of the global total.

France

In 2023, France's wind power capacity reached 22.1956 GW, marking a year-on-year growth of 6.7% and accounting for 2.2% of the global total. Between 2023 and 2027, France is expected to add 95.5 GW of new installations, with a compound annual growth rate (CAGR) of 13%.

Brazil

In 2023, Brazil added 4.9 GW of new wind power capacity. Between 2023 and 2027, the country is expected to install an additional 26.5 GW of onshore wind power. In recent years, Brazil has positioned energy transition as a core component of its economic growth and diplomatic strategy. Wind power is widely recognized by various government departments as a cornerstone of the country's renewable energy economy. According to data from the Brazilian Electricity Regulatory Agency (ANEEL), Brazil constructed 291 new power plants in 2023, adding a record 10.3 GW of new capacity. Wind and solar power dominated this growth, collectively accounting for 90% of the new installations. Specifically, 140 new wind farms were added, contributing 4.9 GW to the total, driving an ongoing expansion in the demand for wind power equipment in Brazil.

With the acceleration of the global energy transition and the advancement of carbon neutrality goals, governments worldwide will continue to increase investment in and support for renewable energy sources such as wind power. In 2023, the global wind power industry achieved remarkable milestones in both new installations and cumulative capacity, demonstrating robust growth momentum. Continuous innovation in wind power technology and further reductions in costs will provide strong support for the industry's sustained development. At the same time, the wind power equipment recycling industry will gradually establish a comprehensive industrial chain, further bolstering the sustainable development of the wind power sector.

2.2 Market Capacity Forecast for Decommissioned Wind Power Equipment

The design lifespan of core wind power equipment is typically 20 years. After more than a decade of large-scale development, wind power installations from the early years are beginning to reach the end of their lifecycle by 2023. Additionally, with continuous advancements and upgrades in technology, wind turbines are evolving rapidly, leading some turbines to face early decommissioning. As a result, many countries are on the verge of a significant wave of turbine decommission.

In addition to the lifespan and technological factors of wind turbines, their decommissioning is also significantly influenced by policies and market dynamics. Adequate policy support and mature technologies can accelerate turbine decommissioning, thereby increasing the volume of equipment requiring recycling. Conversely, a lack of policy incentives and the absence of reliable, advanced technologies may slow down the decommissioning process.

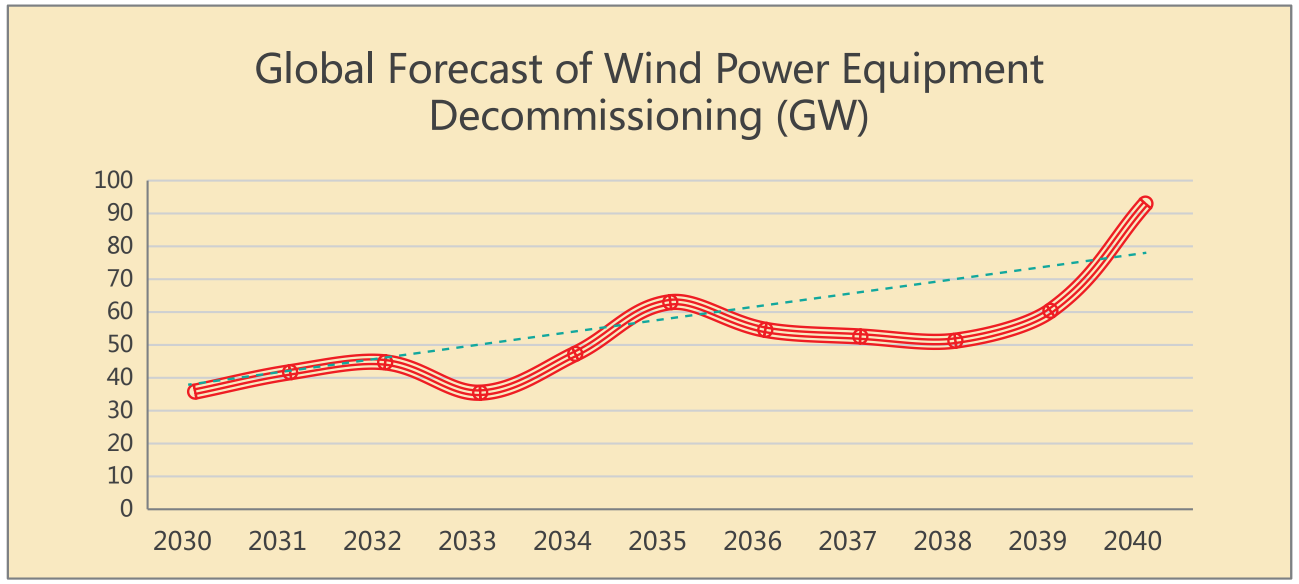


Figure 2-6: Global Forecast of Wind Power Equipment Decommissioning

Between 2024 and 2034, global wind turbine blades are expected to generate approximately 200,000 tons of composite waste. According to forecasts by the International Renewable Energy Equipment Recycling Association, the volume of decommissioned wind power equipment will exhibit continuous growth starting in 2030. By 2035, more than 230 GW of wind turbines are projected to face decommissioning. By 2040, the cumulative volume of decommissioned wind power equipment will reach a significant scale, with an estimated 311 GW of turbines decommissioned between 2036 and 2040.

Current data on decommissioned wind power capacity is primarily calculated based on service life projections. This report, however, provides decommissioning data by tracking the operational status and decommissioning information of major wind farms, as well as analyzing the raw material collection and processing volumes from companies involved in turbine component recycling and blade disposal. By integrating industry information from various countries and considering multiple factors, the report presents a more comprehensive dataset on decommissioned wind power equipment. It is worth noting that the predictive method, based solely on service life, often produces significant deviations due to factors such as early decommission.

Europe

The origins of global wind power technology and industry trace back to Denmark, with significant growth and development in Western Europe. According to the report "Wind Energy in Europe 2023 Statistics and the Outlook for 2024-2030", Europe currently has 22 GW of installed wind power capacity that has been operational for over 20 years.

According to WindEurope statistics, as of 2020, Europe had 34,000 wind turbines that had been in operation for over 15 years. By 2023, approximately 4,000 turbines faced decommissioning, along with about 14,000 wind turbine blades. By 2025, Europe is expected to generate over 25,000 tons of decommissioned blades annually. This volume is projected to double by 2030, reaching approximately 52,000 tons per year, as countries like Italy, France, and Portugal experience significant increases in blade decommissioning. Most aging turbines are located in Germany, Denmark, Spain, and Portugal, where wind farms have some of the longest average operating times. The decommissioning, dismantling, collection, transportation, waste management, and eventual site restoration of these turbines present a substantial challenge. At the same time, this creates a significant market opportunity for onshore wind farm decommissioning over the next decade.

China

According to the report published by the China Resources Recycling Association - Committee for Wind and Solar Equipment Recycling (CRRA-CWSER), China's decommissioned wind power capacity has reached 1424 MW, involving approximately 1,350 turbines. Among these, turbines with a service life of 20 years or more represent only 208.8 MW, accounting for 14.7% of the total decommissioned capacity. Those with a service life of 10 to 20 years amount to 1086.1 MW, making up 76.3%, while turbines with a service life of less than 10 years constitute 129 MW, or 9.0%. Based on China's wind power development trajectory, the first wave of large-scale turbine decommission is expected by 2025. By then, over 1,800 turbines with a cumulative capacity of 1.25 GW will have been decommissioned. Subsequently, the annual number of decommissioned turbines will steadily increase, reaching over 34,000 turbines with a capacity of approximately 45 GW per year by 2030. Between 2030 and 2035, the cumulative decommissioned capacity is expected to exceed 100 GW, and from 2036 to 2040, the cumulative figure will reach 150 GW.

Decommissioning Year	2019	2020	2021	2022	2023
Decommissioned Capacity (MW)	/	5.5	169	600.5	649
Unit Capacity (kW)	/	<750	750-850 1500	660-850 1500-3600	300-850 1500-2500

Table 2-2: Overview of Decommissioned Wind Power Capacity in China

Note: Prior to 2019, there were no large-scale decommissioning or disposal activities for wind farm equipment; therefore, no statistical data is available.

Installation Year	Decommissioned Capacity (MW)	Unit Capacity (kW)	Service Life and Proportion of Total Decommissioned Capacity
<2003	258	300-850	20+ years 14.7% (208.8 MW)
2005	91.8	850	10-20+ years, 76.3% (1086.1 MW)
2006	280.5	750-1500	
2007	141.9	850-1500	
2008	63.75	850	
2009	95.94	660-1500	
2010	116.94	750-3600	
2011	246	750-1500	
2013	95	2500	<10 years 9.0% (129 MW)
2015	34	2000	

Table 2-3: Overview of Decommissioned Wind Power Equipment by Installed Years and Service Life in China

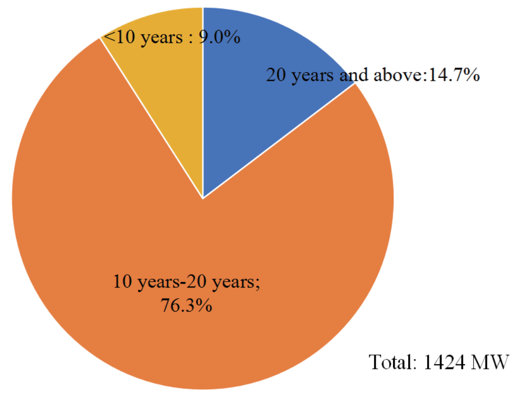


Figure 2-7: Illustration of Actual Service Life of Decommissioned Wind Power Equipment in China

According to the collected information, the longest-serving wind turbine was installed in 1988 with a unit capacity of 550 kW. It was decommissioned in 2020 after operating for over 30 years.

For instance, the Shanghai Lingang New City Experimental Wind Farm, with an installed capacity of 8.1 MW in 2010 (comprising one 1.25 MW turbine, one 2 MW turbine, and two 3.6 MW turbines), was decommissioned in 2022 after 12 years of operation.

Additionally, wind farms installed in 2013 and 2015, with service lives of less than 10 years, were mainly impacted by regional planning adjustments, leading to early decommissioning without normal operation. Wind farms with service lives of 10 to 20 years were primarily part of "repowering" projects aimed at replacing smaller turbines with larger, more efficient ones. A minority of these cases were due to equipment-related issues or site selection factors.

United States

Wind power contributes 10% of the total electricity supply in the United States, with significantly higher shares in several states. Following the passage of the Inflation Reduction Act, short-term growth projections for wind energy have increased by over 30%.

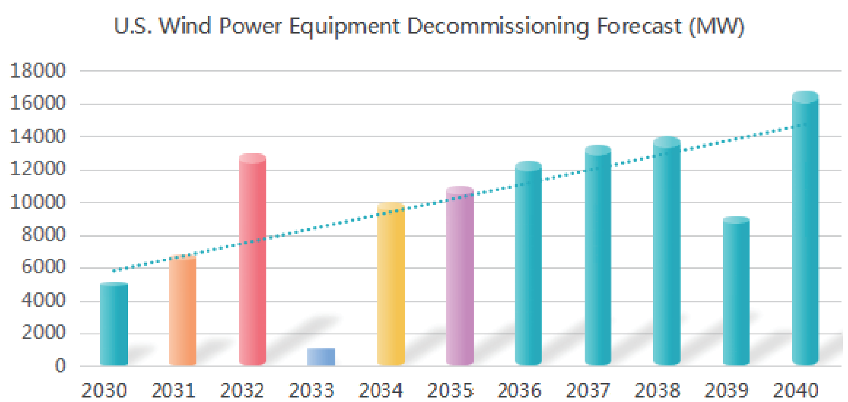


Figure 2-8: Forecast of Wind Power Equipment Decommissioning in the United States

Research by the Electric Power Research Institute indicates that over the next 30 years, the total amount of decommissioned wind turbine blades in the United States will exceed 2.1 million tons. The wind power decommissioning and recycling industry in the U.S. is primarily concentrated in states with significant installed wind power capacities, such as Texas, Illinois, and Kansas. These states have large numbers of wind farms, resulting in a relatively higher volume of decommissioned equipment.

In March 2020, Bloomberg reported that several onshore wind farms in Wyoming were decommissioned, leaving over 1,000 decommissioned blades. These blades were simply stockpiled in local landfills after dismantling. By 2021, approximately 4 GW of wind turbines in the U.S. were approaching the end of their operational lifespans. It is estimated that by 2026, annual wind power growth in the U.S. will exceed 15 GW, and by 2032, 13 GW of wind turbines will be recyclable. Each year, 3,000 to 9,000 blades are expected to be decommissioned, and by 2040, this figure will rise to 10,000 to 20,000 blades, with over 20 GW of wind turbines ready for recycling. By 2050, the cumulative volume of decommissioned blades will reach 2.2 million tons.

Germany

A study by the German Federal Environment Agency (Umweltbundesamt, UBA) revealed that thousands of old wind turbines in Germany are set to be decommissioned. This could overwhelm the country's recycling capacity and place financial strain on turbine operators.

In 2021, Germany decommissioned 233 MW of wind power capacity, with hundreds of turbines in the eastern state of Brandenburg being decommissioned. By the end of 2021, out of approximately 3,900 operational wind turbines, 429 units were set to cease operation.

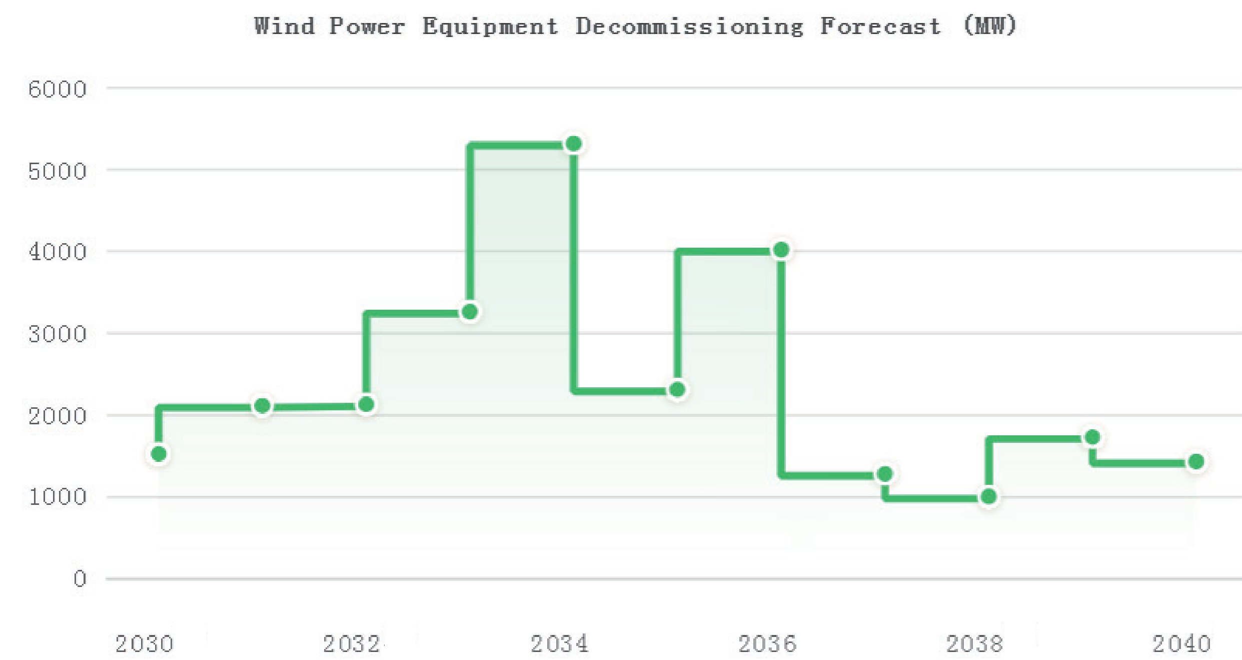


Figure 2-9: Forecast of Wind Power Equipment Decommissioning in Germany

In the first half of 2023, Germany decommissioned 198 old onshore turbines, with a total installed capacity of 239 MW. By the end of June 2023, there were 7,796 onshore wind turbines connected to the grid before 2002 that were still operational, with a total capacity of 8 GW. An additional 5,850 turbines, with an estimated capacity of 10 GW, are expected to enter this category in the near future. By the end of 2023, approximately 750 turbines will have been in operation for over 20 years. By 2024, it is anticipated that around 70,000 tons of old turbine blades will be decommissioned annually.

By 2030, wind turbines with a combined installed capacity of 78 GW will exceed 20 years of operational life and enter the decommissioning phase. In terms of blade recycling, it is projected that by 2040, Germany will generate 10,000 to 75,000 tons of composite materials annually from decommissioned blades. Germany holds a significant position in the global wind power market. According to the German Wind Energy Association (Bundesverband WindEnergie e.V., BWE), the country has successfully installed approximately 23,800 wind turbines. It also has the largest potential capacity for repowering projects, with an estimated 20 GW of turbines already operational for over 15 years.

The German government plans to have offshore wind farms with a total capacity of at least 15 GW by the end of 2030, eventually expanding to a total capacity of nearly 54 GW, with an annual generation of approximately 260 TWh. This would position Germany as the world's second-largest offshore wind power producer. As the offshore wind sector grows, the volume of decommissioned wind power equipment will also increase. The German government and industry are actively advancing the development of the wind power equipment recycling and reuse industry.

Spain

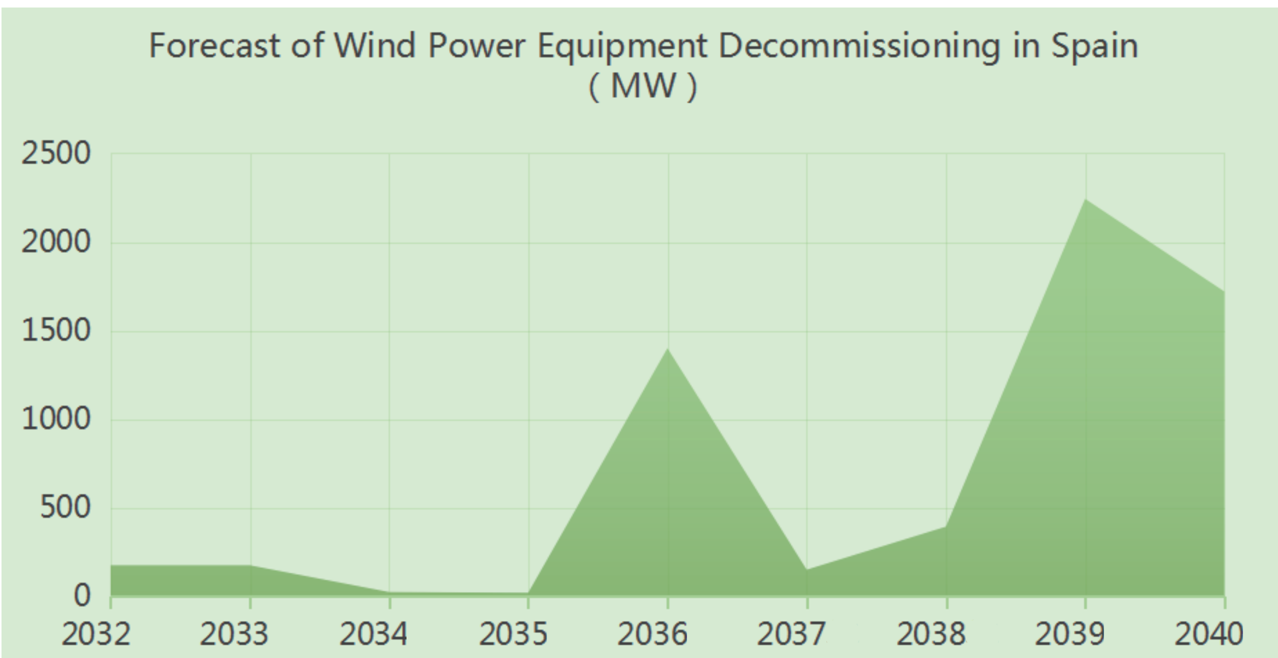


Figure 2-10: Forecast of Wind Power Equipment Decommissioning in Spain

Spain has one of the most developed wind power industries in Europe and globally, encompassing nearly the entire supply chain. The country currently has over 1,300 wind farms, with wind energy contributing 60.46 TWh, or 23.3% of Spain's total electricity consumption.

According to the Spanish Wind Energy Association (Asociación Empresarial Eólica, AEE), by 2023, Spain plans to decommission over 36% of its aging turbines within the next five years. This will involve approximately 7,500 turbines, 20,000 blades, and 7,500 towers. Around 85% of components such as steel, copper wiring, and generators can be reused. To facilitate this process, Spain is building recycling plants to manage these materials.

The decommissioned wind power capacity in Spain is expected to reach 5–10 GW by 2025. 50% of Spain's wind farms have been in operation for more than 15 years, the highest proportion in the European Union. By 2040, an additional 6 GW of wind turbines are projected to face decommissioning. Wind power operators may choose to extend the lifespan of these turbines or opt for recycling.

India

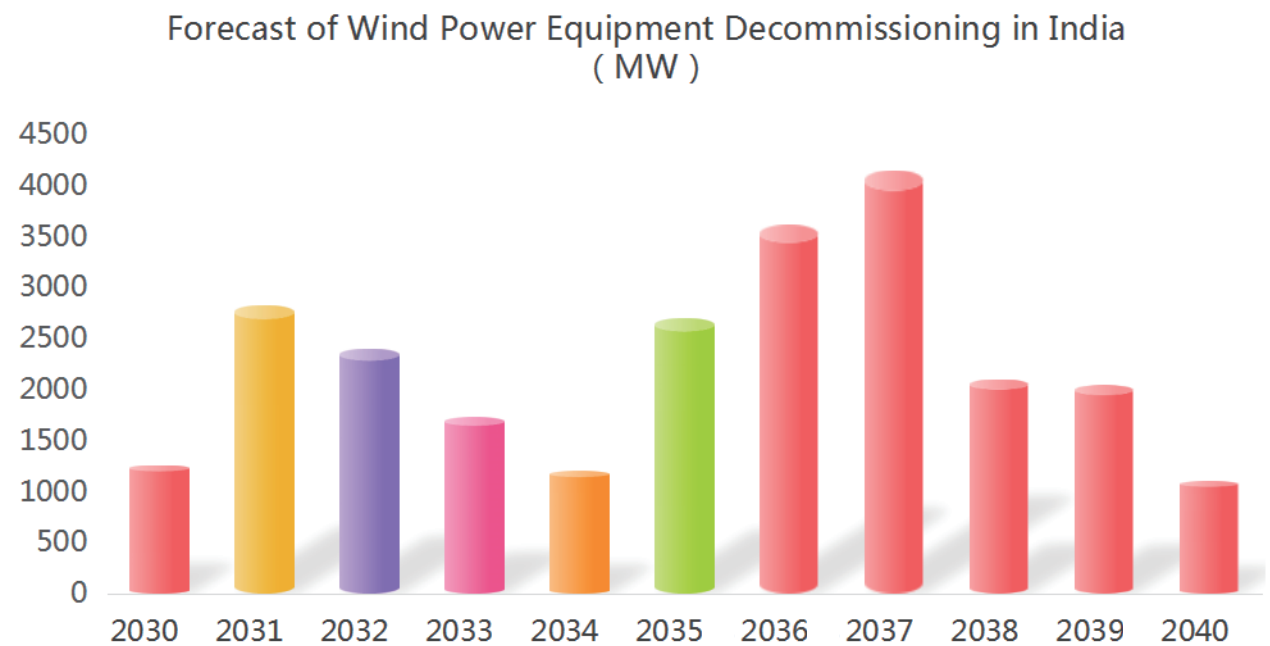


Figure 2-11: Forecast of Wind Power Equipment Decommissioning in India

India has pledged to ensure that 50% of its electricity capacity comes from non-fossil fuel sources by 2030. A significant portion of India's wind power equipment was installed before 2000, predominantly consisting of turbines with capacities below 1 MW. These turbines are located in high wind resource areas but are now nearing or exceeding their design lifespans. By increasing structure heights, rotor diameters, and upgrading components, these turbines can be recalibrated to improve efficiency and extend operational life. According to the National Institute of Wind Energy (NIWE), India has an estimated total wind power potential of 302 GW at a hub height of 100 meters.

In December 2023, the Indian government introduced strategic updates to its wind energy policy, allowing older turbines to be replaced with newer, more efficient models before reaching the end of their design lifespan. The National Institute of Wind Energy (NIWE) estimates that turbines below 2 MW have a repowering potential of 25.406 GW. Under this policy, some turbines in India are expected to face early decommissioning.

According to the International Renewable Energy Equipment Recycling Association (IREERA), India's wind power decommissioning volume is projected to reach 3 GW by 2031. Between 2030 and 2040, total decommissioning is expected to amount to 25 GW, peaking in 2037. By 2050, India is anticipated to generate approximately 1.1 million tons of wind power-related waste, with this figure increasing annually over time.

United Kingdom

By 2022, wind energy had become the second-largest source of electricity in the UK, accounting for 26.8% of total power generation. This marked the first time wind energy exceeded a quarter of the nation's electricity supply. By the end of 2023, the UK had over 11,000 wind turbines with a total installed capacity of 30 GW.

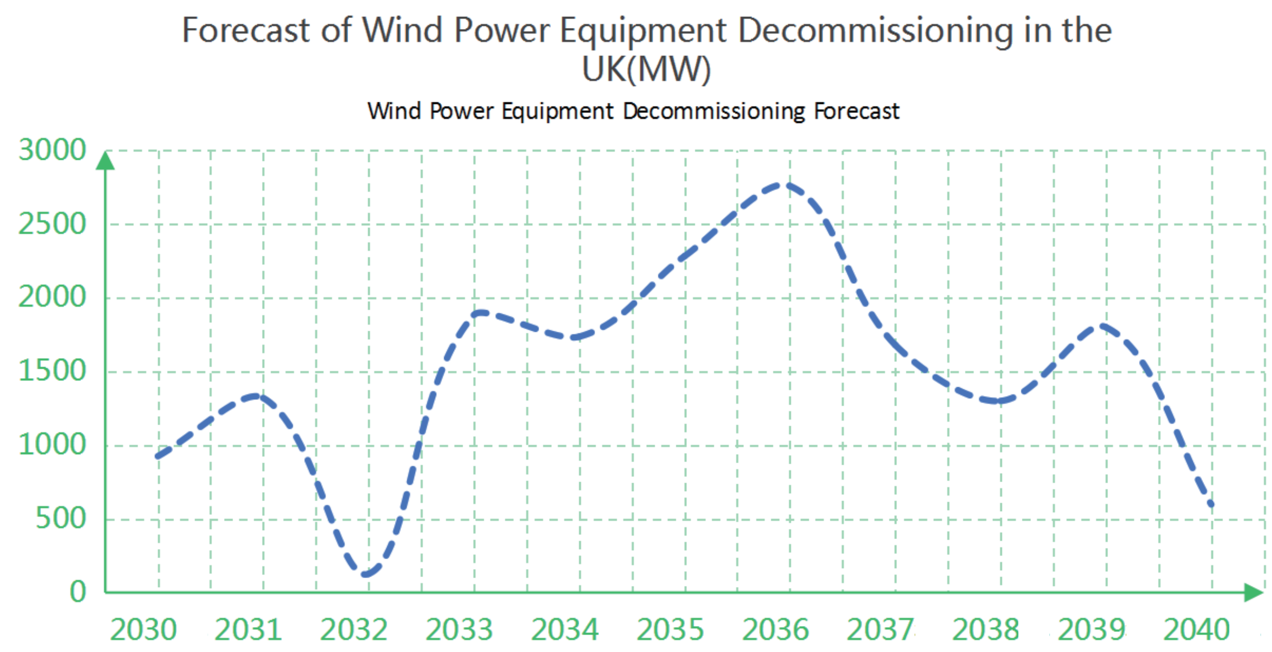


Figure 2-12: Forecast of Wind Power Equipment Decommissioning in the UK

In 2023, up to 50,000 tons of composite materials required recycling and reuse. Around 14,000 wind turbine blades are expected to reach the end of their service life by 2025. According to the International Renewable Energy Equipment Recycling Association, the total decommissioning volume for wind power in the UK is projected to reach 16.4 GW between 2030 and 2040.

The United Kingdom holds a leading position globally in offshore wind power capacity. With the first generation of offshore wind farms set to be decommissioned in the next decade, attention is shifting towards the sustainable management and recycling of end-of-life wind turbine blades. However, offshore wind turbine recycling poses significantly greater challenges compared to onshore systems.

According to the UK Department of Business, Energy and Industrial Strategy (BEIS) report, "Cost Estimation and Liabilities in Decommissioning Offshore Wind Installations", the total estimated decommissioning cost for 37 operational or under-construction offshore wind farms (OWFs) is £1.82 billion. Initial estimates placed the cost of dismantling offshore turbines at £40,000/MW, but recent studies suggest this figure could exceed £200,000/MW. To address these rising costs, a clear strategy is essential, including detailed plans for managing and recycling the removed components sustainably.

France

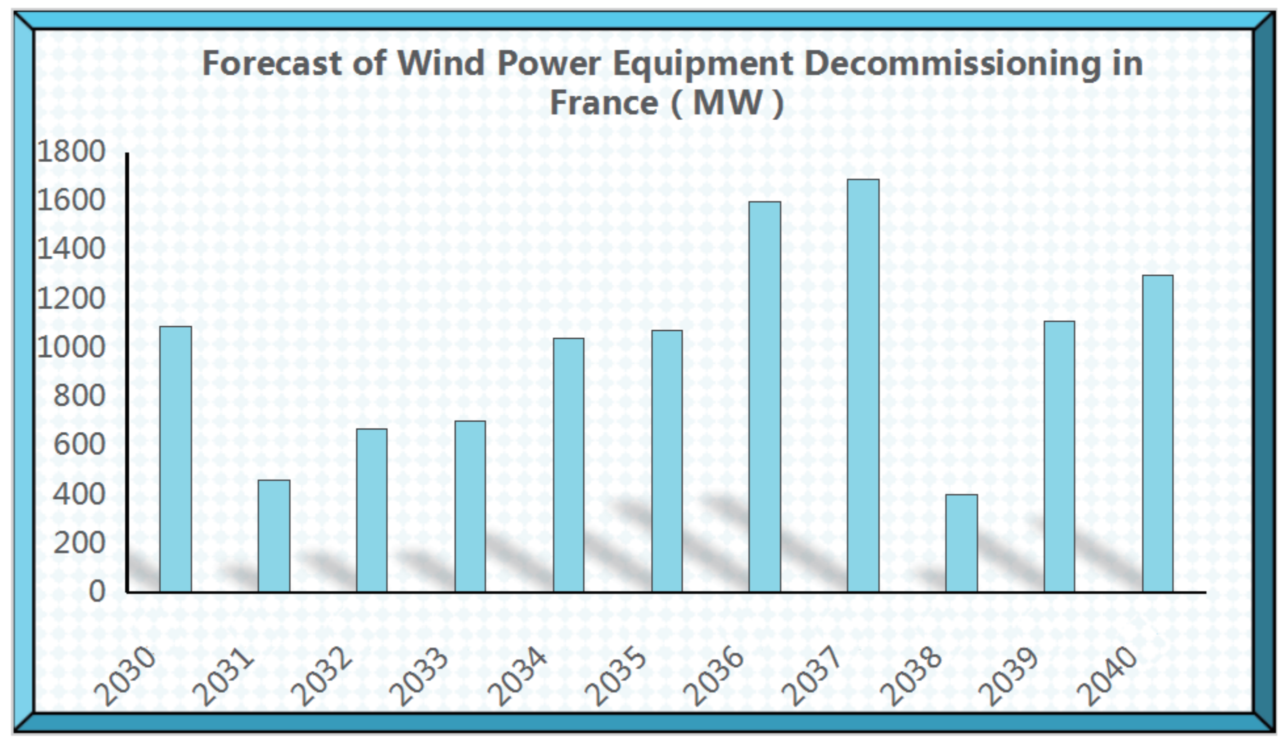


Figure 2-13: Forecast of Wind Power Equipment Decommissioning in France

The French Environment and Energy Management Agency (ADEME) notes that most wind turbines are replaced after 15 to 20 years of operation. In France, wind turbines that have been in service for over 15 years account for less than 5% of the total installed capacity. These turbines are now nearing the end of their design lifespan, and the issue of decommissioning is beginning to emerge. Since 2008, France's wind power industry has had to manage 10,000 to 15,000 tons of polymer waste annually.   In 2021, this volume reached 396 MW. Between 2021 and 2026, France is expected to decommission approximately 1,500 turbines. According to the International Renewable Energy Equipment Recycling Association, by around 2035, 5 GW of wind turbines in France are projected to face decommissioning. France possesses some domestic capacity for handling the decommissioning and recycling of wind power equipment.

Brazil

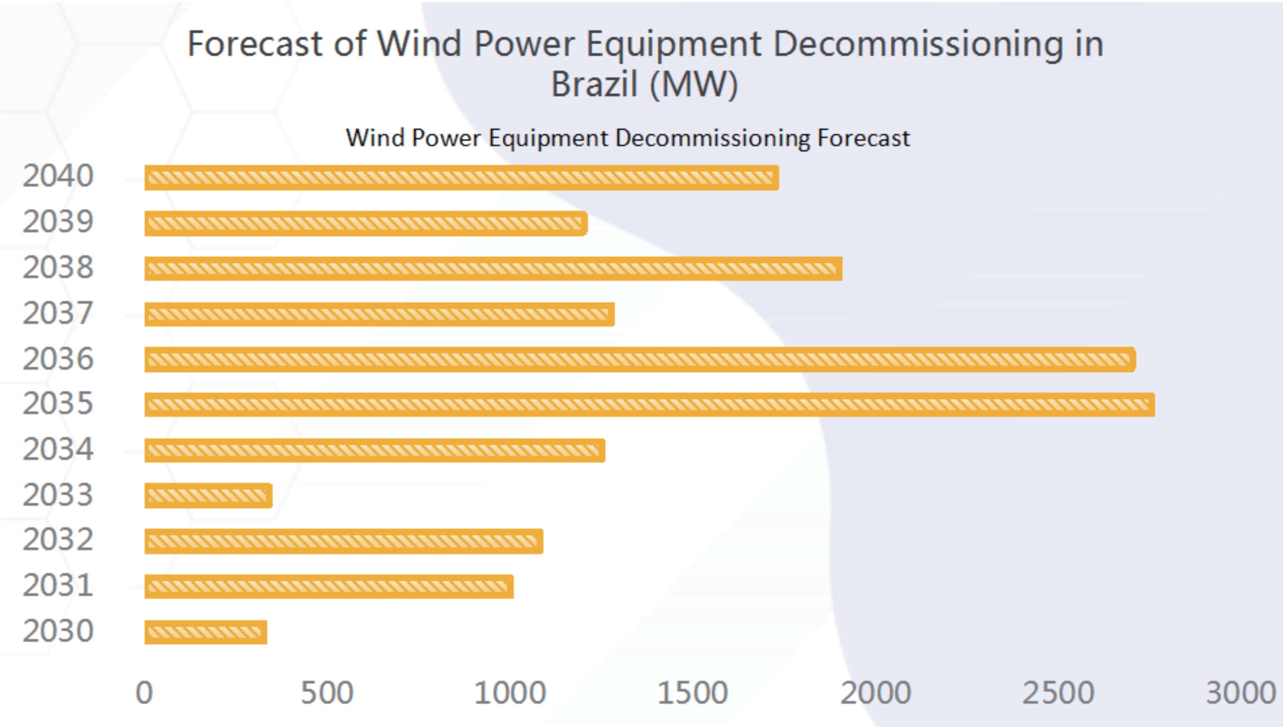


Figure 2-14: Forecast of Wind Power Equipment Decommissioning in Brazil

The South American wind power market, led by Brazil, has emerged as a significant player in the global renewable energy landscape. It is projected that Brazil's wind power capacity will exceed 45 GW by 2028, driven by rising energy demand and supportive policies. According to the World Bank, Brazil's offshore wind power potential is estimated to exceed 1,200 GW, and by 2050, the country could develop a total offshore wind capacity of 96 GW.

The International Renewable Energy Equipment Recycling Association (IREERA) predicts that Brazil will enter a period of significant wind power decommissioning around 2035, with 6 GW of wind turbines expected to be decommissioned. Between 2036 and 2040, nearly 9 GW of wind power equipment is anticipated to reach the end of its lifecycle.

2.3 Global Forecast for Decommissioned Wind Turbine Blades

As composite materials, wind turbine blades pose significant challenges for recycling due to their technical complexity and high costs. While effective recycling systems exist for other materials in wind turbines, such as metals and concrete, there is currently no scalable, ideal solution for blade recycling globally. The following provides a forecast of the volume of decommissioned turbine blades worldwide, offering data to support the development of future blade recycling industries.

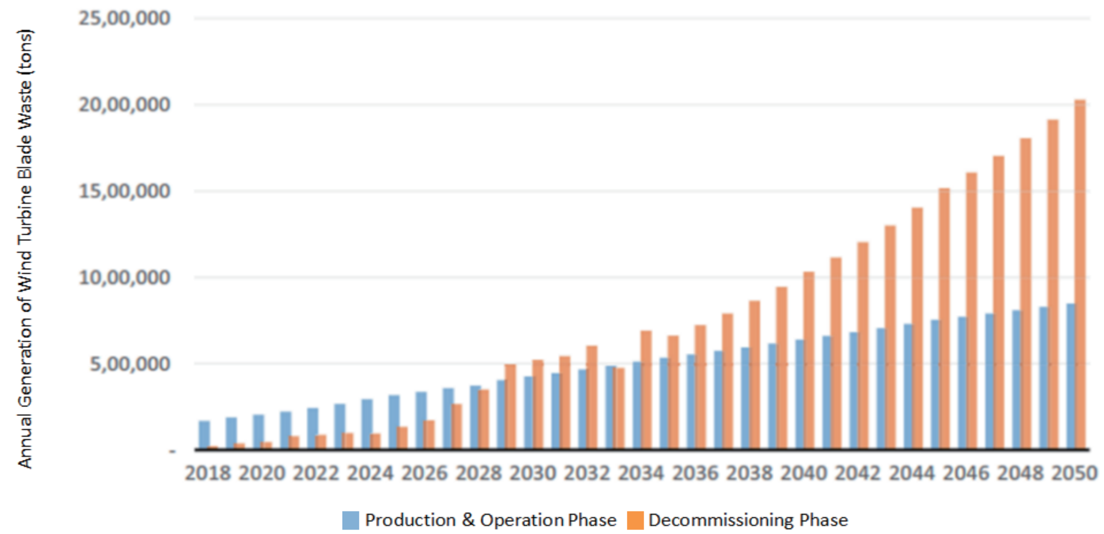


Figure 2-15: Annual Global Generation of Wind Turbine Blade Waste

Since 2018, the annual volume of decommissioned wind turbine blades has steadily increased, driven by the growth in installed wind power capacity during the manufacturing and operational phases. By 2034, this figure is projected to reach 500,000 tons (500 kt) and will continue to rise with the increase in blade production. In comparison, blade decommissioning only began in 2018 because wind turbine installations started in 1998, and the design lifespan of these blades is approximately 20 years. By 2029, decommissioned blade waste will surge sharply, reaching 500,000 tons per year, surpassing all other sources of wind turbine-related waste to become the largest contributor. By 2050, the annual volume of blade waste generated during the decommissioning phase is expected to exceed 2 million tons.

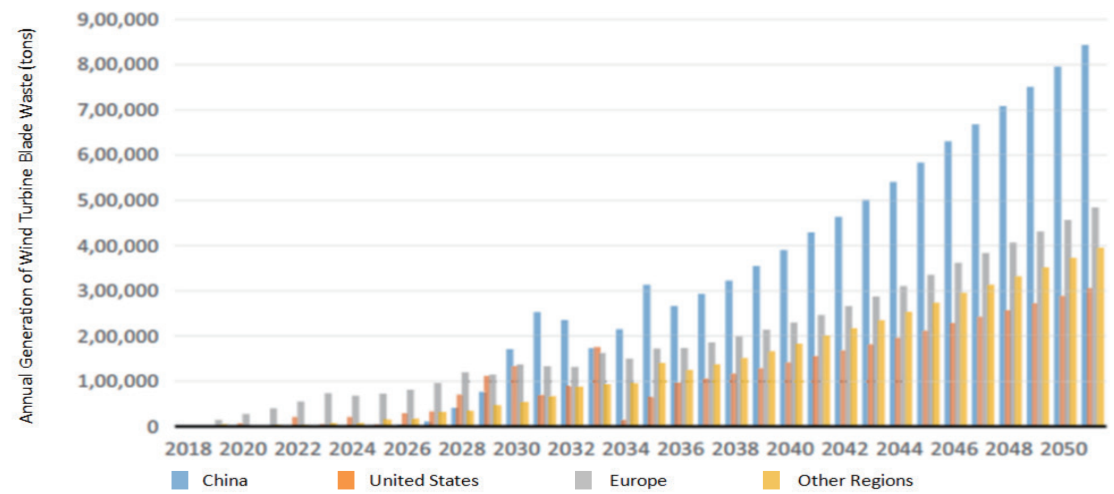


Figure 2-16: Annual Global Generation of Wind Turbine Blade Waste

As shown in Figure 2-16, China will need to handle 40% of the world's decommissioned blades, while Europe and the United States will account for 25% and 16%, respectively. Since Europe began installing large wind turbines earlier than other regions, it will be the first to face the challenge of managing decommissioned blades.

The rapid growth in wind turbine installations has exceeded initial expectations, resulting in a higher actual volume of waste than previously forecasted. This presents even greater challenges for the development of the recycling industry. These data provide a global perspective, illustrating the decommissioning scenarios and market inventories of the wind power industry across various countries. They highlight the rapid growth of the wind power sector and the associated challenges and opportunities in decommissioning and recycling.

Chapter 3
Technologies for the Wind Power Equipment Recycling Industry

If decommissioned wind turbines are disposed of through methods such as stockpiling, landfilling, or incineration, they not only occupy significant land resources and cause resource wastage but also pose environmental risks. Currently, some power generation companies, equipment manufacturers, and recycling enterprises around the world are actively exploring recycling technologies and application scenarios for decommissioned wind power equipment, accumulating valuable experience.

The components requiring handling during turbine decommissioning can be broadly categorized as follows: foundations, towers, blades, nacelles, generators, large mechanical components (such as gearboxes, main shafts, and bearings), and electrical control systems. Additionally, they include materials such as lubricants in gearboxes, batteries in pitch systems, box transformers, and site-specific wiring. Most components, such as foundations, towers, generators, large mechanical parts, and electrical control systems, can be repaired, maintained, and subsequently recycled. Lubricants and batteries can also be recycled after proper treatment, while any hazardous waste must be managed by certified organizations. However, components made from composite materials, such as turbine blades and nacelles, present significant challenges in the recycling process. Given that blades are the largest and most characteristic component of wind turbines, this report uses blades as a representative example for addressing composite material recycling.

3.1 Current Technologies in Recycling

Recycling centers on the principles of "Reduce, Reuse, and Recycle" (3R), emphasizing low consumption, low emissions, and high efficiency as its core characteristics.

3.1.1 Reuse

Reuse refers to the repeated use of items to extend their service life, thereby reducing waste generation. This practice conserves resources, lowers pollution, and reduces transportation and disposal costs. During production, reuse can be facilitated by designing products that are modular, easily dismantled, or reconfigurable. During use, enhanced operations and maintenance measures can prolong the lifespan of equipment. After decommissioning, products can be repurposed for downgraded applications, effectively extending their utility.
This primarily includes entire turbines, towers, generators, large mechanical components such as gearboxes, main shafts, and bearings, as well as electrical control systems, box transformers, and site wiring. Decommissioned wind power equipment components, such as motors and gearboxes, can be repaired and repurposed as spare parts. Blades can be cut and redesigned into pallets, chairs, benches, or landscaping structures. Similarly, photovoltaic modules can undergo inspection and testing for reuse in applications with lower performance requirements.

(1) Entire Turbine

By repairing and retrofitting aging or malfunctioning wind turbines, damaged or worn components can be restored or replaced to enhance the generator's efficiency and reliability, thereby extending its service life.
The implementation of repairs and retrofits not only improves the performance of aging, faulty, or near-decommission wind turbines but also upgrades or enhances control systems and technology. These improvements boost the generator's power output and efficiency, increasing wind energy utilization and overall energy efficiency. This contributes significantly to the development of sustainable energy.

As a result, repairs and retrofitting have become a crucial aspect of the wind power sector.
Repairs and retrofitting can be extended to various scenarios, for example:

① During the early development of the wind power market, operational practices were often rudimentary. Many turbine brands faced quality instability, and some manufacturers exited the market for various reasons, leaving a significant number of "orphaned turbines" behind. These orphaned turbines generally suffer from poor operational conditions and, in some cases, have been out of service for extended periods, leading to idle assets and economic losses. By employing retrofitting and reuse strategies, these turbines can be restored to operational status, effectively addressing the orphan turbine issue.

② Decommissioned turbines can be refurbished and repurposed into 1:1 full-scale training platforms for wind power operations. These platforms can serve as comprehensive training facilities for professional skill development, fault diagnosis, component assembly and disassembly, and operational maintenance. The standardized, professional, and systematic training environment supports the development of skilled personnel in the renewable energy sector. This approach overcomes limitations associated with real-world turbine training, such as operational constraints, power generation targets, and safety concerns. It also reduces time and cost, enhancing the effectiveness of personnel training while meeting the growing talent development needs of the wind power industry.

(2) Towers

Figure 3-1: Dismantling of Wind Turbine Towers

The main structure of wind turbine towers is composed of rolled steel plates, which are metallic materials that can be recycled as scrap metal. Auxiliary components include structural elements, dampers, cable twist protection systems, sealing and lighting systems, flexible connections, ladders, cable trays, cable suspension nets, mechanical and electrical accessories, and environmental control equipment. After dismantling, these auxiliary components can be repurposed as spare parts for further use.

(3) Generators

Figure 3-2: Remanufacturing of Generators

As a core component of wind power equipment, generators may face aging or malfunctions as their service time increases, resulting in decreased efficiency or even operational failure. Repairs and retrofitting can enhance the lifespan of generators, effectively extending the operational time of wind power equipment. Additionally, generators from decommissioned wind turbines can be utilized in a tiered manner, maximizing their value and sustainability.

The general steps for remanufacturing a generator are as follows:

Step 1 Disassembly and Mapping. Before remanufacturing an aging or malfunctioning generator, the prototype generator must be disassembled and thoroughly mapped.

Step 2 Type Testing. This step involves conducting comprehensive tests to obtain accurate performance data and assess the generator's condition. The test results are used to evaluate the operational status and overall state of the generator.

Step 3 Reevaluation of Key Performance Aspects. Based on the disassembly mapping and type testing results, critical performance aspects such as electromagnetic design, ventilation structure, mechanical strength, and bearing load must be reevaluated. This analysis identifies deficiencies in the original structure and prepares for subsequent remanufacturing processes.

Step 4 Redesign. After the analysis, the prototype generator is redesigned using advanced techniques to retain reliable components and optimize or replace defective parts. The redesign must consider feasibility and cost-effectiveness to determine the best possible solution.

Step 5 Remanufacturing. Using the optimized design, the faulty generator undergoes the remanufacturing process. The remanufactured generator is equivalent to a newly manufactured unit and comes with quality assurance and after-sales service. This step emphasizes rigorous testing and quality control to ensure that the remanufactured generator meets or exceeds the performance and quality of the original prototype, guaranteeing reliability and durability.

By upgrading and refurbishing used products, they can be restored to perform with the functionality and efficiency of new products, achieving the goal of "renewing old to new." The cost of remanufacturing wind turbine generators is generally no more than 65% of the cost of manufacturing a new generator. Additionally, tiered utilization allows remanufactured generators to serve as spare parts, reducing downtime losses caused by equipment failures. Remanufactured generators offer reliability, cost-effectiveness, and eco-friendly benefits. In China, several companies have already engaged in wind turbine generator remanufacturing or have implemented tiered utilization practices to enhance resource efficiency and sustainability.

(4) Large Mechanical Components

The gearbox, main shaft, and bearings are critical large mechanical components in wind power equipment. While these components are generally designed to last over 20 years, their actual service life can vary due to various factors. For worn or damaged large mechanical components, remanufacturing technologies such as laser additive manufacturing and plasma spraying are commonly used. These techniques are versatile and effective, enabling the restoration of these components to meet operational requirements and extend their service life.

① Laser Additive Manufacturing Technology

Figure 3-3: Repairing Worn Parts Using Laser Additive Manufacturing Technology

Laser additive manufacturing is a process that utilizes a laser beam to process metal powder layer by layer. This technology is suitable for both manufacturing new gearbox components and repairing damaged ones. Based on its principles, laser additive manufacturing includes methods such as laser cladding deposition (LCD), which involves synchronous powder feeding, and selective laser melting (SLM), which uses a powder bed layering approach.

The typical steps for repairing components using laser additive manufacturing technology begin with scanning the part to obtain precise geometric data. This data is then converted into a 3D model using computer-aided design (CAD) software, incorporating the required repair design. Subsequently, the laser additive process is used to layer materials, creating the desired part.

Laser additive manufacturing offers several advantages for producing or repairing mechanical components. First, it provides highly precise control over the materials used and their deposition, enabling the fine repair of localized damage with micron-level accuracy. This ensures the quality and reliability of the restored parts. Second, the technology allows for the use of a wide range of metal materials, tailored to meet specific remanufacturing requirements. Third, compared to traditional manufacturing and repair methods, laser additive manufacturing is faster and more efficient, reducing both time and costs.

Figure 3-4: Repairing Worn Parts Using Plasma Spraying Technology

② Plasma Spraying Technology

Plasma spraying technology is a method used to create coatings on metal surfaces. It involves feeding non-metallic or metallic powders into a rigid non-transferred plasma arc flame, where the powders are heated to a molten or semi-molten state. These materials are then propelled at high speed with the plasma flame and deposited onto the pretreated surface of the workpiece. This process results in a coating with specialized properties, such as corrosion resistance, wear resistance, oxidation prevention, and thermal conductivity. These enhanced characteristics extend the functionality and durability of the repaired component.

Plasma spraying technology offers numerous advantages, including stable coating performance, smooth and even surfaces, precise thickness control, low oxide and impurity content in the coating, and minimal thermal impact on the base material. The technology is well-established in the market and includes five main types: atmospheric plasma spraying, controlled-atmosphere plasma spraying, liquid-stabilized plasma spraying, reactive plasma spraying, and supersonic plasma spraying.

In the context of remanufacturing, bearings produced using plasma spraying typically cost less than 50% of newly purchased bearings. Green remanufacturing also reduces raw material usage by over 80% compared to new manufacturing and cuts energy consumption during processing by approximately 70%. These benefits result in significant social and environmental advantages, promoting sustainability and resource efficiency.

(5) Electrical Control Equipment

Electrical control equipment in wind turbines typically includes components such as power supplies, controllers, inverters, transformers, circuit breakers, and protective devices. These components play a crucial role in monitoring turbine operations, regulating rotor speed and output power, and protecting the turbine from damage. However, due to prolonged use or environmental factors, electronic components may age over time, leading to an increased failure rate of the electrical control systems.

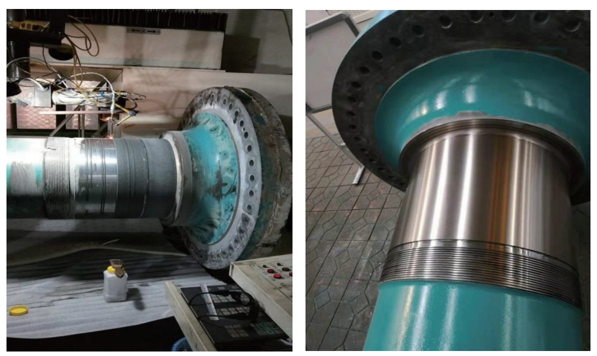


Figure 3-5: Bearing Seat Before Repair and After Repair

(6) Box Transformers and On-Site Wiring

The dismantling of box transformers and on-site wiring is a relatively standardized process. After removal, the materials are sorted and recycled for further utilization.

3.1.2 Recycling

Recycling refers to the process of sorting, recovering, and processing waste materials to transform them into new resources for reuse. Recycling helps reduce waste accumulation, lowers environmental pollution, and conserves energy and resources. To effectively implement recycling, it is essential to understand the appropriate recovery channels and methods for different types of waste and to ensure proper sorting and disposal. For instance, decommissioned wind turbine blades can be processed into glass or carbon fibers and resin. Used lubricating oil can be treated through dialysis and other methods to produce recycled turbine gear oil. Photovoltaic modules can be dismantled to extract reusable materials such as silicon and silver.

(1) Foundations

After the removal of turbine foundations, steel reinforcements and other metal materials are recovered and processed alongside industrial scrap metal for reuse. Concrete and other foundation materials can be repurposed by enlarging and reusing them as a new foundation base or recycled for use as construction materials.

Figure 3-6: Dismantling of Wind Turbine Foundations

(2) Wind Turbine Blades, Nacelle Covers, and Hub Covers

Wind turbine blades, nacelle covers, and hub covers are typically made of thermoset polymer composites, which use polymers such as epoxy resin, polyurethane, or polyester as a matrix, reinforced with core materials and fibers like glass or carbon. These components are manufactured using vacuum infusion and heat-curing processes, resulting in lightweight, high-strength materials with extremely stable structures. However, this stability, while advantageous during operation, poses significant challenges for recycling after decommissioning. Unlike thermoplastics, thermoset composites are notoriously difficult to recycle and are often referred to as "millennium-resistant" and "imperishable for eons." The key challenge in the recycling of these materials lies in efficiently separating the fibers from the polymer resin to ensure the highest-value recovery. This issue remains a major focus and difficulty in the circular economy of wind power equipment.

Figure 3-7: Dismantling of Wind Turbine Blades and Nacelle Covers

In wind turbines, blades are the largest components. Currently, the length of decommissioned blades ranges mostly between 18 meters and 72 meters. Since the introduction of 100-meter blades in 2019, blade lengths have continually increased, reaching 108 meters, 111 meters, 115 meters, and 123 meters, with the longest onshore wind turbine blade globally, measuring 131 meters, recently completed.

As a result, the proper disposal of composite materials represented by wind turbine blades has become a topic of global concern.
Currently, there are several methods for recycling composite materials from wind power equipment:

① Partial or Complete Tiered Utilization

This method can be classified as reuse, as it involves repurposing decommissioned materials for secondary applications. However, due to its relatively low proportion in the overall blade recycling process, it is discussed alongside other recycling methods in this section.

Method 1 - Tiered Utilization for Smaller Turbine Models: Decommissioned wind turbine blades can be modified and repurposed for use in smaller turbine models, enhancing the power output of the original turbines. This recycling approach requires detailed project planning and high technical expertise. However, due to the rapid advancements in wind power technology—resulting in larger blades and higher turbine capacities—this method has limited application scenarios.

Method 2 - Use as Structural Panels: The composite materials in turbine blades have been extensively studied and applied as structural panels. These materials offer excellent mechanical properties, corrosion resistance, and aging resistance. After cutting the blades into appropriately sized panels, they can be repurposed for uses such as fencing, pallets, and other local applications in agriculture or logistics.

Method 3 - Use in Building Materials like Tiles: Blades can be cut into strips or blocks, typically 10 cm–20 cm or other dimensions, depending on the application, to serve as new composite materials replacing traditional wood composites. These materials can be used in floor tiles, plastic road barriers, and similar applications. As this method does not separate the composite materials within the blades but instead directly repurposes them as building materials, it incurs relatively low processing costs. This approach was developed by Washington State University in collaboration with Global Fiberglass Solutions, Inc. in Seattle.

Method 4 - Landscape Applications: Using decommissioned turbine blades for landscape purposes has become a popular solution and is widely implemented globally. This includes transforming old blades into artistic installations for urban parks, exhibitions, and other public venues. These installations not only capture attention through creative design but also raise public awareness of environmental protection.

Figure 3-8: Visual Representation of Landscape Applications

② Physical Recycling Method

In simple terms, the physical method involves altering the physical structure of turbine blades without inducing any chemical changes. This method can be further divided into two approaches. The first approach involves crushing discarded blades, nacelle covers, and fairings into composite material fragments without separating the components. These fragments are then processed into new composite materials using adhesives and other auxiliary materials. The second approach involves cutting, crushing, and grinding the materials through mechanical processing, followed by sorting and separation to obtain pure fiber-resin composites. Both methods enable secondary utilization in various fields, such as adding short reinforcement fibers to concrete and other construction materials. Regardless of the approach, as well as subsequent methods like pyrolysis and chemical recycling, the initial step always involves on-site dismantling and preliminary cutting.

③ Pyrolysis Recycling Method

Pyrolysis, also known as high-temperature cracking, is a process where wind turbine blades are dismantled and cut according to treatment requirements, then heated in an oxygen-deficient or oxygen-free environment. This process breaks down the organic macromolecular substances into pyrolysis gases composed of alkanes, alkenes, aromatics, and syngas, leaving behind solid residues such as fibers and fillers. The pyrolysis gases can be further processed through condensation, catalysis, and distillation to produce light fuel oils. However, due to the complex composition of pyrolysis gases from composite materials—which include alkanes, alkenes, aromatics, and aliphatics—their separation is significantly more challenging compared to pyrolysis gases from rubber or plastic.

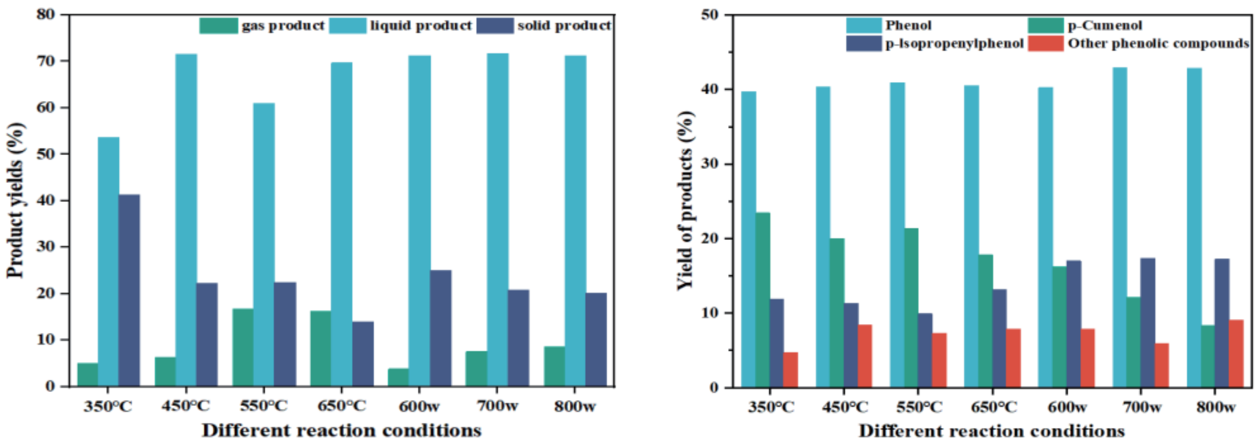


Figure 3-9: Distribution of Pyrolysis Liquid Products Under Different Reaction Conditions

Pyrolysis can be carried out in various types of reactors, such as fixed-bed reactors, auger (screw) reactors, rotary kilns, or fluidized bed reactors, with fluidized bed and rotary kiln reactors being the most commonly used. The decomposition temperature of composite materials made from different matrix resins varies, generally ranging between 450°C and 700°C. Specifically, the pyrolysis temperature of unsaturated polyester resin-based composites is typically no less than 550°C, while that of epoxy resin-based composites is not less than 650°C. Higher pyrolysis temperatures tend to cause greater destructive impact on fibers, making it challenging to reuse them as original fiber materials. Typically, for wind turbine blades, the pyrolysis temperature is controlled within the range of 500°C to 550°C. At this temperature, the residual glass fibers

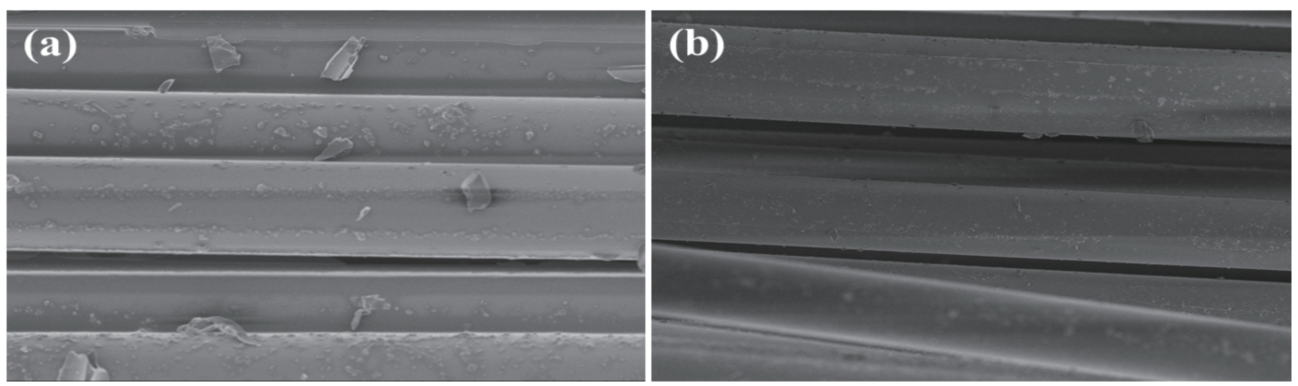


Figure 3-10: (a) SEM of Fibers Before Decarbonization (b) SEM of Fibers After Decarbonization

exhibit a reduction in material properties of approximately 50% compared to the original fibers (the rate of material property degradation may vary depending on specific processes and control conditions). This range is currently considered the optimal method for retaining the tensile strength of glass fibers.

The pyrolysis method allows for the extraction of fibers with relatively high residual value. Additionally, the heat generated during pyrolysis can be recovered and utilized. Currently, pyrolysis recycling is one of the primary research pathways for the recycling and utilization of decommissioned wind turbine blades.

④ Chemical Degradation Method

The chemical degradation method involves chemically modifying or decomposing thermoset composites to convert them into other recyclable materials. This approach can be further categorized into supercritical fluid degradation and solvent-based decomposition. Although chemical degradation requires advanced technical capabilities, involves significant processing challenges, and is less cost-effective, it offers superior recycling outcomes. As a result, this method has garnered significant attention in the field of recycling decommissioned wind turbine blades.

Supercritical Fluid Method: Supercritical fluids are substances in a state where their temperature and pressure exceed their critical temperature and pressure, exhibiting unique solubility and mass transfer properties. These characteristics enable the decomposition or degradation of polymer macromolecular waste, producing gas-phase, liquid-phase, and solid products. In recent years, many countries have reported research advancements in this method. The supercritical fluid method primarily uses water or alcohol as the decomposition medium. With this approach, the removal rate of epoxy resin can exceed 95%, while the tensile strength of the fibers is largely preserved, retaining over 90% of the original material's performance. Due to the high process control requirements and costs associated with this method, it is generally applied to the treatment and recycling of carbon fiber composites.

Solvent Degradation Method: The solvent degradation method uses organic or inorganic chemical solvents to break the carbon-nitrogen bonds in polymers under appropriate temperature and pressure conditions. This process depolymerizes the thermoset resin in composite materials into a soluble form, allowing the recovery of long-chain monomers or resins. Additionally, this method enables the separation and recovery of fibers with relatively good performance. Due to variations in the materials used in wind turbine blades, the choice of solvent, reaction time, temperature, pressure, and other conditions varies. Currently, research into this method is highly diverse, with numerous approaches under exploration. However, all efforts share a common goal: achieving high-value recycling and reuse of turbine blades.

In summary, the solvent degradation method typically involves the following steps:

First, the composite materials from decommissioned wind turbine blades are cut into small pieces and immersed in a chemical solvent.

Next, under controlled temperature and pressure conditions, the mixture is stirred while being heated and pressurized. This process degrades the polymers in the composite materials, achieving separation from the fibers.

Finally, the fibers and degradation products are obtained through filtering, washing, and drying.

A critical aspect of the chemical degradation process is minimizing the generation of secondary pollutants, such as waste gas, wastewater, and solid waste. If such byproducts are generated, they must be treated to meet discharge standards or disposed of properly.

(3) Lubricating Oil

Lubricating oil used in wind turbine gearboxes, yaw systems, and pitch reduction gears has significant recycling value. The recycling process typically consists of four main steps: the pre-treatment module, core refining module, post-treatment module, and enhancement module.

Figure 3-11: Lubricating Oil Recycling Process

The pre-treatment module is designed to remove larger particulates, water, ferromagnetic particles, and similar impurities. The core refining module typically employs a combination of techniques in a "dialysis-like" treatment process to eliminate oxidized and degraded additives, base oil degradation products, insoluble or oil-soluble substances formed during operation, and dissolved metal ions. This step yields a high-quality intermediate product. The post-treatment module further removes residual particulates and water to improve the cleanliness of the oil. Finally, the enhancement module incorporates proprietary strengthening formulations, which generally include base oil reinforcement and additive supplementation. This process results in a fully restored and high-performing gear oil product.

3.1.3 Final Disposal

Apart from thermoset composite materials like wind turbine blades, nacelles, and fairings, most components and lubricating oil from wind turbines can be reused and recycled after proper treatment. However, certain thermoset composite components from turbines still require final disposal. According to Wind Energy Magazine in Europe, the majority of decommissioned wind turbine blades in countries and regions like the UK and the EU end up in landfills or are shredded for incineration. In Germany, during the early phases of large-scale equipment replacement, incineration was commonly used, with the residual ash incorporated into cement clinker. Similarly, U.S. energy company GE

Renewable Energy announced a multi-year partnership with Veolia to process decommissioned turbine blades from American wind farms. These blades are shredded and used as substitutes for gravel, clay, and other materials in cement production, enabling their recycling into the construction sector.

(1) Landfilling

Figure 3-12: Centralized Storage and Landfilling

Landfilling was once the dominant method for disposing of wind turbine blades due to its simplicity and low energy requirements. In this process, blades are either crushed and directly buried in landfills or incinerated. The resulting fiberglass, whose mechanical properties degrade after burning, is also buried. However, wind turbine blades contain organic materials that release significant amounts of harmful gases during landfilling. Additionally, the fiberglass is non-degradable, consuming substantial land resources during disposal. Many European countries have prohibited the landfilling of decommissioned wind turbine blades. German authorities ban blades and similar materials from entering landfills, while the United Kingdom imposes high landfill taxes to discourage this practice. As public awareness of the issues surrounding landfill disposal grows, the wind power industry, which prides itself on its green reputation, risks damaging its credibility if it continues to rely on landfilling for the disposal of decommissioned composite materials like turbine blades.

(2) Incineration

The incineration of decommissioned wind turbine blades and other thermoset composites involves two main methods: direct incineration and co-processing in cement kilns. Direct incineration primarily aims to recover thermal energy for power generation or heating. In the co-processing method, blades are cut into smaller pieces and burned in cement kilns. The combustible components provide heat, while the fiberglass serves as a raw material for producing clinker cement.

Key factors influencing incineration include residence time, combustion temperature, turbulence, and excess air ratio, commonly referred to as "3T+E." Blade incineration does not adversely affect these parameters, and the technology is considered mature. However, the fibers recovered through this process are of low value, and incineration generates harmful gases. This approach is seen as inconsistent with the principles of wind energy as a clean energy source. As a result, many countries currently discourage using incineration as a disposal method for decommissioned turbine blades.

3.1.4 Comparative Analysis of Current Disposal Methods for Decommissioned Wind Power Equipment

Disposal Methods & Targeted Components		Method Summary	Advantages	Disadvantages	Application Scenarios
Reuse Reuse primarily targets decommissioned or damaged components such as complete turbines, towers, generators, large mechanical parts (gearboxes, shafts, and bearings), and electrical control systems. Additionally, wind turbine blades can achieve partial reuse.		Since some of their functions remain intact, these components can be repaired or refurbished for repeated use.	Enables true circular economy	Except for blade reuse, the reuse of other components is the most ideal approach, with virtually no drawbacks. However, due to the high level of specialization required, the need for project compatibility, and the rapid pace of technological upgrades, the application scope is somewhat limited. The reuse of blades generates residual scrap during processing. Additionally, due to their fixed shape and performance limitations, achieving large-scale, industrialized recycling is challenging. Furthermore, once their remaining functionality is exhausted, blades still require further recycling and processing.	Retained functions allow reuse of large components, such as generators, primarily as spare parts. Metal materials are recycled for metal recovery. Blades are repurposed into landscapes or logistics applications.
Recycling Primarily targets the disposal of turbine blades	Physical Recycling	Involves altering the physical form without chemical changes. It can be divided into two modes: 1. Crushing without separation, where adhesives and other auxiliary materials are used to process the fragments into composite materials. 2. Cutting, crushing, and grinding to separate and utilize short fibers.	The technology is straightforward and cost-effective.	Fibers are severely damaged during the recycling process, making it impossible to recover long fibers. The high mechanical strength and hardness of composite materials present challenges for mechanical crushing. Organic components cannot be effectively recycled into valuable materials. The process generates cutting dust.	Recycled materials can be used as thermoplastic modifiers. Fibers can serve as reinforcement for building panels and other applications.
	Pyrolysis Recycling	Through high-temperature heating, organic macromolecules are broken down into smaller molecules. These are then processed through condensation, catalysis, and distillation to produce light fuel oils while retaining components such as reinforcing fibers and core materials.	Recovers light fuel oils, reinforcing fibers, and thermal energy.	It is relatively costly, with high carbon emissions. The high processing temperatures significantly reduce the performance of recovered glass fibers, and the carbonized layer on the surface of the fibers is difficult to remove, limiting their applications.	Recovered oils can be used as fuels, fibers can be repurposed for building panels and crack-resistant mortar, and reclaimed heat can be utilized for industrial processes or heating purposes.
	Chemical Degradation	This method uses organic solvents under specific temperature and pressure conditions to break carbon-nitrogen bonds in polymer chains, producing soluble products while separating the fibers.	The process effectively separates glass fibers from resin with minimal damage to the fibers.	It has challenges such as difficult reaction control and high costs. The use of solvents and other chemicals may generate pollutants, including waste gases and solid waste, requiring consideration of environmental and health impacts.	Recovered polymers can be used in products like plasticizers, while fibers, depending on their form, can be utilized in composite material products.
Final Disposal Primarily targets the disposal of turbine blades	Landfilling	Disposed of as solid waste in landfills.	Simple operation and low energy consumption.	Release of harmful gases, significant land usage, and resource wastage.	
	Incineration	Direct combustion or co-processing in cement kilns	Mature technology and the recovery of thermal energy	Generates secondary pollutants such as waste gases, low value of recovered thermal energy, and limitations on blending ratios. The variability in glass fiber composition (e.g., alkali content and inorganic metal elements) can lead to instability in cement quality. Additionally, incinerators or kilns have strict size requirements for input materials.	Thermal energy recovery and the production of cement-based materials.

Table 3-1: Advantages and Disadvantages of Current Disposal Methods for Decommissioned Wind Power Equipment

3.2 Existing Issues in the Industry

Globally, the recycling and reuse market for decommissioned wind power equipment is still in its infancy. There is no definitive consensus on how to achieve efficient and high-value disposal of decommissioned wind power equipment. Challenges include unclear responsibilities for equipment disposal, a shortage of specialized recycling enterprises, and underdeveloped commercial models. The practices of simple incineration and landfilling of low-value waste have yet to be fully eradicated. The current issues in the industry are mainly reflected in the following aspects:

(1) High Recycling Costs and Low Economic Returns

The costs of dismantling and transporting a single wind turbine vary significantly depending on the geographic location and infrastructure conditions of the wind farm. When developing onshore wind projects a decade or two ago, most developers gave little consideration to the future costs of decommissioning and recycling turbines. The high dismantling costs reduce the enthusiasm of stakeholders and, to some extent, hinder the development of recycling and disposal efforts. Many companies currently opt to temporarily store decommissioned turbines at suitable locations. This approach avoids immediate challenges such as cutting, dismantling, and long-distance transportation while waiting for the related industries to mature further, potentially reducing costs and even creating revenue opportunities. However, the limited recycling value compared to the high dismantling and transportation costs makes it difficult to motivate wind power companies and recycling enterprises to adopt circular methods for processing decommissioned turbines.

(2) Lack of Mature Recycling Technologies

The thermoset composites in decommissioned wind power equipment are challenging to degrade, and the recycling process is complex. Landfilling, while previously common for solid waste disposal, has significant ecological impacts and is increasingly being phased out or prohibited. Across the wind power industry value chain, stakeholders are actively exploring recycling solutions. Initial progress has been made in developing several technical approaches for blade recycling, including mechanical grinding, pyrolysis, and chemical degradation. However, none of these methods have yet achieved large-scale, efficient recycling in practice. Currently, the majority of decommissioned turbine blades are processed through incineration or landfilling, both of which have environmental repercussions. The challenges are compounded by the inherent non-biodegradability and recycling difficulties of composite materials. Furthermore, the industry lacks specialized environmental recycling enterprises capable of handling and comprehensively utilizing these materials.

(3) Lack of a Comprehensive Wind Power Equipment Recycling Supply Chain

Most countries have yet to establish robust systems for the recycling and utilization of solid waste from decommissioned wind power equipment. The recycling supply chain for turbine blades lacks systemic integration. Upstream industries often fall short in implementing green design practices, and production processes remain constrained by unresolved technical bottlenecks. These limitations hinder the advancement of environmental management across the entire industry and impede efforts to support resource circularity and sustainable development.

(4) Insufficient R&D Capacity for Eco-Friendly Materials in Wind Power Equipment

Currently, research institutions and manufacturing companies show insufficient emphasis on the development of new materials for wind turbine blades. Limited funding has constrained the adoption of next-generation blade materials, slowing progress. Globally, large companies such as General Electric, Vestas, and Siemens Gamesa have begun to establish recycling initiatives for turbine blades and have launched forward-looking demonstration projects, such as "zero-waste turbines." However, these initiatives are still far from achieving large-scale application.

(5) Lack of Unified International Standards and Regulations

The global wind power recycling sector has yet to establish unified international standards and regulations. This results in discrepancies among countries in recycling technologies, processes, and material classification. Such inconsistencies hinder international cooperation and exchange, impeding the globalization and harmonized development of the wind power recycling industry.

(6) Insufficient Policy Support

Some countries have yet to introduce dedicated policies for the wind power recycling industry. The absence of financial subsidies, tax incentives, and other support measures discourages businesses from actively participating in wind power recycling, thereby slowing the industry's growth.

Chapter 4
Exploratory Directions for the Wind Power Recycling Industry

4.1 Industry Layout and Strategic Planning

The global wind power decommissioning and recycling industry is an emerging and rapidly growing sector, shaped by factors such as policies, technologies, and market demand.

Europe: As a pioneer in global wind power development, Europe hosts a significant number of early wind farms now facing decommissioning. The region possesses relatively advanced technologies for wind power equipment recycling and reuse.

North America: Wind power capacity continues to grow in North America. As wind farms age, the decommissioning and recycling industry is gradually emerging. The U.S. government has provided policy support to drive the industry's development.

Asia: Countries like China and India have enormous and rapidly expanding wind power capacities. As their wind farms age, these nations are placing significant emphasis on the development of wind power decommissioning and recycling industries.

(1) Comprehensive Coordination in Wind Power Project Development

Environmental and ecological issues are critical challenges that must be addressed for the sustainable development of wind power. Achieving an eco-friendly and green approach throughout the entire lifecycle—encompassing development, construction, operation, usage, and decommissioning—is essential. During the early stages of project planning, site selection must be thoroughly evaluated through multi-faceted investigations and discussions. It is crucial to align with overarching plans and to maintain close communication with departments responsible for energy, environmental protection, and natural resources to ensure compatibility with the surrounding environment. This helps avoid situations where ecological redline adjustments necessitated by environmental protection requirements lead to premature decommissioning of wind farms. In some instances, during the initial phases of wind power construction, insufficient attention to ecological conservation and soil and water retention has caused significant soil erosion and delayed vegetation restoration, negatively impacting the environment. To ensure sustainable growth in the wind power industry, it is essential to adopt protective development practices that integrate wind power projects with local ecological environments. Wind farm development and ecological restoration should progress simultaneously, enabling the industry to sustain its vast potential and promising future.

(2) Planning for Offshore Wind Power Decommissioning

Compared to onshore wind power, the offshore wind sector is relatively new, and there is limited experience in dismantling or disposing of decommissioned equipment. During the current phase of rapid growth, the focus has primarily been on development and construction, often neglecting post-lifecycle activities. However, it is increasingly important to address end-of-life details during the design phase. Failure to do so could significantly impact the economic returns of wind farms and hinder the recycling and reuse of decommissioned equipment.

A recent study by the UK's Offshore Renewable Energy Catapult (OREC) highlights that the complete dismantling of offshore wind farms at the end of their lifecycle is the least economically viable option. Nevertheless, devising sustainable recycling and disposal plans for offshore wind power involves multiple challenges. Factors such as in-field subsea cables, substations, and export transmission lines must all be carefully considered to develop effective solutions.

Extending the service life of offshore wind farms after their operational period expires is a relatively moderate approach. This method does not involve replacing major equipment and infrastructure, such as turbines, foundations, or subsea cables, and only requires maintenance and repairs. It is the most cost-effective option among all available strategies.

Another option is the complete replacement of all equipment and infrastructure at the wind farm. However, this is economically inefficient, as it involves not only replacing turbines but also incurring significant construction costs for new turbine foundations, in-field cables, and other facilities.

The optimal approach is to retrofit part of the wind farm's turbines and allow the rest to continue operating. This strategy requires only the installation of larger turbines on existing foundations, without the need to replace in-field cables, substations, or export transmission lines. However, this retrofitting approach has certain prerequisites. Firstly, developers must obtain extensions for site lease agreements from regulatory authorities. Technically, proactive design considerations must be made at the outset to prepare for the future installation of larger turbines, including the construction of reinforced foundations. If these provisions are not made initially, an assessment will be needed at the end of the operational period to determine whether the existing foundations can support larger turbines. This could significantly influence the cost of retrofitting the wind farm. To ensure better outcomes, stakeholders are encouraged to plan offshore wind farm construction with foresight, emphasizing enhanced recyclability and reuse of equipment at the end of its service life.

(3) Policy Guidance

European countries, which are already experiencing a small-scale peak in wind power decommissioning, have yet to unleash the full potential of this market due to policy gaps. This shortfall poses challenges for achieving the EU's carbon neutrality targets. Other nations should learn from Europe's experience, planning ahead and establishing robust policies to invigorate the decommissioned wind power market. Emphasis should be placed on the recycling and reuse of decommissioned wind and photovoltaic equipment. Policymakers should encourage the development of innovative technologies, foster a large-scale recycling industry, and promote the sustainable growth of the wind and photovoltaic sectors. Governments should support the creation of industrial clusters for recycling wind and photovoltaic equipment in key regions and explore collaborative regional recycling models. Efforts should also be directed at nurturing industry leaders within the wind and photovoltaic recycling sector. However, addressing challenges such as consolidating fragmented and subpar enterprises, enhancing recycling technologies, and promoting industrial-scale adoption is a complex process requiring careful planning. The transformation from disorganized to centralized, from inefficient to standardized, from polluting to eco-friendly, and from high-carbon to low-carbon practices, as well as the shift from resource waste to circular utilization, demands systematic strategies and long-term execution. A comprehensive approach should involve establishing lasting cooperative mechanisms among manufacturing, power generation, operations, recycling, and utilization enterprises. This would streamline recycling channels, strengthen coordination across the upstream and downstream sectors, and support the development of a one-stop service model encompassing the dismantling, transportation, recycling, disassembly, and reuse of decommissioned renewable energy equipment.

(4) Development of Industrial Parks

To ensure the establishment and sustainability of recycling centers and industrial parks dedicated to the circular utilization of decommissioned wind and photovoltaic equipment, foundational infrastructure must be planned in advance. This includes provisions for power, energy, transportation, and supporting facilities such as solid (hazardous) waste treatment centers, enabling the industry to "take root" and "flourish."

The infrastructure for such parks is typically categorized into productive infrastructure, production service facilities, and residential infrastructure. These generally encompass roads, water supply, drainage, power supply, telecommunications, wastewater treatment, internet access, and land leveling—commonly referred to as "seven connections and one leveling."

Under the "Dual Carbon" goal, industrial parks face the dual pressure of rapidly advancing energy decarbonization and promoting green industrial development. The low-carbon economy is poised to inject new vitality into the high-quality development of these parks, making them leaders and demonstration zones for regional low-carbon progress.

At the same time, full use should be made of renewable energy sources such as solar, wind, hydro, and biomass. By interconnecting distributed generation facilities for wind, solar, and hydro energy with storage systems and energy networks, a full industrial chain energy storage park can be established. This will enable the shared and intelligent utilization of the "renewable energy + storage" industry. Moreover, integrating the recycling of decommissioned wind and photovoltaic equipment will complete the green industrial loop.

Integrating technological innovation infrastructure construction with the development of core and future industries, the focus should be on new technologies, products, and services. Guided by new development concepts and driven by technological innovation, with information networks as the foundation, efforts should support scientific research, technological development, and product innovation with public welfare attributes. These initiatives aim to meet the needs of high-quality development while facilitating the digital transformation, intelligent upgrades, and technological advancements of the industrial park.

4.2 Environmental Requirements

The environmental requirements for the global wind power recycling industry form a comprehensive system aimed at minimizing the negative impact on the environment during the disposal of decommissioned wind power equipment, while maximizing resource utilization.

(1) Policy and Regulatory Framework

Establishing relevant laws, regulations, and policy documents is essential to define standards and responsibilities for handling decommissioned wind power equipment, thereby providing legal support for wind power recycling. This framework should cover all stages, including decommissioning, recycling, remanufacturing, and reuse.

(2) Strengthening Regulatory Oversight

A robust regulatory system should be established to provide comprehensive supervision throughout the wind power recycling process. This ensures that all environmental requirements are effectively implemented and adhered to.

(3) Establishing a Comprehensive Recycling Network

A well-developed network and system for recycling decommissioned wind power equipment should be established to facilitate efficient collection, recycling, and resource recovery.

(4) Emphasizing Green Design

Manufacturers should be encouraged to incorporate green design principles during the product design and production stages, focusing on lightweight structures, ease of disassembly, transportability, and recyclability.
Additionally, stricter regulatory oversight should be applied to the entire process of recycling and disposing of decommissioned wind and photovoltaic equipment. This includes enforcing stringent pollution control measures for the safe disposal of decommissioned equipment to ensure compliance with national environmental protection standards and to mitigate the environmental pollution risks posed by terminal solid waste.

China

Industrial parks, processing centers, and enterprises must enhance their environmental awareness. They should integrate economic development indicators, eco-industrial characteristics, ecological protection benchmarks, and green management metrics. From establishment to operation, compliance with relevant departmental management regulations is essential. This includes adhering to requirements for project approval, environmental impact assessments, pollutant discharge permit applications and implementation reports, and environmental information disclosure as outlined in related environmental documents.

United States

The United States Environmental Protection Agency (EPA) and other federal agencies are responsible for developing and enforcing environmental regulations related to wind power recycling. These regulations may cover aspects such as waste management, pollution control, and resource recovery. Individual states also have the authority to enact their own environmental regulations, which can complement federal rules or, in some cases, be more stringent. According to guidelines from the EPA and other authoritative bodies, decommissioned wind power equipment must be dismantled, processed, and recycled following specified procedures. Waste management regulations require proper handling of waste generated during the dismantling of wind power equipment to prevent contamination of soil, water sources and air.

Germany

Germany's Renewable Energy Act, implemented in 2000, has not only promoted the development of wind power and other renewable energies but also outlined the responsibilities and obligations of wind turbine operators for decommissioned equipment.

In 2002, the German government introduced the Environmental Compatibility Monitoring Act, which requires that wind power installations be located in environmentally and ecologically appropriate areas. This regulation extends to the decommissioning and disposal of wind power equipment, ensuring minimal environmental impact throughout its lifecycle.

Spain

Regarding the environmental requirements of Spain's wind power recycling industry, while specific regulations or standards targeting this sector may not be as publicly detailed as in other countries, Spain's general renewable energy policies and environmental awareness provide clear guidance. Compliance with EU and Domestic Environmental Regulations:

As a member of the European Union, Spain's wind power recycling industry must adhere to EU environmental regulations and standards. These include directives on waste management, resource recovery, and emissions control, ensuring that practices align with both EU and national environmental goals.

United Kingdom

The Renewable Energy Obligation Act is a key piece of legislation driving renewable energy development in the United Kingdom. While it primarily focuses on increasing the use of renewable energy, it implicitly addresses environmental requirements for wind power recycling. The Act mandates that electricity operators purchase a certain proportion of renewable energy, which indirectly encourages the recycling and reuse of wind power equipment to support the sustainability of the sector.

Brazil

In Brazil, power construction projects typically undergo stringent environmental reviews conducted sequentially by federal and local environmental agencies. Throughout this process, three key environmental permits are crucial: the Preliminary License (Licença Prévia, LP), the Installation License (Licença de Instalação, LI), and the Operating License (Licença de Operação, LO). The issuance of these permits ensures that wind power projects comply with environmental requirements throughout their lifecycle, from project approval and construction to operational phases.

Chapter 5
Case Studies and Emerging Technologies


Figure 5-1 On-Site Implementation Photos

China

The decommissioned GW750 turbine upgrade solution by Beijing Goldwind Huineng Technology Co., Ltd. is based on the advanced design experience of the GW1500 model and the GW50/750 nacelle platform. The solution retains major components such as the original generator, gearbox, tower, and transformer, while integrating a 1 MW full-power water-cooled converter. The upgrade involves comprehensive improvements in both mechanical and electrical systems.

The mechanical system is primarily upgraded by optimizing components such as the rotor, drivetrain, base, and yaw system. For the electrical system, a new full-speed converter and control strategy are introduced to enhance performance. This technology maximizes the high-value components of decommissioned GW750 turbines, integrating the latest wind power design concepts to create newly designed wind turbines tailored to current demands, thereby achieving component reuse and recycling. Through these upgrades, the rotor diameter has been increased from 50 meters to 77 meters, expanding the swept area by 137%. This significantly improves the power curve of the turbine under low wind speed conditions.

Beijing Hexin Ruifeng New Energy Development Co., Ltd. has developed a generator recycling and reuse technology that addresses common operational issues. For the stator, the replacement of stator slot wedges with upgraded materials eliminates issues related to wedge loosening and detachment. For the rotor, structural modifications to the rotor shaft resolve vibration problems caused by shaft instability, preventing severe failures such as rotor damage. Additionally, a complete structural redesign of the rotor lead wires, including the outgoing wires, slip rings, and fixing methods, resolves the original design flaw that caused lead wire burnout. This technology focuses on the retrofit and repair of wind turbine generators to address common faults and improve their operational quality. For example, technical innovations and enhancements to critical components of the Nanyang 1.5 MW doubly-fed generator such as the rotor shaft, rotor lead wires, and slip rings enhance the generator's reliability and reduce vibrations. These advancements effectively eliminate design flaws, laying a solid foundation for improved wind farm operational efficiency. This work also serves as a valuable case study for addressing complex generator repair challenges and provides new directions for the remanufacturing of wind turbine generators.

Luoyang Bearing Group Co., Ltd. conducts precise scientific evaluations of used bearings to develop appropriate remanufacturing plans. By combining performance testing and operational validation of repaired bearings, the company has established a comprehensive set of technical standards for bearing repair and remanufacturing. These standards include processes, methods, finished product specifications, and quality control measures, ensuring that the remanufactured bearings meet the requirements of original equipment manufacturers.

Shandong Longneng Renewable Resources Utilization Co., Ltd. repurposes decommissioned wind turbine blades from wind farms into products such as park landscapes, rest benches, and artificial reefs through processing and manufacturing. These products are widely used in landscaping, marine aquaculture, and other fields.

Chongqing Chengfei New Materials Co., Ltd. processes decommissioned wind turbine blades, initially cut on-site, into reusable sheet materials such as livestock fencing poles based on downstream user requirements. Other materials are crushed into fibers, PVC, structural adhesives, and powders, each reused for different applications. This method represents a typical and widely used physical recycling technology for wind turbine blades. All outputs are recyclable, and the technology is relatively mature. The company has established a production line capable of handling 10,000 tons of decommissioned blades annually. However, due to the current low volume of decommissioned wind turbine blades, which have yet to peak, the facility is not operating at full capacity. It is expected to achieve normal operation by 2025.

Jiangsu Huana Environmental Technology Co., Ltd. primarily employs physical crushing methods to process materials through segmentation, shredding, crushing, sorting, grinding, and modification to produce wood-plastic reinforced panels. These products are widely used in municipal engineering, garden landscaping, and building decoration. Performance testing was conducted on wood-plastic panels made with 50% wood powder and those made with 30% recycled fiberglass powder. Results indicate that even with low filler content, panels made with recycled fiberglass powder exhibit high tensile, compressive, and flexural strength compared to those made with wood powder. However, due to the low filler content, the tensile, compressive, and flexural modulus performance of recycled fiberglass powder panels shows less pronounced advantages compared to wood powder panels.

Figure 5-2 10,000 Tons/Year Processing Line

United States

REGEN Fiber, based in Fairfax, Iowa, USA, specializes in developing innovative recycling solutions for wind turbine blades to meet the critical needs of the wind energy sector at the end of blade lifecycles. The company employs a 100% mechanical process, avoiding the use of heat or chemicals. This approach significantly reduces the handling of hazardous waste and eliminates blade incineration.

Figure 5-3 Recycling Production Line

REGEN Fiber's process involves extracting reusable components, shredding the blades, and processing materials such as fiberglass mesh and polyester resin into products suitable for use in concrete and asphalt production. This innovative technology not only enhances the recycling rate of wind power equipment but also provides a sustainable source of building materials for the construction industry.

Global Fiberglass Solutions Inc. (GFSI), headquartered in Bothell, Washington, is a pioneer in industrial fiberglass recycling across the wind energy, aerospace, and maritime sectors. GFSI's team dismantles and cuts decommissioned blades on-site, then transports the materials to its processing facilities. There, the materials are treated using chemical and pyrolysis methods and transformed into granules and panels for producing the company's eco-friendly products. The flagship product, EcoPoly granules, made from recycled materials, began commercial production in January 2019.

In December 2020, GE Renewable Energy, a U.S. energy company, announced a multi-year partnership agreement with Veolia North America to process decommissioned wind turbine blades from wind farms across the United States. The blades are shredded and used as a substitute for sand, gravel, and clay in cement manufacturing, enabling their recycling into the construction industry. This method not only facilitates the recycling of wind turbine blades but also reduces the total carbon dioxide emissions in cement production by up to 27%.

Figure 5-4 Fiberglass Recycling

Carbon Rivers LLC, based in Tennessee, has developed and successfully commercialized the Glass to Glass☒ recycling technology with support from the U.S. Department of Energy (DOE) and in collaboration with the University of Tennessee. This innovative method advances the wind energy industry toward a circular manufacturing model by enabling the recycling of glass fibers from decommissioned wind turbine blades. The process begins by shredding collected materials into raw fragments, followed by a pyrolysis procedure to remove the resin matrix and other fillers from the glass fibers. The recovered glass fibers are transformed into the desired polymer composite materials, effectively preserving their mechanical properties. This enables the recycled fibers to be used in new composite applications, including manufacturing new wind turbine blades, while the process also produces oil suitable for energy generation.

Researchers at the University of Michigan have developed an innovative resin that combines glass fibers with plant-derived and synthetic polymers. This new resin can be recycled into its constituent components, enabling the creation of various products such as new turbine blades, laptop cases, power tools, and even gummy candies.

Canvus, based in Ohio, specializes in transforming decommissioned wind turbine blades into practical public goods. The company cuts and coats the discarded blades with epoxy paint to create public items such as park benches, flowerpots, and picnic tables. Additionally, Canvus collaborates with a network of artists to paint the recycled products, enhancing their artistic value.

Germany

Germany has developed relatively mature industrialized methods for recycling wind power equipment, such as physical crushing techniques. Additionally, German wind power companies are actively pursuing the development of "zero-waste turbines," with a commitment to achieving 100% blade recycling by 2040.

The Fraunhofer Institute for Ceramic Technologies and Systems (Fraunhofer IKTS) in Germany has developed efficient metal recovery technologies for processing complex waste materials such as wind turbine and photovoltaic equipment. The institute has also pioneered a novel wood recycling technique specifically for recovering balsa wood from decommissioned wind turbine blades. This method uses high-pressure water jets to cut the discarded blades into smaller pieces, followed by an impact crusher to separate the balsa wood from fiberglass and resin. The recovered balsa wood can then be processed into ultra-light wood fiber insulation materials with a density of less than 20 kg/m³, offering thermal insulation properties comparable to polystyrene insulation boards. Additionally, the reclaimed balsa wood can be used to produce innovative elastic wood foam. This foam derives its strength entirely from the cohesive forces of the wood fibers themselves, without requiring resin, adhesives, or additives, making it a promising option for eco-friendly packaging materials.

German wind turbine blade manufacturer Voodin has announced the successful installation of the world's first wooden wind turbine blade. Measuring 19.3 meters in length, the blade is crafted from laminated veneer lumber. Compared to traditional wind turbine blades, wooden blades offer advantages such as lightweight construction and 100% recyclability. The production process for wooden blades eliminates the need for molds, providing greater flexibility to manufacture blades of any type. Additionally, wooden blades are more durable and exhibit superior fatigue resistance compared to traditional composite materials. The introduction of wooden blades represents a significant step in addressing the recycling challenges associated with wind turbine blades while reducing environmental pollution.

Spain

Spain's infrastructure and renewable energy company Acciona, in collaboration with Acciona Energía and RenerCycle, is constructing the Waste2Fiber wind turbine blade recycling plant in Lumbier, Navarre. Scheduled to begin operations in 2025, the plant will utilize proprietary thermal methods to separate materials from wind turbine blades for reuse. This technology operates under moderate and controlled temperature and atmospheric conditions, preserving the properties of reinforcing fibers, reclaiming organic fractions, and transforming composite materials into high-value secondary raw materials that match the quality of the original materials. The thermal process decomposes the composite materials in the blades into distinct components such as glass fibers, carbon fibers, and organic compounds. These recovered materials can be further processed into new products: glass and carbon fibers can be used in industries such as automotive and construction, while organic compounds have applications in the chemical sector. The facility will have an annual processing capacity of 6,000 tons of materials, encompassing all stages of the recycling process—from blade dismantling and shredding to the production of final products and quality control.

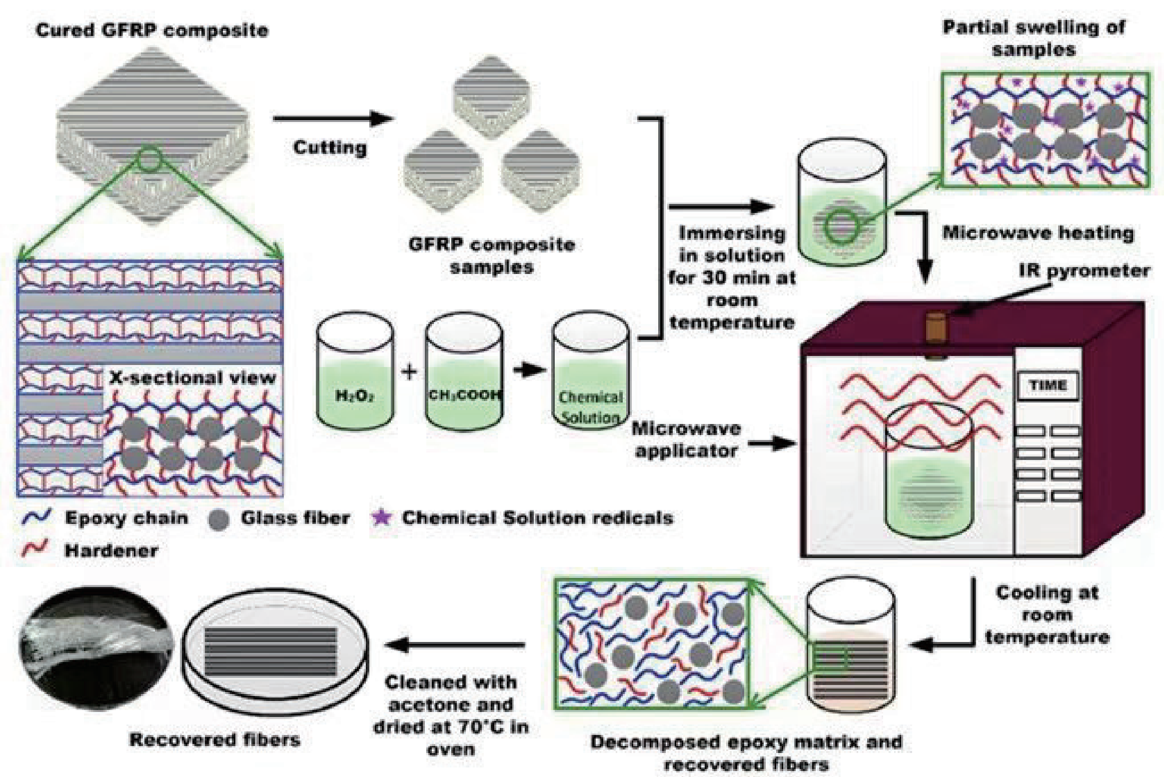
Spain's largest wind energy developer, Iberdrola, has partnered with FCC Servicios Medio Ambiente to establish EnergyLOOP, a company dedicated to recycling components from renewable energy installations. EnergyLOOP plans to invest €10 million in developing a blade recycling facility in Navarre, Spain. The facility aims to recycle wind turbine blades by recovering materials such as glass fibers, carbon fibers, and resins. These materials will be repurposed for use in various industries, including energy, aerospace, automotive, textiles, chemicals, and construction. The project aspires to become Europe's first industrial-scale blade recycling plant, setting a benchmark for sustainable recycling practices in the renewable energy sector.

India

Researchers at the Indian Institute of Technology (IIT) Mandi have developed a microwave-assisted method for recycling glass fiber-reinforced polymer (GFRP) materials. This approach is rapid, sustainable, and environmentally friendly, utilizing a microwave-assisted chemical recycling process. The method employs eco-friendly chemicals, such as hydrogen peroxide and acetic acid, to chemically degrade GFRP composites. Both of these chemicals are considered environmentally benign, making this recycling process an innovative and sustainable solution for handling GFRP materials.

Researchers at the Indian Institute of Technology Mandi (IIT Mandi) have developed a microwave-assisted technique to recover fiber-reinforced polymer (FRP) composites from decommissioned wind turbine blades. Reportedly, this method is faster, more sustainable, and more environmentally friendly compared to conventional approaches such as landfill disposal and thermal recovery currently in use.

The study was led by Dr. Sunny Zafar, Assistant Professor at the School of Mechanical and Materials Engineering, and Dr. Venkata Krishnan, Associate Professor at the School of Chemical Sciences, both from IIT Mandi, with contributions from their students. The findings, titled "Development of a Sustainable Microwave-Based Method for Recycling Glass Fibers from Wind Turbine Blade Composite Waste," were published in Resources, Conservation and Recycling. The research employed microwave-assisted chemical degradation of GFRP composites using hydrogen peroxide and acetic acid. This process achieved a 97.2% decomposition rate of the epoxy resin while successfully recovering the glass fibers. Tests on the recovered fibers revealed their performance was nearly equivalent to virgin fibers, retaining approximately 99% of their strength and over 90% of their other mechanical properties.



United Kingdom

The UK government has funded a pioneering project named PRoGrESS with a budget of £2 million. This three-year initiative, partially supported by Innovate UK and industry partner Aker Offshore Wind, aims to develop the UK's first wind turbine blade recycling solution. Led by Aker Offshore Wind with the involvement of Scottish researchers, the project seeks to ensure a more sustainable future for the global wind industry and the broader composite manufacturing sector while accelerating progress toward net-zero emissions and waste reduction goals. The wind power industry is committed to achieving full recyclability of turbines, aligning with the UK's climate change objectives, creating green jobs, and supporting the ambitions of the EU Circular Economy Action Plan and the European Green Deal.

The Lightweight Manufacturing Centre (LMC), part of the National Manufacturing Institute Scotland (NMIS) group, is actively involved in a wind turbine blade recycling project aimed at establishing the UK's first pilot blade recycling plant. This project focuses on commercializing wind turbine blade recycling using a revolutionary method developed by the University of Strathclyde. The innovative technique enables the separation of glass fiber and resin components in composite materials. The recovered glass fiber can then be reprocessed and reshaped for use in other industries, such as automotive and construction. This initiative represents a significant step toward sustainable wind turbine blade recycling.

France

The ZEBRA (Zero wastE Blade ReseArch) Project, led by the French Institute of Technology IRT Jules Verne, brings together seven companies, including Arkema, CANOE, ENGIE, LM Wind Power, Owens Corning, and SUEZ, to demonstrate a fully recyclable wind turbine blade lifecycle. The project successfully recovered Arkema's Elium® resin and Owens Corning's Ultrablade® fabric from turbine blades and production waste, repurposing them into reusable materials. The recyclable thermoplastic resin blades were manufactured by LM Wind Power at their factory in Castellón, Spain. Measuring 77 meters in length, the blades incorporate Arkema's Elium® liquid thermoplastic resin and adhesive technology from Arkema's subsidiary Bostik. Notably, the ZEBRA blade represents the first-ever use of recycled Elium® resin in critical structural components such as shear webs. Elium®, part of Arkema's thermoplastic matrix series, is a liquid resin suited for manufacturing a variety of composite components. Compared to epoxy resins, it cures rapidly at room temperature and enables recyclability through physical or chemical processes. This innovation paves the way for sustainable solutions in wind turbine blade recycling, significantly enhancing resource efficiency and reducing waste in the wind energy sector.

Chapter 6
Overview of the International Photovoltaic Equipment Recycling Industry

6.1 Development of the Photovoltaic Industry

Solar energy, a widely distributed, green, and clean energy source, is both renewable and sustainable. Against the backdrop of global climate change and energy transition, solar energy has become an integral part of the world's energy mix and continues to experience significant growth. Solar energy utilization primarily occurs through two methods: photothermal conversion and photovoltaic conversion. Solar power generation, in particular, represents an emerging and environmentally friendly approach to energy utilization. Photovoltaic (PV) power generation is a technology that directly converts light energy into electrical energy through the PV effect at the semiconductor interface. The key component of this technology is the solar cell. When solar cells are connected in series and encapsulated for protection, they form large-area solar cell modules. Combined with components such as power controllers, these modules constitute a complete photovoltaic power generation system.

PV power generation produces no pollutants or greenhouse gases during its operation, making it a significant contributor to mitigating climate change. The widespread adoption of solar energy also helps reduce dependence on limited fossil fuel resources, thereby protecting the environment and maintaining ecosystem stability. Consequently, photovoltaic power generation plays a vital role in both energy supply and environmental conservation.

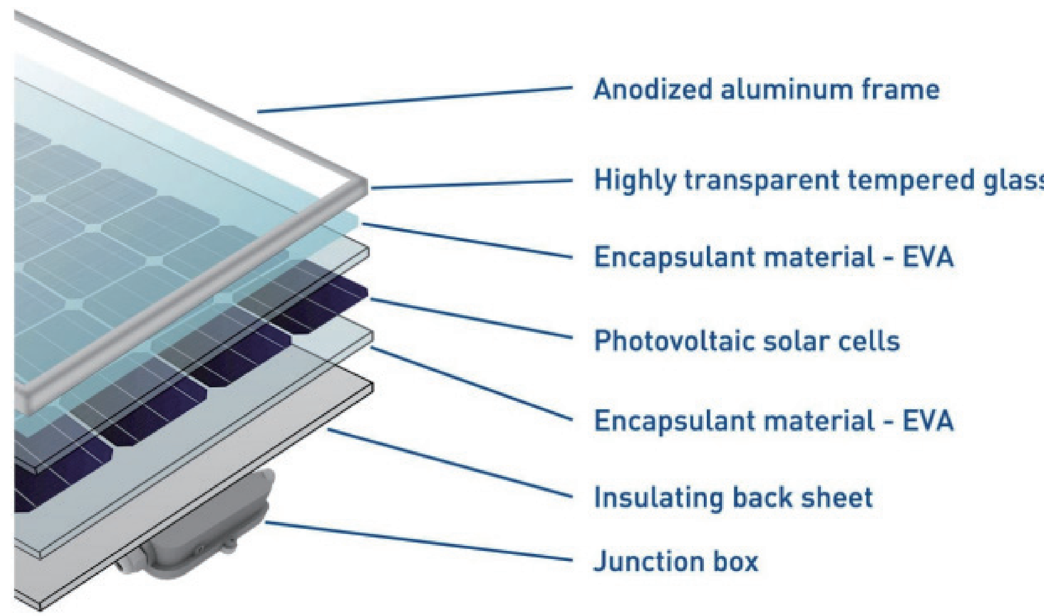
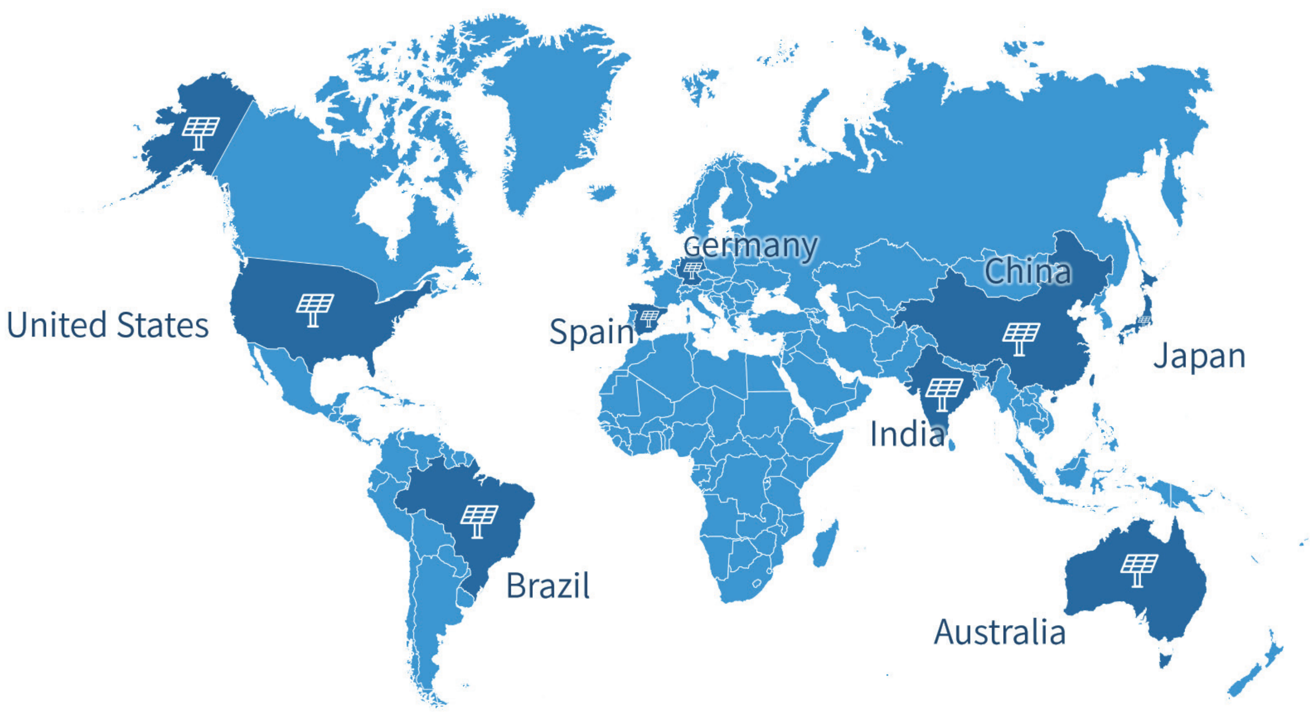


Figure 6-1 Composition of a Solar Panel

The photovoltaic (PV) industry originated in developed nations in Europe and North America. The oil crisis of the 1970s spurred these governments to seek alternative energy sources, leading to rapid advancements in renewable energy industries, including photovoltaics. By the early 21st century, PV power had seen widespread adoption in countries like Germany, Spain, and Japan, further driving the industry's development. As global environmental challenges intensify, low-carbon emissions and renewable energy have increasingly become a focal point for nations worldwide.

6.2 Photovoltaic Equipment Recycling Industry



The application of new technologies across various stages of the photovoltaic (PV) industry chain is accelerating, with advancements such as larger silicon wafer sizes and improvements in cell conversion efficiency. These technological developments have driven a continuous decline in the cost of PV power generation. However, as the global photovoltaic industry flourishes, the issue of equipment decommission has become increasingly prominent.

Recycling photovoltaic equipment plays a critical role in reducing the extraction of virgin resources, thereby lowering carbon emissions. Statistics show that for every MW of decommissioned PV equipment, 60–80 tons of materials such as copper, aluminum, and plastic can be recycled. The reuse of these materials minimizes the need for virgin resource extraction, further reducing the carbon emissions associated with their mining and processing.

Raw Material	Emission(kg/kWp)	Cumulative Contribution Ratio
Aluminum	64.32	15.00%
Silicon Wafer	13.72	3.20%
Silver	1.29	0.30%6
Glass	300.16	70.00%6
Copper	6.43	1.50%
EVA	42.88	10.00%
Total	428.8*	100%

Table 6-1 Reduction in Carbon Emissions through PV Equipment Recycling

Carbon Dioxide Emissions from PV Module Production (Data Source: Greenpeace)
This data is an estimate based on the carbon emissions generated during the production of a single photovoltaic panel using current technology. The total carbon emissions reduced by utilizing recycled PV modules may change with advancements in technology and the optimization of PV panel structures.

This report will provide an overview of the photovoltaic equipment recycling industries in China, the United States, India, Japan, Germany, Brazil, Spain, and Australia.

6.2.1 Industry Foundations

From 2019 to 2023, the global photovoltaic (PV) installed capacity achieved an average annual growth rate of 28%. Between 2010 and 2022, the average weighted cost of solar power generation dropped by 89%, reaching US$0.049 per kWh. In 2023, the global PV installed capacity surpassed that of hydropower, and the PV industry is expected to maintain high growth rates over the next decade. By 2044, solar power is projected to contribute to more than half of the world's electricity generation.

The typical lifespan of PV equipment is 20 to 25 years, meaning that early installations are now gradually reaching their decommissioning phase. Addressing how to manage these decommissioned devices has become an urgent issue. The global PV equipment recycling industry is an emerging and rapidly developing field, primarily focused on the recovery and processing of decommissioned PV modules. It encompasses green design, standardized recycling, high-value utilization, and environmentally safe disposal of decommissioned PV equipment.

6.2.2 Policy Support and Guidance from Various Countries

With the continuous increase in global photovoltaic (PV) installed capacity, the management of PV equipment waste has become a topic of widespread concern in the international community. Governments around the world are introducing policies to support the development of the PV equipment recycling industry. Effectively managing this waste and preventing potential environmental hazards represent common challenges faced by nations globally.

The International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS) released the PV Module Design for Recycling Guidelines. These guidelines aim to enhance the recyclability of photovoltaic modules through a series of design recommendations, including general design principles and specific guidelines tailored to PV modules. The initiative supports the circular economy and seeks to mitigate constraints on raw materials at the end of a photovoltaic module's lifecycle.

European Union

The European Union is among the earliest regions to address photovoltaic (PV) equipment waste management, with its policy framework primarily rooted in the Waste Electrical and Electronic Equipment (WEEE) Directive. In 2012, the EU revised the WEEE Directive to include photovoltaic modules, mandating the collection, recycling, and recovery of waste generated from electrical and electronic equipment, including PV panels, within EU member states. Under the directive, producers are required to bear responsibility for the end-of-life recycling and processing of their products. The WEEE Directive sets a recycling rate of 85% for PV modules, with a reuse and material recovery rate of at least 80%, ensuring that the majority of waste is effectively managed to minimize resource waste and environmental impact. To meet these objectives, EU member states must establish comprehensive recycling systems and support the development and promotion of advanced PV equipment recycling technologies.

China

The Chinese government places significant emphasis on the development of the PV equipment recycling industry, introducing a series of supportive policies. For instance, the Implementation Plan for Large-Scale Equipment Renewal in Key Energy Sectors explicitly promotes the renewal and recycling of PV equipment and supports the development of PV module recycling and reuse technologies. Additionally, the government encourages participation in the PV recycling industry through financial subsidies, tax incentives, and loan support for enterprises and individuals. In January 2024, the Ministry of Ecology and Environment issued the Catalogue for Solid Waste Classification and Codes (Announcement No. 4 of 2024), which, for the first time, listed discarded PV modules separately and assigned them specific solid waste codes. The implementation of this catalog is expected to significantly advance the green circular development and high-quality recycling of China's wind and photovoltaic industries. It will provide clear guidance for all stakeholders involved in the production, waste generation, recycling, and disposal of discarded PV modules, as well as used wind turbines, blades, and offcuts, while strengthening environmental oversight.

Waste Type	Waste Code	Solid Waste Name	Notes
SW17 Renewable Waste	900-015-S17	Discarded PV Modules	**Waste PV modules generated during production, technological upgrades, or decommissioning.**

Table 6-2 Excerpt from Catalogue for Solid Waste Classification and Codes

United States

In the United States, laws related to the recycling of decommissioned photovoltaic (PV) systems trace back to the 1976 Resource Conservation and Recovery Act (RCRA). This act established strict requirements for the production, handling, storage, recycling, and disposal of waste PV modules but did not include specific regulations targeting PV waste. Currently, most PV module recycling management relies on state-level legislation. In 2016, California passed the SB 489 Bill, which streamlined the recycling and disposal processes for waste PV modules. Washington became the first state to regulate PV manufacturers' recycling obligations through the Photovoltaic Module Stewardship and Takeback Program Act in 2017, mandating manufacturers to develop and fund recycling programs while exempting PV system owners from additional costs.

In 2020, the U.S. Environmental Protection Agency (EPA) issued a solar panel recycling framework aimed at requiring manufacturers to develop recycling plans and reduce hazardous material pollution from discarded solar panels. Subsequently, California implemented regulations in 2021 that categorized decommissioned PV modules as general waste, simplifying regulatory and disposal processes and reducing associated costs. Other states, including Illinois, Hawaii, Arizona, North Carolina, and New Jersey, are actively considering policy mechanisms for managing PV waste. However, the U.S. lacks unified federal regulations, leading to fragmented policies. Variations in recycling standards and enforcement among states result in low recycling rates for decommissioned PV equipment.

India

India's Ministry of Environment, Forest and Climate Change (MoEFCC) introduced the E-Waste (Management) Rules, 2022 in November 2022 to regulate the management of waste from solar cells and modules. These rules mandate that manufacturers of solar cells and modules manage their waste under the Extended Producer Responsibility (EPR) framework.Under the new classification, decommissioned PV modules are categorized as e-waste, making stakeholders such as producers and manufacturers responsible for the management of this waste in accordance with the EPR framework. This policy aims to ensure proper recycling, reduce environmental harm, and promote sustainable practices within the solar industry.

Japan

In 2018, Japan released the second edition of its guidelines promoting the proper handling of end-of-life (EOL) PV modules, including reuse and recycling. These guidelines provide fundamental information on decommissioning, transportation, reuse, recycling, and industrial waste management in accordance with relevant laws and regulations. The Ministry of the Environment and the Ministry of Economy, Trade, and Industry jointly assessed strategies for managing EOL PV modules and published guidelines to encourage their proper handling and recycling. In May 2021, the Ministry of the Environment issued a new guideline specifically aimed at promoting the reuse of PV modules, further advancing the circular utilization of these components in the solar energy sector.

Germany

Germany, as one of the leading countries in PV installations within the European Union, introduced the Electrical and Electronic Equipment Act (ElektroG) in 2015. This law established clear producer responsibilities for PV modules and created a system for the collection and disposal of decommissioned PV components. It complies with the requirements outlined in the EU's WEEE Directive and sets specific targets for recycling and reuse rates for decommissioned PV modules. Under ElektroG, manufacturers and retailers must register PV modules on designated platforms before introducing them to the market. These platforms classify the modules based on size, and different scenarios of decommissioned modules require specific treatment processes to ensure proper recycling and disposal. In 2021, the German Environmental Action Organization released the White Paper on Strengthening Photovoltaic Circularity, which explored challenges and opportunities throughout the PV lifecycle. It emphasized the need to enhance recyclability at the design stage, improve public collection systems, and establish clearer processes and responsibilities for recovering and disposing of PV modules. Furthermore, it called for better communication platforms to ensure transparency for stakeholders and the public while advocating for the development of innovative recycling technologies to improve material recovery efficiency. These initiatives reflect Germany's commitment to sustainable management practices for PV modules, aligning with its broader goals of advancing a circular economy and achieving long-term environmental sustainability.

Australia

Australia has made strides in PV waste management at the state level, with some states enacting specific regulations. For instance, Victoria implemented legislation effective from December 1, 2019, banning the landfill disposal of all electronic waste, including PV modules. Both Victoria and South Australia have established dedicated recycling facilities and mandated that manufacturers and installers classify and process discarded PV equipment responsibly. Despite these efforts, the overall recycling rate for PV waste in Australia remains low and falls significantly short of the targets set in the National Waste Policy Action Plan. This highlights the need for more comprehensive national policies and infrastructure to improve recycling and resource recovery in the country's rapidly growing solar industry.

France

France is at the forefront of PV waste management in the European Union. In 2014, the country enacted the Environmental Code, setting mandatory recovery and recycling targets for PV products at a minimum of 85% and 80%, respectively, aligning with the EU's WEEE Directive. That same year, France amended its Waste Electrical and Electronic Equipment Management Law, requiring PV manufacturers and importers to fund the recycling of discarded modules. Organizations like PV Cycle, the only nonprofit approved by ministerial decree to manage PV waste in France, spearhead these recycling operations. The volume of recycled PV waste in France has grown significantly. In 2019, the amount of recycled PV waste reached 4,905 tons, an approximately 13-fold increase compared to 366 tons in 2015. This rapid growth highlights France's proactive approach to managing end-of-life PV equipment effectively.

South Korea

with PV manufacturers to include PV cells in the Extended Producer Responsibility (EPR) list, with implementation in the PV sector starting in 2023. Additionally, the Act on Resource Circulation of Electrical and Electronic Equipment and Vehicles came into effect in 2023, classifying PV modules alongside existing waste categories.

Globally, policy frameworks and implementation approaches for managing PV equipment waste vary significantly among countries. As the challenges posed by PV equipment waste intensify, nations must refine their regulations and policies. These measures should not only focus on environmental protection but also emphasize the recovery and reuse of renewable resources from discarded modules. This approach would foster sustainable economic development, advance recycling technologies, and collectively drive the PV industry's sustainable growth.

Chapter 7
Current Status of the Photovoltaic Equipment Recycling Industry

7.1 Installed Capacity and Cumulative Scale of the Photovoltaic Industry in 2023

Global New Installations

According to the International Renewable Energy Agency (IRENA) in its annual report, Renewable Energy Capacity Statistics 2024, the global photovoltaic (PV) sector reached a new milestone in 2023, with 345.5 GW of new PV capacity installed, setting a historic record. Projections indicate that by 2030, the total global renewable energy capacity could surpass the aggregate of national targets by approximately 25%, sufficiently accommodating the rising global electricity demand. The global annual PV additions are expected to reach around 390 GW, reflecting significant year-over-year growth. The Asia-Pacific region continues to dominate the global PV market, driven by robust installations. The United States has witnessed a marked recovery in demand for PV installations, while the Middle East and Africa maintain a high growth trajectory propelled by accelerated energy transition strategies. In Europe, 61 GW of new PV capacity was installed in 2023, with approximately 55.8 GW in EU member states, representing a more than 40% year-on-year increase.

Global Cumulative Installed Capacity

The early stages of global PV development were significantly influenced by incentive measures introduced in Europe, particularly in Germany, with the European market reaching its peak in 2008. Initially, the global market grew at a slow pace, expanding from approximately 200 MW in 2000 to about 1 GW in 2004. In 2008, Spain emerged as a key driver of market expansion. By 2010, Europe accounted for over 80% of the global market, with installations rising from 8 GW in 2006 to 17 GW in 2010. From 2011 onwards, the share of Asia and the Americas began to grow rapidly. Asia's share fluctuated between 50% and 75% during this period, underscoring its pivotal role in the global PV market's transformation.

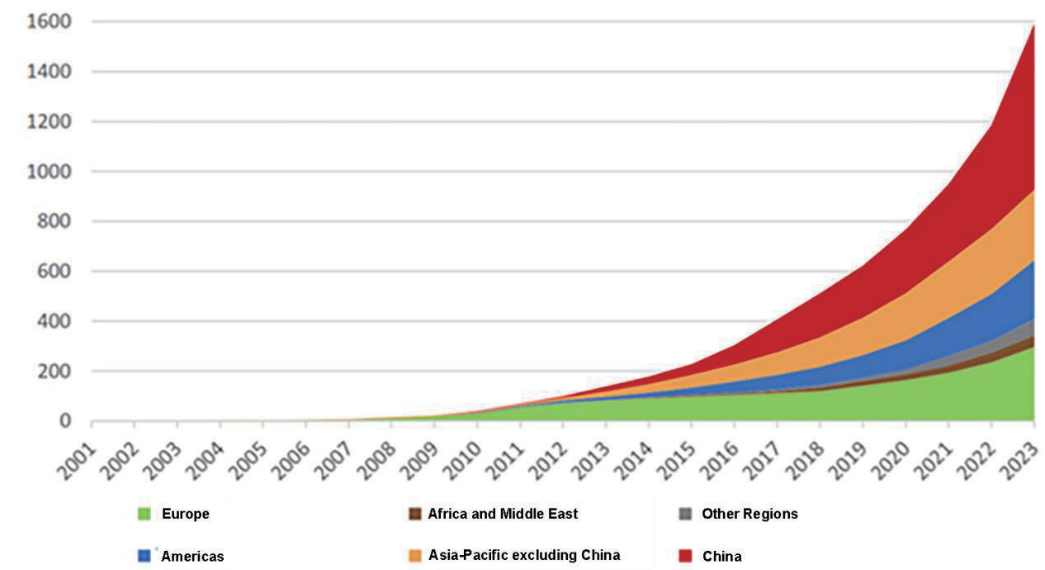


Figure 7-1: Global Cumulative PV Installations by Region (IEA, 2024).

According to the Snapshot of Global PV Market - 2023 report released by IEA-PVPS, the cumulative installed capacity of photovoltaic (PV) systems worldwide increased from 1.2 TW in 2022 to 1.6 TW in 2023 (ranging between 1581 GW and 1624 GW). A significant portion of this capacity is located in the Asia-Pacific region, whose share further rose in 2023, exceeding 60% with a cumulative capacity of at least 947 GW. Notably, it is China, rather than the entire Asia-Pacific region, that has been driving this growth. Outside of China, the shares of the other three major regional markets—Asia-Pacific, Europe, and the Americas—are roughly comparable in installed capacity.

Compared to 2022, PV markets in other Asia-Pacific countries showed slight contraction or remained stable overall in 2023. Over the past decade, Japan's annual PV installations have ranged between 6 GW and 10 GW. India's cumulative installed capacity is comparable to that of Japan but has exhibited greater fluctuations, growing from less than 1 GW in 2014 to 18.6 GW in 2022. During the same period, South Korea's market rebounded between 2.6 GW and 5 GW, stabilizing at over 3 GW annually in the past two years.

Across the European region, Germany remains the primary contributor to installed PV capacity, followed by Spain and Italy, each exceeding 30 GW in cumulative capacity. Trailing closely are France, with a cumulative capacity of 23.6 GW (adding 3.9 GW in 2023), the Netherlands at 22.4 GW (adding 4.2 GW), and Poland, which saw an increase of 6 GW to reach a total cumulative capacity of 18.5 GW. In 2023, more than 12 other European countries each surpassed 1 GW in installed capacity.

The PV market in the Americas is largely driven by the United States. After a slowdown in 2022, the U.S. market rebounded to levels similar to 2021, adding 33.2 GW to reach a cumulative capacity of 169.5 GW, accounting for over 70% of the region's total installed capacity. Meanwhile, Brazil's dynamic growth continued, reaching a cumulative capacity of 44 GW. Chile, which added 1.3 GW to achieve a total of 9.2 GW, may cross the 10 GW threshold by 2024, while Canada, with a cumulative capacity of 7.3 GW, is projected to reach double-digit figures within the next three years.

In the Middle East and Africa, South Africa led the region with nearly 3000 MW of installed capacity, accounting for the majority of new additions in the region. Other areas contributed an estimated total of less than 700 MW. Despite numerous projects being announced in recent years, the capacity to bring these projects to fruition remains to be demonstrated.

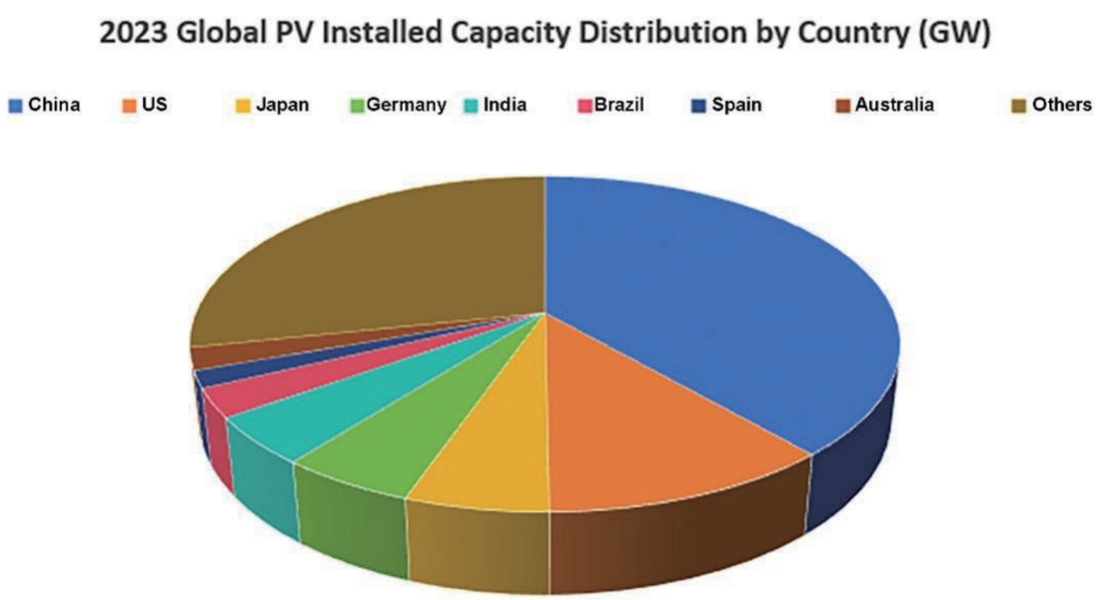


Table 7-2: Proportional Distribution of Total PV Installed Capacity by Country in 2023

China

China serves as the primary driver of the global PV industry, with newly installed capacity reaching 216.3 GW in 2023, marking a year-on-year growth of 147.5%. As the world's largest manufacturer and user of PV equipment, China's PV recycling sector is in a phase of rapid development, demonstrating promising prospects in terms of industry lifecycle and current stage of growth. In 2023, solar power accounted for over 75% of all newly installed renewable energy technologies and contributed nearly 60% of the newly added renewable energy generation capacity.

By the end of December 2023, China's cumulative installed PV capacity reached approximately 610 GW, representing a 55.2% year-on-year increase.

Year	2008	2009	2010	2011	2012	2013	2014	2015
New Installations (MW)	/	12	65	2200	5040	12920	10600	15130.5
Cumulative Capacity (MW)	13	25	90	2290.1	7330	19420.2	26522	42630
Year	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
New Installations (MW)	34540.4	53061	44260	30110	48204	54930	87413	216880
Cumulative Capacity (MW)	77420	130250	174630.4	204680.3	253830	306560.8	392610.8	609495

Table 7-1 Historical PV Installation Data in China

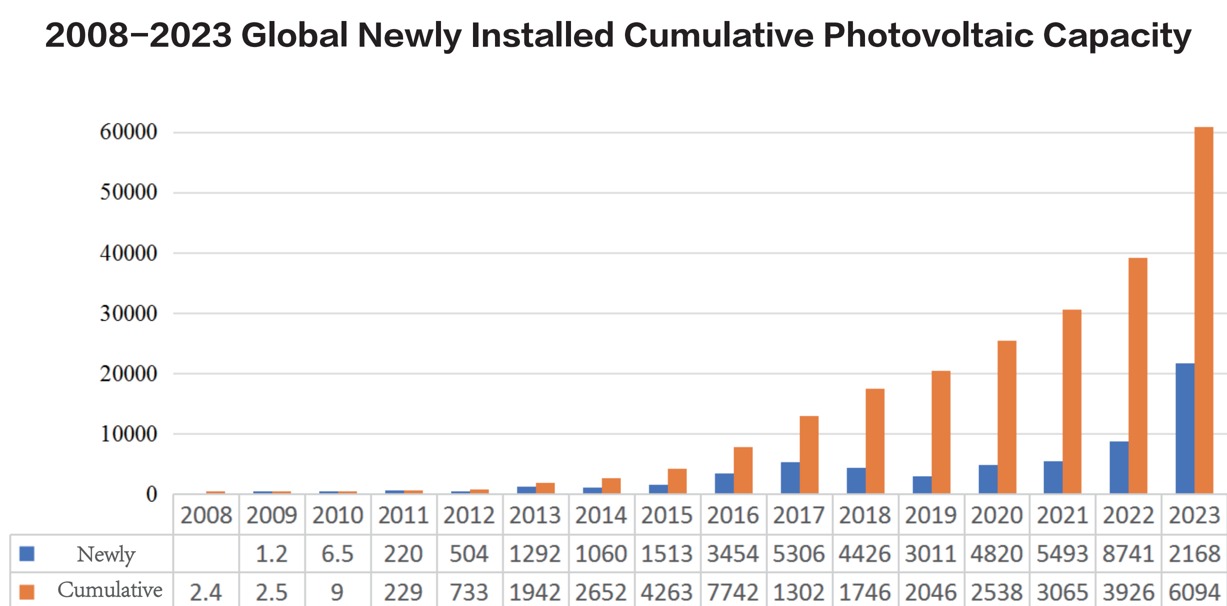


Figure 7-3 Annual New and Cumulative PV Installation Data in China

United States

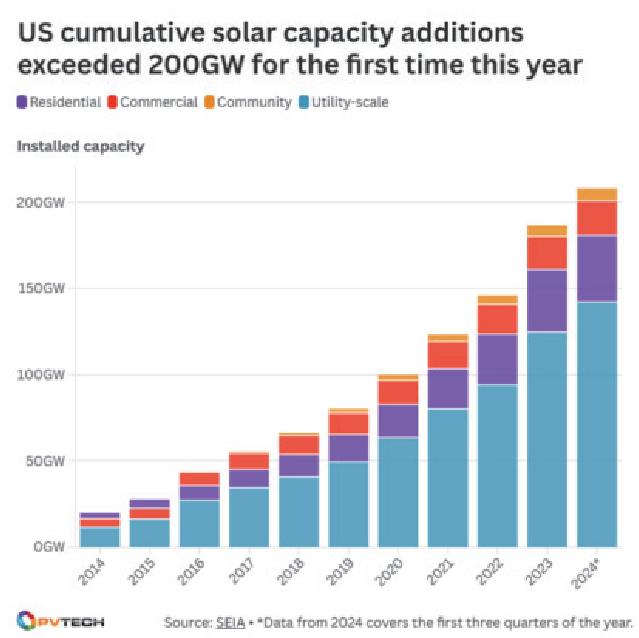


Figure 7-4 illustrates that for the first time, the cumulative newly added solar power capacity in the U.S. exceeded 200 GW this year.

According to data from the Solar Energy Industries Association (SEIA), the U.S. added 32.4 GWdc of new PV capacity in 2023, representing a significant year-on-year growth. Data from the U.S. Energy Information Administration (EIA) shows that the country added 29.1 GW of utility-scale PV systems in 2023, based on earlier projections, though actual figures may vary.

As per SEIA data, by the end of 2023, the cumulative U.S. solar capacity ranged between 162 GW and 179 GW, marking a 13.5% growth compared to 2022. By 2029, the solar energy sector alone is projected to supply power to over 71 million households.

India

In 2023, India added 20.8 GW of new PV capacity, including approximately 13.2 GW of utility-scale PV installations and 3.2 GW of rooftop solar projects. The Indian government launched initiatives for solar parks and ultra-mega solar power projects, aiming to add 40 GW of PV capacity by 2025-2026.

According to data from the Press Information Bureau of the Government of India, by the end of 2023, India's cumulative solar PV capacity reached 72.7 GW. As of December 2023, the distribution of cumulative utility-scale solar capacity across Indian states included Madhya Pradesh (17.4 GW), Rajasthan (23.1 GW), Karnataka (8.9 GW), and Gujarat (8.7 GW), among others.

Japan

In 2023, Japan added 1.1 GW of new PV capacity, primarily concentrated in small-scale projects (below 50 MW). Notably, 45% of these projects fell under the 50 MW threshold.

By the end of 2023, Japan's cumulative PV capacity reached 87 GW. This cumulative capacity accounted for 12% of Japan's total electricity generation, highlighting the critical role of photovoltaics in the nation's energy mix.

Germany

According to data from the Federal Network Agency of Germany, the country installed 14.2 GW of new PV capacity in 2023, marking a 91% increase compared to 7.45 GW in 2022. This represents the highest annual PV installation in Germany's history. Among the newly installed capacity, approximately 7 GW came from residential systems, reflecting a 135% year-on-year growth; around 4.3 GW was from ground-mounted power plants, with a 40% increase; and about 2.5 GW originated from commercial rooftop installations, up by 75%.

By the end of 2023, Germany's cumulative PV capacity had risen to approximately 82.4 GW.

Brazil

In 2023, Brazil's newly installed PV capacity was estimated to range between 14 GW and 16.9 GW.

By the end of 2019, Brazil had implemented a total of 215,000 PV projects. By the end of 2023, the country's cumulative PV capacity had reached approximately 44 GW, accounting for 18.9% of Brazil's total electricity supply. This highlights the significant role of solar energy in Brazil's energy mix. Of the total cumulative capacity, 21 GW was derived from distributed generation systems, while the remaining 9 GW came from large-scale solar power plants. Within the distributed generation capacity, around 10 GW was attributed to residential PV systems with capacities under 7 kW.

Spain

According to data from Spain's grid operator Red Eléctrica de España (REE), Spain added 5.594 GW of new PV capacity in 2023.

The Spanish PV market maintained strong growth in both 2023 and 2024. In 2023, Spain's total installed PV capacity reached 25.54 GW, marking a 28% year-on-year increase and setting a historical record.

Australia

In 2023, Australia added 4.6 GW of new PV capacity, with distributed PV accounting for a significant share of 68%. Distributed PV primarily consisted of residential rooftop systems and commercial and industrial rooftop systems, achieving installation capacities of 2.5 GW and 0.9 GW, respectively.

By the end of 2023, Australia's total installed solar PV capacity reached 34 GW, equating to more than 1.33 kW of solar capacity per capita and encompassing at least 3.36 million rooftop solar systems. The Australian government places a high priority on renewable energy development and has set a target for 82% of electricity to come from renewable sources by 2030.

7.2 Market Capacity Forecast for Decommissioned Photovoltaic Equipment

As emerging markets and developing countries experience rapid growth in photovoltaic (PV) installation capacity, the demand for PV equipment recycling is expected to expand significantly. However, many countries currently do not report this data using consistent standards, indicating that the global recycling market is still in its infancy.

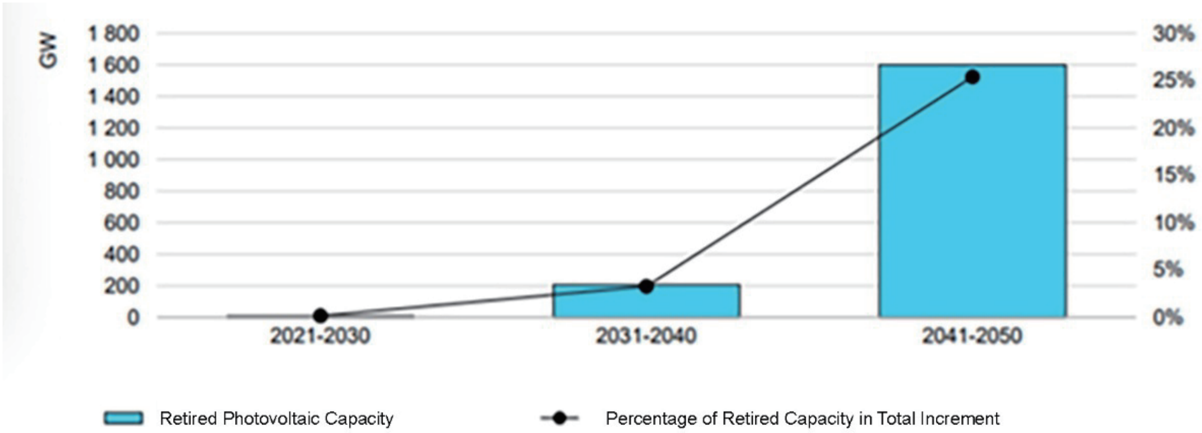


Figure 7-5: Projected Global Decommissioned PV Capacity (2020–2050)

According to a report released by the International Energy Agency (IEA) in July 2022, the global cumulative decommissioned PV capacity is projected to reach approximately 7 GW by 2030. The cumulative value of recyclable raw materials from PV panel technology is estimated to be around US$450 million. By 2040, this figure is expected to exceed 200 GW.

If PV panels are systematically collected and recycled at the end of their lifecycle, the supply generated from recycling could meet over 20% of the PV industry's demand for aluminum, copper, glass, silicon, and silver according to the International Energy Agency's (IEA) Net Zero Emissions by 2050 Roadmap. Between 2040 and 2050, recycled materials could fulfill nearly 70% of the silver demand for PV manufacturing. By 2050, PV waste is projected to reach 88 million tons, and the cumulative recoverable value of these materials could exceed US$15 billion. These estimates are derived from historical capacity increments and the incremental calculations in the IEA Net Zero Scenario model for 2050, which assumes the lifespan of decommissioned PV modules follows a Weibull distribution. The median lifespan for utility-scale installations is set at 25 years, while for distributed installations, it is 30 years.

According to an analysis conducted in 2016 by the International Energy Agency Photovoltaic Power Systems Program (IEA-PVPS) Task 12 and the International Renewable Energy Agency (IRENA), the report estimated the future generation of decommissioned PV module waste. Under the early-loss scenario, it was projected that PV waste could increase to 8 million tons by 2030, as this scenario assumes a higher percentage of early PV module failures compared to the regular-loss scenario (see Figure 7-6). However, these projections are likely underestimated due to the rapid pace of development in the PV industry, which has exceeded expectations at the time of the report.

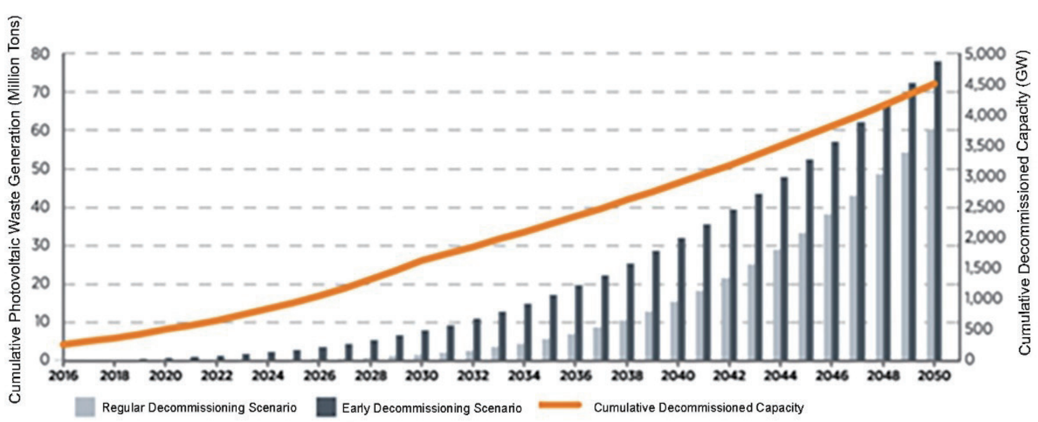


Figure 7-6: Forecast of Cumulative Decommissioned PV Capacity and Waste Generation (IRENA, 2016)

According to IRENA's latest report, World Energy Transitions Outlook 2022, the global volume of PV module waste from solar photovoltaic projects is expected to rise to 4 million tons by 2030, nearly 50 million tons by 2040, and surpass 200 million tons by 2050. These updated projections highlight the escalating scale of PV waste generation as the solar industry expands globally.

China

The history of PV power generation in China spans just half a century. Counting from the creation of the first silicon monocrystal, it has a history of only 60 years. Yet, within a few short decades, China's PV industry has risen to a position of global leadership. By the end of 2023, China had maintained its status as the world's largest producer of PV modules for 16 consecutive years, while its cumulative installed capacity had topped global rankings for eight consecutive years. China's PV market began to develop significantly around the year 2000. With PV modules typically having a lifespan of 20 to 25 years, a significant portion of the installed systems has now reached the replacement phase.

The China Photovoltaic Industry Association (CPIA) predicts that by 2025, the first batch of PV modules will begin to retire. By then, the cumulative decommissioned PV modules across the country will reach approximately 9 GW, with over 2.7 GW being decommissioned that year alone. According to projections from the International Energy Agency (IEA), China will face the task of recycling 2 million tons of PV modules by 2030, with the volume expected to peak in 2034. This emerging market for recycling decommissioned PV modules, estimated to be worth hundreds of billions of yuan, is developing rapidly. Due to the surge in installations around 2015, the volume of modules requiring recycling is anticipated to grow exponentially starting in 2035. By 2040, the cumulative recycling volume is projected to reach 250 GW.

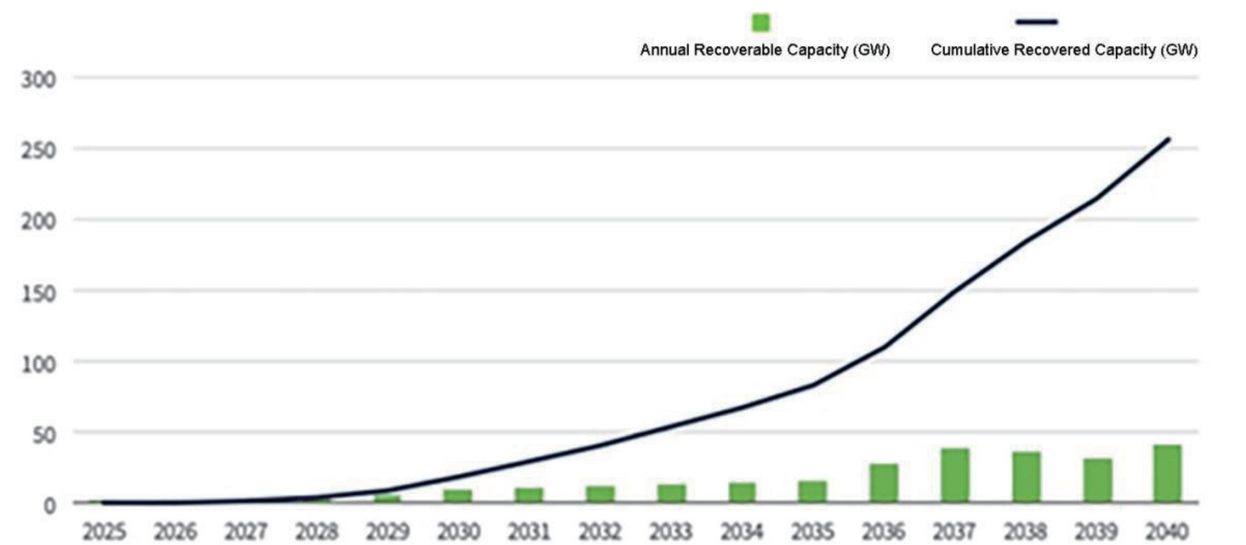


Figure 7-7: Cumulative Forecast of PV Equipment in China (2025–2040)

The large-scale replacement of PV equipment due to technological upgrades, combined with the wave of early PV module decommissioning, is imminent. Currently, the decommissioned modules circulating in the industry primarily originate from production defects, construction waste, or replacement caused by unavoidable events such as sandstorms, typhoons, floods, and earthquakes. These factors contribute to a significant increase in the number of decommissioned modules, making future projections less predictable. Preliminary estimates indicate that each MW of decommissioned PV equipment yields approximately 60–80 tons of recyclable materials such as glass, aluminum, silver, copper, and plastics, with this report adopting an average value of 70 tons. Based on these assumptions, it is projected that decommissioned PV modules will amount to approximately 2 million tons by 2030 and reach around 17.5 million tons by 2040.

The above data does not include the volume of modules scrapped during the manufacturing process. Based on the experiences of major manufacturers, production scrap rates vary significantly depending on the process, with an average rate of approximately 0.5% of the total product output. Additionally, with initiatives such as the "Light Up Thousands of Households" campaign organized by China's National Development and Reform Commission, the National Energy Administration, and the Ministry of Agriculture and Rural Affairs, the installed capacity of distributed photovoltaics in China is expected to grow further, leading to an increase in the volume of decommissioned modules.

United States

Although solar power capacity in the United States has continued to grow, the growth rate has slowed in recent years. From an application perspective, the U.S. Energy Information Administration (EIA) forecasts that solar power will become the primary source of electricity generation growth in 2024 and 2025, as PV generation expands. The share of solar energy in the U.S. total electricity generation is expected to rise from 4% in 2023 to 6% in 2024 and 7% in 2025, while the share of traditional energy sources is projected to decline.

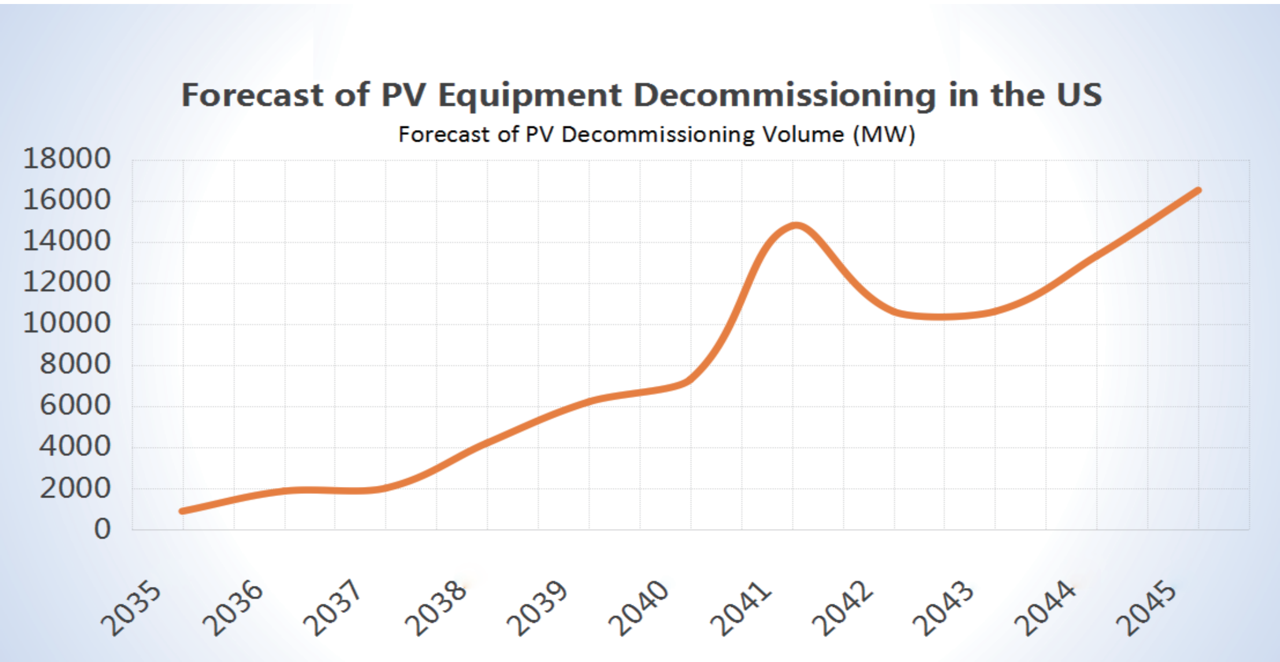


Figure 7-8: Forecast of PV Equipment Decommissioning in the US

By June 2027, the decommissioning of PV modules in the United States is projected to reach 99 MW, based on decommission between June 2024 and May 2027. Solarcycle, a solar panel recycling company, plans to build a 5 GW solar module recycling facility in Georgia, which is expected to handle approximately 25-30% of decommissioned solar modules in the United States by 2030. According to forecasts from the International Renewable Energy Recycling Association, the period from 2035 to 2040 will see 22.5 GW of PV systems reaching the end of their operational life. Between 2036 and 2045, this figure will rise sharply, with over 65.8 GW of PV systems anticipated to be decommissioned.

According to the U.S. National Renewable Energy Laboratory (NREL), the current recycling rate for PV modules is only about 10%. Since landfill disposal remains a cheaper and simpler option, recycling has yet to become an economically viable process. To address this issue and reduce the costs associated with module recycling and disposal, the U.S. Department of Energy announced in April 2023 an investment of over $8 million in research and development projects focused on recycling and waste management technologies.

India

According to India's 14th National Electricity Plan (NEP14), the country's installed PV capacity is expected to reach 185.6 GW by the fiscal year 2026–2027 and increase to 364.6 GW by 2030. The Indian government has set an ambitious goal of achieving 500 GW of renewable energy capacity by 2030, with renewables accounting for 50% of the power system. Solar PV will play a crucial role in achieving this target. To support these objectives, the government is actively promoting the development of the PV recycling industry to minimize resource wastage and mitigate environmental pollution.

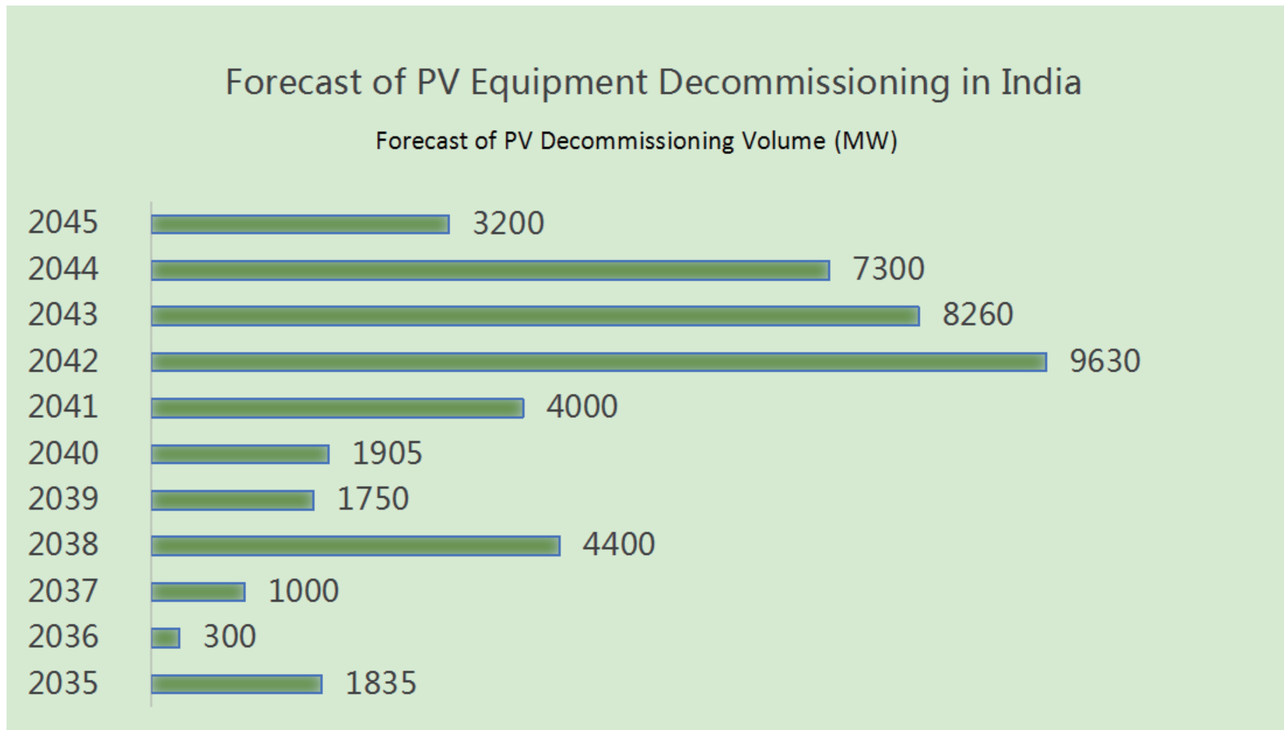


Figure 7-9: Forecast of PV Equipment Decommissioning in India

In 2023, 2025, and 2030, the decommission and end-of-life scale of PV modules in India is projected to reach approximately 0.35 GWp, 0.50 GWp, and 1.16 GWp, respectively. This corresponds to an estimated material volume of about 20,400 tons, 28,800 tons, and 63,800 tons. The rapid growth of the Indian PV market is driving an increasing need for recycling and the circular utilization of solar equipment.

According to estimates by the Council on Energy, Environment and Water (CEEW), India has already generated a substantial volume of solar waste due to early losses from its existing 40 GW of grid-connected capacity. By the end of FY 2021, cumulative solar waste was approximately 285 kilotons, with projections suggesting waste volumes will rise to between 915 and 1,279 kilotons by 2040, with 95% of this waste expected to come from crystalline silicon panels. The International Renewable Energy Recycling Association predicts that between 2035 and 2040, 11.2 GW of PV capacity in India will reach the end of its lifecycle, and this figure will exceed 32.3 GW between 2036 and 2045. This creates a vast market opportunity for the solar equipment recycling industry.

Japan

The Japan Photovoltaic Energy Association (JPEA) has released a new industry outlook titled "PV Outlook 2050," revising its projections for cumulative PV capacity in Japan. The forecast anticipates reaching 125 GWAC by the fiscal year 2030 and 376 GWAC by the fiscal year 2050. With the increasing volume of decommissioned PV equipment, the focus of the Japanese government has shifted to promoting the circular use of PV systems. This involves reducing environmental pollution and improving resource utilization efficiency, reflecting the nation's commitment to sustainable energy practices.

Japan's cumulative installed PV capacity has reached 87 GW, with the majority of these plants having been operational for over a decade. Compared to newer projects equipped with advanced PV technologies, the efficiency of these older plants lags significantly. As a result, the renovation of aging solar power plants is poised to become a major market focus in Japan.

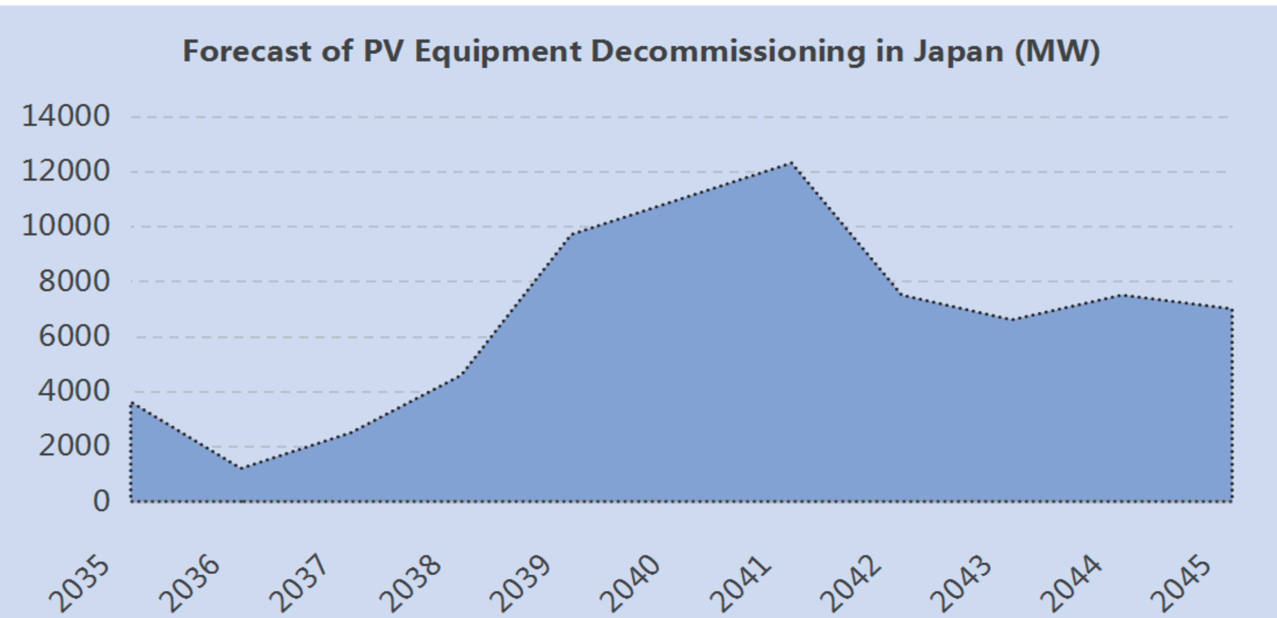


Figure 7-10: Forecast of PV Equipment Decommissioning in Japan

It is estimated that Japan generates approximately 4,400 tons of PV waste annually, with around 3,400 tons of components being reused and 1,000 tons being recycled. The Japan Photovoltaic Energy Association (JPEA) has compiled a nationwide list of facilities capable of properly handling discarded PV modules. This list currently includes 27 recycling plants, effectively covering the entire country.

Japan's PV module recycling market is expanding and is projected to reach $465.8 million by 2033, with a compound annual growth rate (CAGR) of 9.96% from 2023 to 2033. Starting in the mid-2030s, approximately 800,000 tons of solar panels are expected to be decommissioned annually. Between 2035 and 2039, the quantity of discarded photovoltaic modules will increase to 170,000–280,000 tons per year, exceeding the current capacity of identified PV recycling facilities by more than tenfold. According to the Japanese Ministry of the Environment, the volume of solar panel waste in Japan is anticipated to grow significantly, rising from 2,351 tons in 2015 to around 800,000 tons by 2040. Additionally, the International Renewable Energy Recycling Association forecasts that from 2040 to 2045, more than 52 GW of PV equipment in Japan will be decommissioned.

Germany

According to Eurostat data, in 2018, Germany introduced 211,142 tons of PV modules into the market and recovered 7,865 tons from the market. Of the recovered modules, 2,259 tons were collected through household recycling, while 5,606 tons were recovered through other channels. Among the 7,708 tons of recovered modules, 6,896 tons were recycled, and 909 tons were designated for reuse.

Germany's PV market experienced robust growth in 2023, with the total installed capacity required to reach 215 GW by 2030. This growth was particularly evident in the residential sector (systems up to 10 kW) and the commercial sector (systems ranging from 10 to 500 kW), where installed capacities increased year-on-year by 131% and 145%, respectively. In 2023, Germany consumed 61 terawatt-hours (TWh) of PV electricity, avoiding approximately 4.2 million metric tons of CO_2-equivalent greenhouse gas emissions.

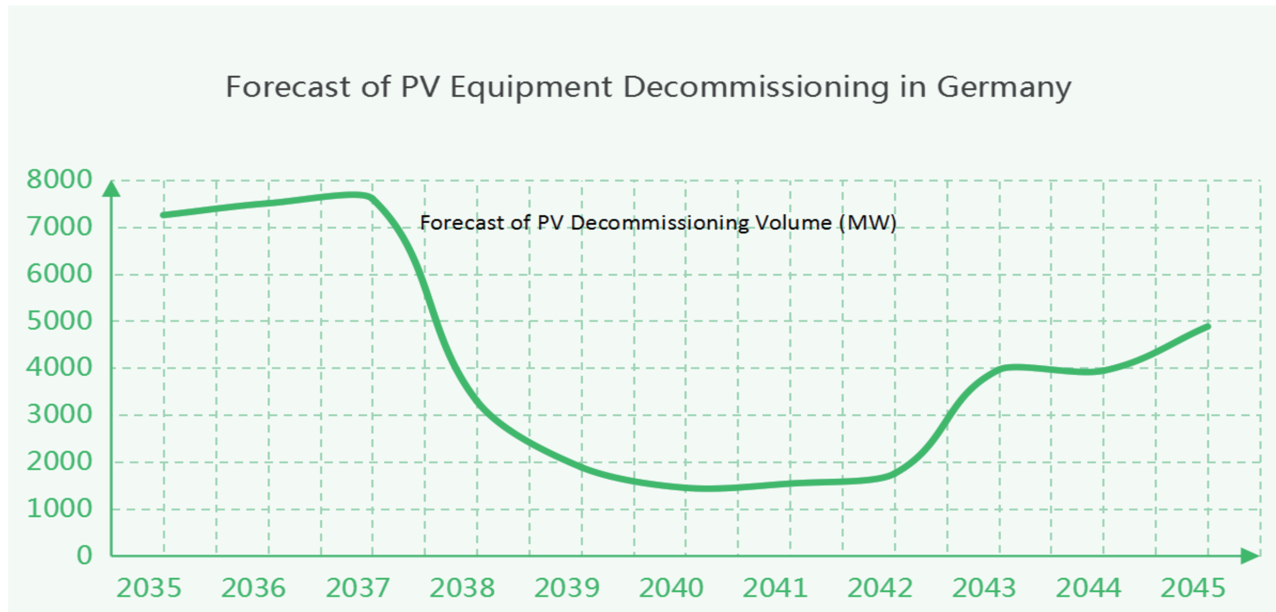


Figure 7-11: Forecast of PV Equipment Decommissioning in Germany

According to the IRENA/PVPS Task 12 report on decommissioned PV modules, Germany is projected to generate between 400,000 and 1,000,000 tons of discarded PV components by 2030. The implementation of Germany's Renewable Energy Act (EEG) in 2000, with generous subsidies, significantly spurred the growth of the PV sector between 2001 and 2013. During this period, installed capacity increased steadily. However, in 2013, the German government began imposing strict controls on the scale of PV installations and further reduced feed-in tariff rates in 2014. The profitability of rooftop solar projects saw a sharp decline, with feed-in tariff yields dropping from approximately 16% in 2013 to about 13% in 2014. These policy changes greatly impacted the economic viability of PV projects, leading to record-low installation rates. As a result, the volume of decommissioned PV systems in Germany is projected to show a decline between 2035 and 2042. According to the International Renewable Energy Equipment Recycling Association, approximately 29 GW of PV equipment is expected to be decommissioned between 2035 and 2040.

Germany aims to achieve nearly 100% renewable energy power supply by 2050. To meet this ambitious target, the country is expected to maintain rapid growth in PV installation capacity.

By 2050, the volume of discarded photovoltaic modules in Germany is expected to further increase to 4.3 million tons.

Brazil

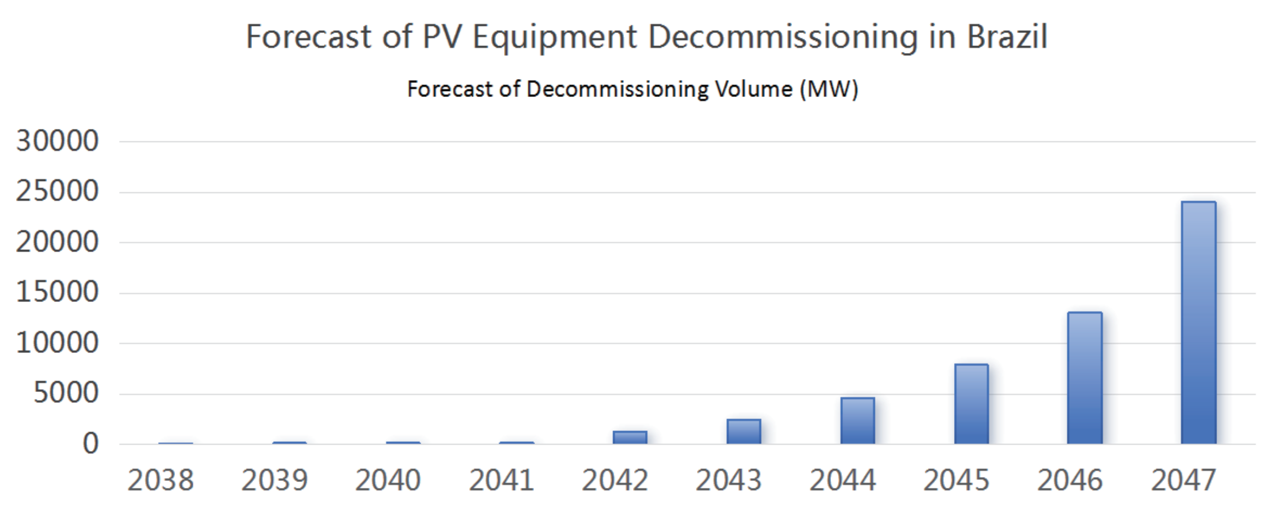


Figure 7-12 Forecast of PV Equipment Decommissioning in Brazil

Brazil boasts some of the world's best solar resources, with PV systems generating twice as much electricity as equivalent systems installed in Germany or the United Kingdom. The rapid development of the solar PV industry in Brazil provides a solid market foundation for the PV equipment recycling industry. The Brazilian PV market is currently in a phase of rapid growth, having generated over 1.4 million cumulative jobs in the solar sector since 2012. The number of PV projects has increased significantly, with Brazil's PV module imports reaching 4.14 GW in 2019, a remarkable 120.3% increase from 1.88 GW in 2018. Despite this growth, Brazil's PV recycling volume remains relatively small. According to predictions by the International Renewable Energy Equipment Recycling Association, PV equipment decommissioning in Brazil is expected to total just 1.5 GW from 2038 to 2042. However, this figure is anticipated to rise significantly from 2043 onward, with approximately 52 GW of PV equipment projected to face decommissioning by 2047.

Spain

Spain, one of Europe's sunniest countries, enjoys an average of approximately 3,000 hours of sunlight annually, making it a prime location for solar energy development. This abundant solar resource places Spain among the top European nations for PV installed capacity, second only to Germany. In its energy strategy submitted to the European Commission, the Spanish government has set an ambitious target of achieving 76 GW of PV capacity by 2030. This aligns with its goal to meet more than 80% of the country's electricity demand with renewable energy sources.

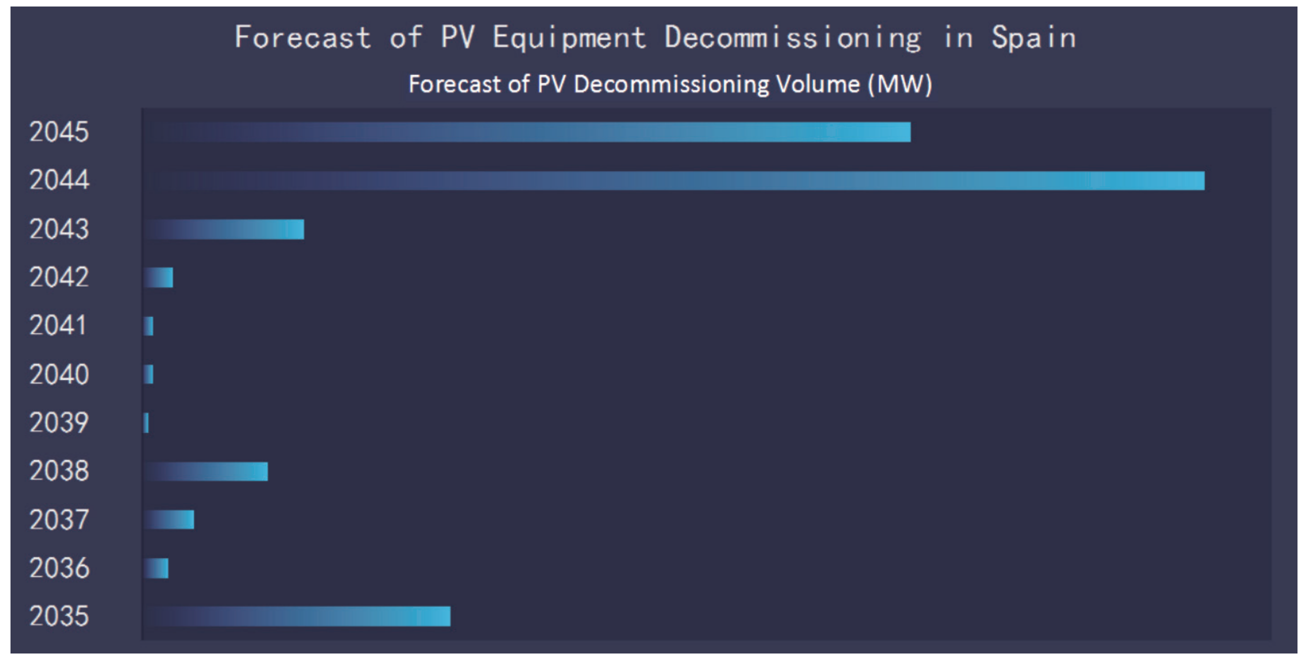


Figure 7-13: Forecast of PV Equipment Decommissioning in Spain

In Spain, the management of discarded PV modules remains at a very early stage. In 2013, the Spanish government introduced Law 24, which provided significant special compensation for utility-scale ground-mounted solar power plants. However, following the implementation of Royal Decree 413 in 2014, which established a bidding mechanism for PV projects, the annual growth of PV installations saw a decline. As EU countries faced the binding renewable energy targets set for 2020, Spain initiated a 3,900 MW PV project auction in 2017 to ensure these projects would be operational by the end of 2019. This spurred a significant increase in the deployment of PV projects. Between 2017 and 2020, the amount of PV modules introduced into the Spanish market surged dramatically from 1,532 tons in 2017 to 221,998 tons in 2020, representing an approximate 144-fold increase. Despite this rapid market expansion, the volume of discarded PV modules collected and recycled annually in Spain remains relatively low. Between 2017 and 2019, the country recycled 155.13 tons, 461.89 tons, and 226.15 tons of PV modules, respectively. The corresponding amounts treated were 149 tons, 276 tons, and 120.53 tons, while the recyclable/reusable amounts stood at 102 tons, 240 tons, and 104 tons. According to the International Renewable Energy Equipment Recycling Association, the retirement volume of PV equipment in Spain is expected to remain relatively low between 2039 and 2042, reaching approximately 3.2 GW by 2045. The retirement peak is projected for 2044, with total retirements between 2040 and 2045 estimated to reach 9 GW.

Australia

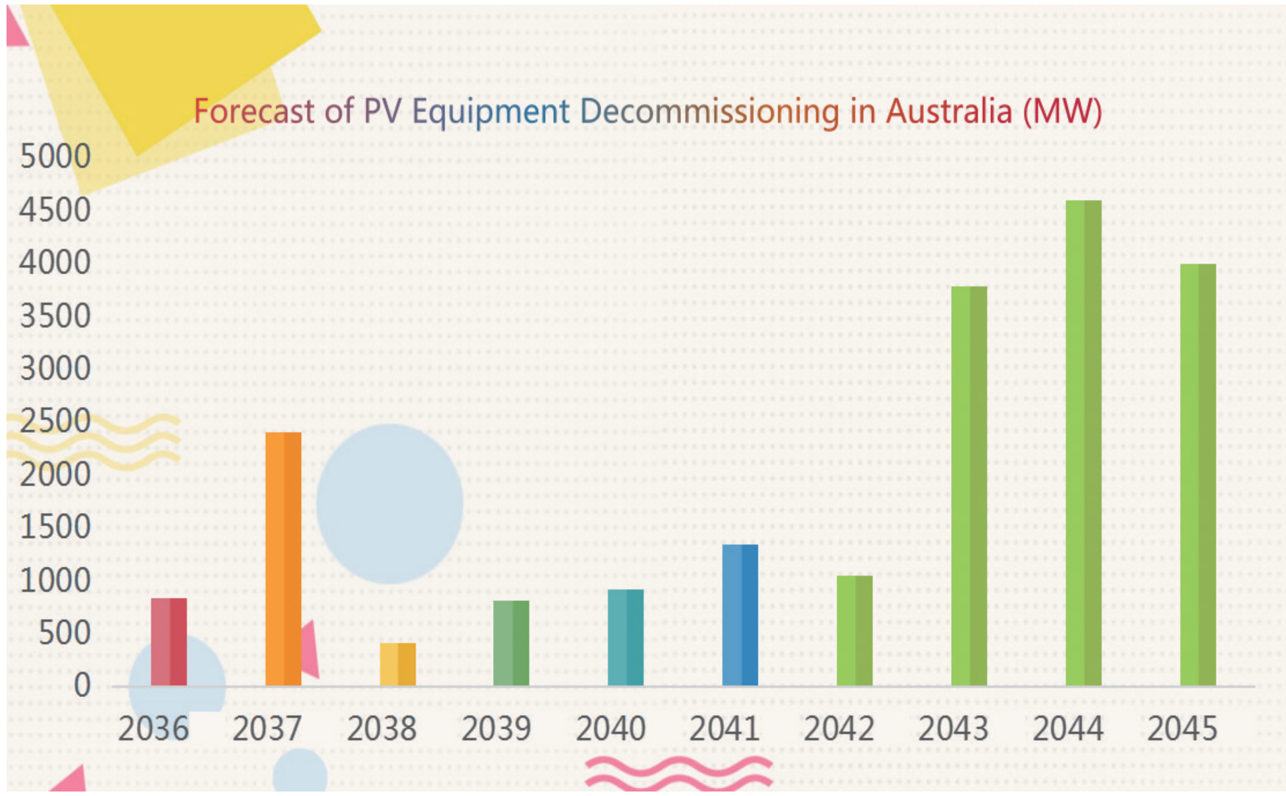


Figure 7-14: Forecast of PV Equipment Decommissioning in Australia

The New South Wales Environmental Protection Authority (EPA) predicts that by 2025, the state will generate between 3,000 and 10,000 metric tons of waste from solar panels and battery storage systems annually. This figure is expected to rise significantly, reaching between 40,000 and 71,000 metric tons per year by 2035.

According to estimates by Professor Peter Majewski from the University of South Australia, more than 100,000 metric tons of solar panels will be decommissioned by 2035. By 2047, PV waste is projected to reach 800,000 metric tons. A team of researchers from Macquarie University has calculated that the materials contained in these panels hold an economic value of approximately $1.25 billion. The International Renewable Energy Equipment Recycling Association predicts that between 2036 and 2040, around 5.4 GW of PV equipment will be decommissioned, with a peak in recycling activity in 2037. From 2041, the decommissioning rate will begin to rise significantly, with an estimated 14.7 GW of PV equipment projected to be decommissioned between 2041 and 2045.

The recycling rate for PV panels in Australia is currently very low, falling far short of the targets set by the National Waste Policy Action Plan, which aims to increase the country's resource recovery rate to 80% by 2030. Establishing an effective collection system is a key priority for any recycling pathway.

Chapter 8

Predicted Development Trends in the Photovoltaic Equipment Recycling Industry

8.1 Current Technologies in Recycling

As the replacement of photovoltaic (PV) equipment accelerates due to technological upgrades and the initial wave of early PV installations reaches the end of their lifecycle, a global surge in PV equipment retirements is imminent. Effectively recycling these resources has become one of the critical challenges facing the PV industry today. The PV equipment recycling industry not only helps reduce resource waste and environmental pollution but also promotes the sustainable development of the PV sector. Decommissioned PV modules contain valuable materials such as silver and silicon, offering significant recycling potential. However, challenges remain, including the generation of toxic and hazardous gases and liquids during processing, as well as risks of heavy metal contamination.

PV modules can be categorized structurally and materially. Structurally, they primarily consist of PV cells, array brackets, DC combiner boxes, DC distribution cabinets, grid-connected inverters, AC distribution cabinets, as well as power monitoring and environmental monitoring devices. Among these, PV cells are the most critical component. Materially, PV modules are primarily made up of a glass backsheet, solar cells, aluminum alloy frames, EVA, copper ribbons, and junction boxes. Glass, aluminum, and semiconductor materials constitute up to 92% of the total weight, with additional components including silver and indium, both of which are heavy metals with significant environmental risks. Recycling PV modules offers dual benefits. On one hand, it helps prevent potential environmental harm caused by decommissioned modules. On the other hand, it allows for the recovery and reuse of valuable resources, generating economic benefits. Furthermore, raw material recycling reduces reliance on imports of critical resources, which is crucial for mitigating raw material supply risks.

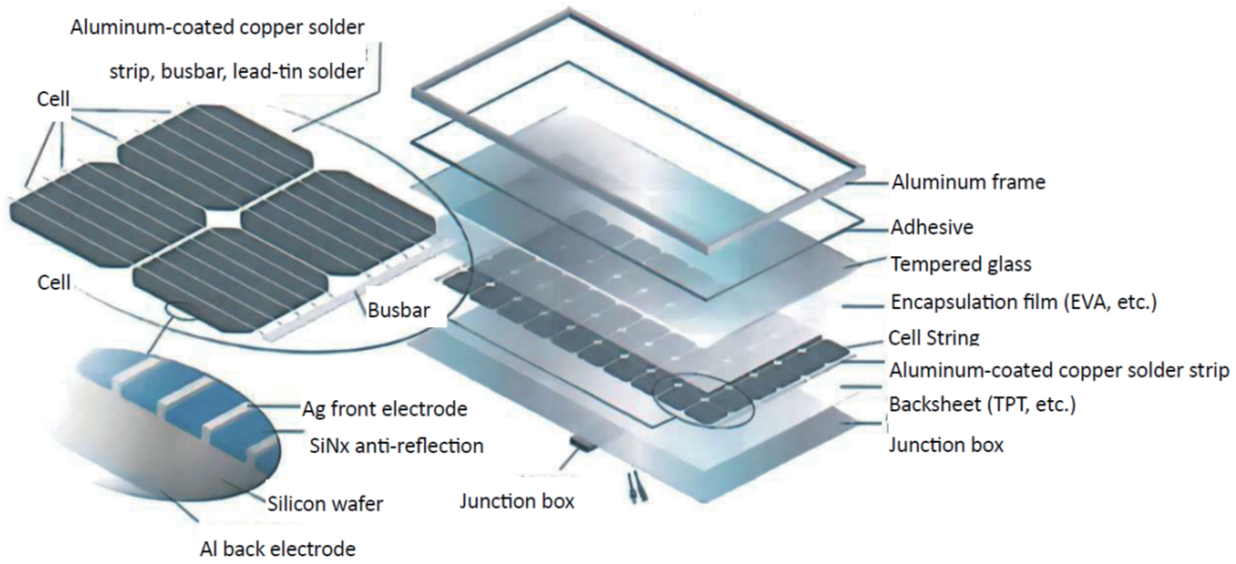


Figure 8-1 Representative Structural Diagram of Crystalline Silicon Cell (Left) and PV Module (Right)

Unlike the large-scale and difficult-to-transport characteristics of wind power equipment, PV modules feature modular structures that are easy to disassemble and transport. The basic recycling process for PV modules involves disassembling the assembled components, classifying and cleaning each part, and then separating their constituent materials. Recoverable resources such as metals, silicon, and plastics are recycled and reused, while components containing hazardous substances, such as mercury, silver, lead, acidic materials, and halides, undergo specialized treatment. Finally, non-recyclable parts and solid waste generated during the disposal process are subjected to final disposal methods, such as landfilling or incineration.

The following discussion is divided into three sections from the perspective of a circular economy: reuse, recycling, and final disposal.

8.1.1 Reuse

After PV modules are decommissioned, their reuse refers to their downgraded application as individual units, either in their entirety or after undergoing processes such as processing, classification, inspection, repair, and remanufacturing. Repair techniques are typically straightforward, involving operations like replacing cables, bypass diodes, junction boxes, and back sheets. More complex repairs, such as replacing cells, must be conducted in specialized workshops, while other operations can be performed on-site. Reuse represents the most value-preserving utilization method and is currently one of the primary pathways for decommissioned PV modules. Common reuse applications include, but are not limited to, microgrid systems, off-grid power systems, billboards, decorative architecture, charging stations, bus stops, art installations, and signage.

Figure 8-2 Innovative Application Scenarios for PV Recycling

8.1.2 Recycling

Currently, decommissioned PV modules are predominantly crystalline silicon (c-Si) modules. A common structure of crystalline silicon PV modules is the single-glass backsheet-encapsulated module. In this design, solar cells with consistent or similar performance are first interconnected into strings using solder ribbons. These strings are then connected together via busbars. The module assembly involves lamination of glass, solar cells, and a backsheet using an organic encapsulant. EVA is a typical encapsulant, while the backsheet is often a fluorine-containing composite material (TPT: Tedlar/PET/Tedlar). The laminate is framed with aluminum alloy along its edges, and a junction box is installed on the back of the module, representing the mainstream technology in early manufacturing processes.

The primary material composition of representative crystalline silicon PV modules, by weight percentage, consists of approximately 70% encapsulation glass, followed by aluminum at 18%, EVA at 5%, and silicon at 3.65%. Copper and silver are present in smaller amounts, with silver accounting for about 0.06% of the total weight. However, when converted into economic value proportions, silver contributes approximately 47% of the total economic value, while glass, which has the largest weight percentage, only accounts for about 8% of the economic value. It is important to note that this estimation considers only the intrinsic value of the materials themselves, excluding factors such as recycling technologies and associated costs.

The recycling process of crystalline silicon PV modules involves reversing the encapsulation process through three primary stages. The initial stage is pre-treatment, which involves dismantling the frame and junction box. By removing these components, the module is reduced to its laminate form, comprising layers of glass, encapsulation material, cells, and the backsheet. Following this, the laminate undergoes dismantling to separate it into its core constituents, such as glass, cells, backsheet, ribbon, encapsulation materials, and other mixed materials. Lastly, the process focuses on component separation, where the extracted cells, ribbons, or mixed materials are refined to recover higher-purity fractions of materials. This enables the effective recovery of valuable components like silicon, silver, aluminum, and copper.

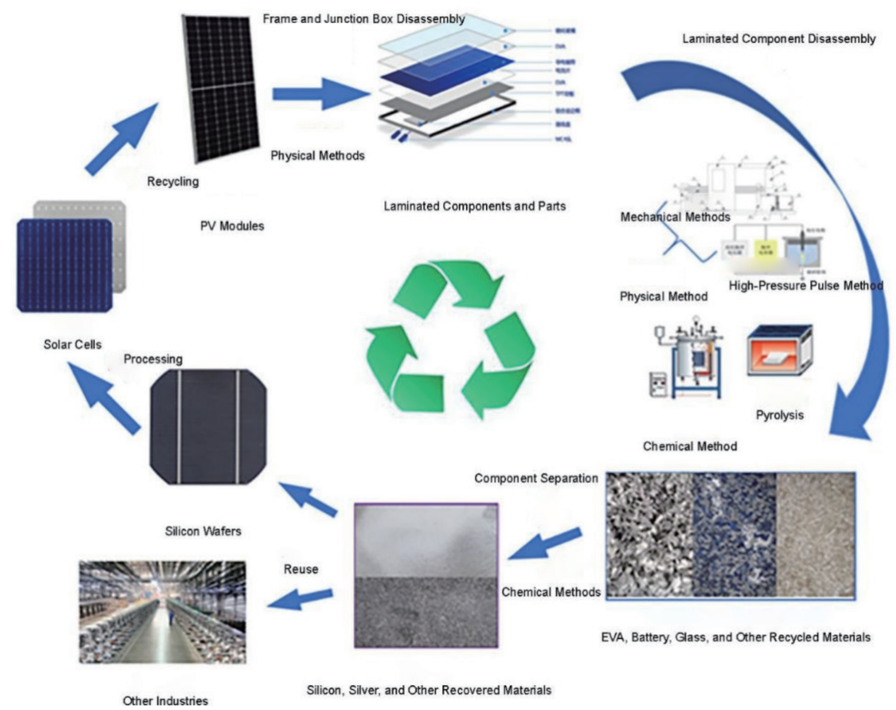


Figure 8-3: Diagram of Recycling and Circular Utilization Process for Crystalline Silicon PV Modules

(1) Frame and Junction Box Dismantling

Figure 8-4: Automatic Frame Dismantling System and Automatic Backsheet Dismantling Tunnel Kiln

The aluminum frame is mechanically fastened to the laminated module and sealed with adhesives such as silicone. The junction box is adhered to the module's backsheet using silicone, with its internal circuitry connected to the busbar leads from the crystalline silicon PV module. Subsequent processing of PV modules typically begins with dismantling and separating these components before moving on to the next processing steps.

The dismantling of aluminum frames and junction boxes is generally performed mechanically. The removal of aluminum frames typically involves applying external force to pull them apart, while junction boxes are removed using blade cutting. This process is straightforward and easy to implement. Scalable dismantling equipment that ensures efficiency and quality in disassembly is key to this step. High-quality equipment should be capable of handling various specifications and models of PV modules, including damaged, deformed, or incomplete ones.

(2) Dismantling of Laminates

The structure of the laminate consists of glass, encapsulant, solar cells, encapsulant, and backsheet. The dismantling process typically involves three main methods: physical, chemical, and pyrolytic.

① Physical Method

The physical method for disassembling laminated structures commonly employs mechanical crushing techniques. This typically begins with shredding or cutting machines to divide the solar module into smaller pieces. These smaller pieces are then processed using blade or rotor crushers to further break them down into fragments, granules, or powders of varying sizes. Given the high viscoelasticity of EVA, crushers must apply sufficient shear force, often requiring multiple stages of crushing: primary coarse crushing, secondary fine crushing, and tertiary grinding. Due to the differences in physical properties among materials such as glass, silicon, silver, copper, encapsulants, and back sheets, the composition of the crushed output varies depending on particle size. For example, the viscoelastic encapsulants tend to form larger fragments, brittle materials like silicon and silver are ground into finer powders, and the bulkier glass components exhibit a wide size range from granules to powders. To prevent dust pollution during crushing, the process can be conducted in a liquid medium.

In addition to mechanical crushing, the physical crushing method can employ high-voltage pulse crushing. This process involves placing crystalline silicon photovoltaic modules in a specific liquid dielectric medium and applying short-duration high-voltage pulses to the medium. The resulting electrical discharge impacts the modules, causing them to fracture. Conducted within a liquid medium, this method, also known as electrohydraulic crushing, has the advantage of eliminating dust pollution.

After crushing, the resulting mixture must undergo material separation, with common methods including density screening and electrostatic separation.

Density screening utilizes a suitable liquid with a specific density. When the mixed materials are placed in this liquid, components with lower density float, while those with higher density sink. For larger pieces or particles, static liquid screening is typically effective. However, for smaller powdered materials, static screening is less efficient due to surface tension effects. In such cases, dynamic screening with circulating liquid is preferable.

Electrostatic separation takes advantage of the different electrical conductivity of components, which leads to varying electrostatic polarization effects under an electric field, enabling separation. However, the purity of materials obtained through physical separation is inherently limited. For instance, silicon powder may contain traces of metals and glass, while glass or metal powders may still include small amounts of silicon.

Building upon the physical crushing method, additional processes can be introduced to improve material fragmentation and separation, particularly to minimize the adhesion of the encapsulant to inorganic components such as glass, silicon, and silver. These processes primarily include low-temperature freezing and supercritical carbon dioxide treatment. Low-temperature freezing employs liquid nitrogen to induce brittleness in the encapsulant, thereby reducing its adhesive properties. Supercritical carbon dioxide treatment involves subjecting carbon dioxide to high temperatures and pressures, enabling it to penetrate the encapsulant and disrupt its structure, thereby weakening its bonding strength. These techniques enhance the efficiency of material separation and reduce contamination among components.

Figure 8-5: Demonstration Line for Physical Disassembly of Modules (20MW/a)

② Chemical Method

Chemical solvent-based methods involve immersing photovoltaic modules in organic or inorganic chemical solvents to dissolve the EVA and disrupt its interfacial adhesion. Inorganic solvents, such as nitric acid, are highly corrosive and can dissolve the silver on the solar cells, thereby damaging them. Organic solvents offer a broader range of options, with highly effective examples including trichloroethylene, toluene, tetrahydrofuran, and o-dichlorobenzene. The effectiveness of chemical solvents is limited by their ability to penetrate the EVA encapsulant only from the edges of the solar cells. As a result, weakening the adhesive strength of the entire encapsulant can take several days or even longer. This slow process is a significant limitation of the chemical method.

Figure 8-6. Demonstration Line for Chemical Method Silicon PV Module Recycling (12 MW/year)

To improve the processing speed of the chemical solvent method, it can be combined with physical crushing. By first breaking the intact photovoltaic modules into smaller pieces, particles, or powders, the contact area between the EVA encapsulant and the chemical solvent increases, accelerating the dissolution and swelling process.

Additionally, auxiliary techniques can be employed to enhance the effects of solvent immersion. These enhancements include ultrasonic waves, microwaves, and supercritical carbon dioxide. For instance, under microwave irradiation, trichloroethylene in the solution more readily penetrates the encapsulant, expediting the swelling of the EVA layer and weakening its interfacial adhesion.

③ Pyrolysis Method

The pyrolysis method involves subjecting the photovoltaic module to high temperatures, initiating a thermal chemical reaction that decomposes the EVA. This process separates components such as glass, solar cells, solder ribbons, and busbars.

Figure 8-7. Conventional Pyrolysis Equipment

The pyrolysis process of EVA occurs in two distinct stages. The first stage, occurring at temperatures between 300°C and 400°C, primarily involves the breaking of ester bonds, releasing acetic acid. The second stage takes place at approximately 400°C to 520°C, during which the remaining organic material undergoes further chain scission, producing a mixture of olefins and alkanes. To ensure complete removal of EVA pyrolysis products, the process can be conducted in an oxygen-containing atmosphere, where decomposition products are oxidized into carbon dioxide.

As the backsheet contains fluorine, its co-pyrolysis with EVA can result in the release of fluorine-containing substances, posing environmental hazards. Thus, removing the backsheet prior to pyrolysis is a preferable approach. For large-scale photovoltaic modules, fixed-bed pyrolysis furnaces are suitable. For continuous batch processing, tunnel kilns are recommended, while fluidized-bed pyrolysis furnaces are effective for granular materials, ensuring more thorough contact between materials and the pyrolysis atmosphere, leading to complete EVA removal.

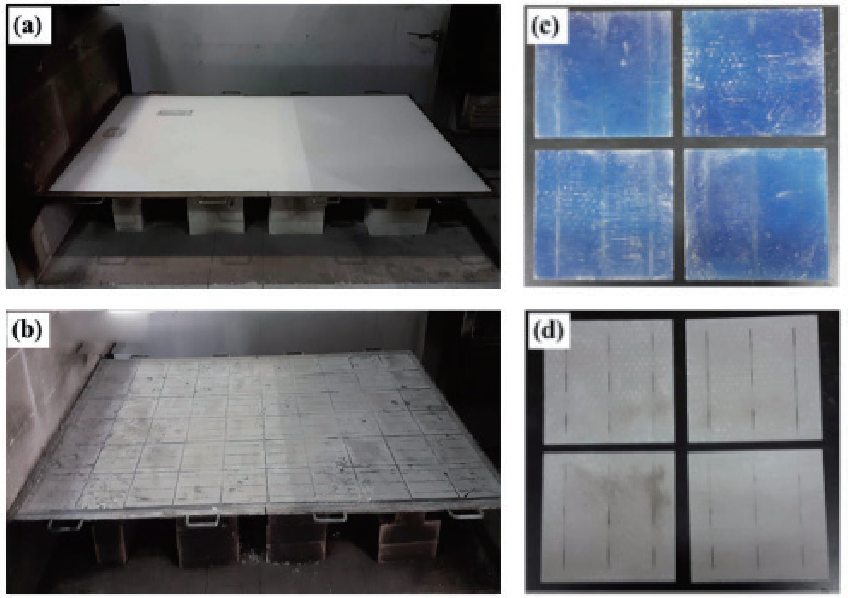


Figure 8-8 PV Panels Before and After Pyrolysis

When the pyrolysis process is well-controlled, it can yield intact glass sheets and solar cells. If the gases generated during the decomposition of EVA lack proper release channels, excessive gas pressure can cause stress shocks that break the solar cells. Similarly, overly rapid heating and cooling rates can induce internal stress in the glass sheets, leading to cracking. Additionally, it is crucial to prevent the carbonization of EVA residues, which could leave carbon contamination on the surface of the glass or solar cells during the pyrolysis process.

(3) Component Separation

Component separation involves the process of recovering metals. The glass sheets and/or encapsulant films obtained from the disassembly of the laminate have relatively homogeneous compositions. However, solar cells and solder ribbons have more complex compositions. For example, in aluminum back-surface field (Al-BSF) crystalline silicon solar modules, which currently dominate market installations, the solar cells consist primarily of silicon wafers. These wafers include a diffusion layer on the front surface, a silicon nitride passivation and anti-reflective coating, silver grid lines, an aluminum back-surface field, an aluminum back electrode, and silver-aluminum grid lines on the back surface. The core material of solder ribbons is copper, with the surface typically coated in a low-temperature alloy, such as a lead-tin alloy.

Improper disposal of PV modules can lead to significant environmental and health risks. Elements such as silver and copper contained within PV modules can gradually leach into the soil through physical and chemical processes, contaminating soil, groundwater, and other environmental media. This contamination can harm vegetation and animals and may ultimately pose a threat to human health through bioaccumulation. Moreover, incineration of waste PV panels can release toxic gases such as sulfur dioxide, hydrogen fluoride, and hydrogen cyanide. These gases can irritate the respiratory system, and prolonged exposure may lead to poisoning and damage to organs like the liver, kidneys, and heart.

Given these risks, the recovery and treatment of metal materials in PV modules are essential. High-value materials such as silicon, silver, and copper offer substantial recycling potential due to their economic worth. For elements like lead and tin, which are present in smaller quantities, the focus should primarily be on environmentally responsible disposal to prevent pollution.

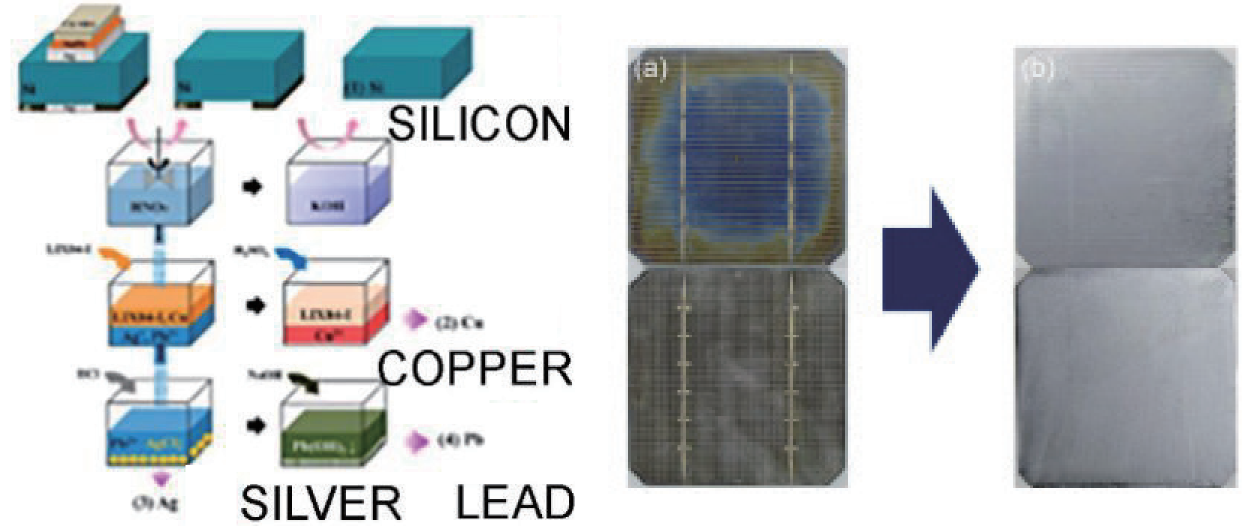


Figure 8-9: Metal Material Recovery

① Silver Recovery

Silver, a precious metal, is found in the metal gridlines on the surface of solar cells. The recovery process begins with reacting silver with nitric acid to produce silver nitrate, transferring the silver into a solution. The silver is then extracted from the solution using one of three main methods: electrolysis, displacement, or precipitation.

② Aluminum Recovery

Aluminum is primarily found on the back surface of crystalline silicon solar cells, including the silver-aluminum gridlines, aluminum electrodes, aluminum-silicon alloy layer, and aluminum back-surface field layer.

One recovery method involves dissolving aluminum components in an alkaline solution to produce aluminum hydroxide, which can be further thermally decomposed into alumina (aluminum oxide). Another approach uses an acidic solution, such as hydrochloric acid, to dissolve aluminum, yielding aluminum chloride. This can be processed further to produce polyaluminum chloride, which is widely used in wastewater treatment applications.

③ Silicon Recovery

To recover high-purity silicon materials or wafers, it is essential to remove all structural layers from both the front and back surfaces of the solar cell. On the front surface, silver gridlines can be dissolved and eliminated using nitric acid. Following this, the silicon nitride passivation and anti-reflective layer are removed with the application of phosphoric acid or hydrofluoric acid. To address the heavily doped silicon diffusion layer, sodium hydroxide is used to etch it away. For the back surface, the silver-aluminum gridlines are similarly dissolved with nitric acid. The aluminum electrode, aluminum-silicon alloy layer, and aluminum-doped back-surface field layer are then etched away using sodium hydroxide. Once these structural layers are removed, semiconductor cleaning processes are employed to thoroughly clean the silicon material or wafer surfaces. The final silicon purity achieved through this method is comparable to the original purity of the wafer.

④ Copper Recovery

Copper is primarily found in solder strips and busbars, often coated with a lead-tin alloy layer. In some cases, it also carries traces of silver from metal gridlines, and its surface may be oxidized. One method for copper recovery is pyro-metallurgical processing. At approximately 800°C, methane gas is introduced to reduce the lead-tin oxide layer on the surface. Due to the low melting point of the lead-tin alloy, it liquefies and flows away from the solder strips and busbars, leaving behind high-purity copper. Another recovery approach involves hydrometallurgical techniques. Suitable solvents, such as hydrochloric acid, dissolve lead and tin into soluble ions, which can then be recovered as chlorides or oxides. Trace amounts of dissolved copper in the solution can be further processed using sulfuric acid or ammonia to convert it into copper hydroxide, which is subsequently dehydrated and thermally decomposed into copper oxide. If silver is present on the surface, it can first be dissolved using nitric acid.

⑤ Lead & Tin Recovery

Lead and tin are mainly found in the silver gridlines of solar cells as well as in the copper solder strips and busbars. The lead in the silver gridlines originates from the glass frit, while the lead and tin in solder strips and busbars come from the lead-tin alloy coating on their surfaces. A typical lead and tin recovery process involves dissolving them using hydrochloric acid or nitric acid, which transforms lead and tin into soluble ions. Subsequently, an alkali is added to precipitate lead as lead hydroxide, which can be thermally decomposed into lead oxide. Alternatively, sodium sulfide can be introduced into the lead-containing solution to form lead sulfide.

Figure 8-10 Demonstration Project for Recycling Decommissioned Crystalline Silicon Photovoltaic Modules (30 MW/year)

8.1.3 Final Disposal

After disassembly and recycling, the non-recyclable portions and low-value waste generated during the process are subjected to final disposal, such as landfilling or incineration.

8.1.4 Comparative Analysis of Current Disposal Methods for Decommissioned PV Equipment

Disposal Methods & Targeted Components		Method Summary	Advantages	Disadvantages	Application Scenarios
Reuse Primarily aimed at decommissioned or damaged units that have reached the end of their service life,these can be repaired and repurposed for downgraded applications in their entirety.		Since some of their functions remain intact, these components can be repaired or refurbished for repeated use.	Enables true circular economy	This is the most ideal method with virtually no drawbacks, but limited by rapid iterations and upgrades. Ultimately, components with no remaining functionality will still require further recycling.	Based on retained functionality, downgraded applications include billboards, decorative buildings, charging stations, bus stops, art installations, and signage.
Recycling Primarily targets non-functional units or production scraps.	Physical Recycling	Also known as Mechanical Crushing. This typically involves shredding, shearing, or rotor crushing, and can also employ high-pressure pulse crushing.	The technology is straightforward and cost-effective.	Typically generating dust, which requires collection and treatment.	The recovered aluminum frames and similar components can be recycled as metallic materials.
	Pyrolysis Method	The pyrolysis chemical reaction at high temperatures decomposes and removes EVA.	It enables the recovery of materials such as glass and solar cells.	EVA cannot be recovered after high-temperature decomposition, and the process generates exhaust gases that require treatment to meet emission standards.	Recycled glass and other materials are utilized in specific fields based on their specifications.
	Chemical Method	Organic or inorganic chemical solvents are used under specific temperature and pressure conditions to weaken the adhesive force of EVA interfaces, enabling the separation of laminate components.	Most of the EVA remains intact and can be recovered.	Typically, strong acidic or alkaline corrosive reagents are used, requiring careful control of the process to manage "three wastes" emissions and prevent secondary pollution.	Recycled glass and other materials are utilized in specific fields based on their specifications.
	Component Separation (Metal Recovery)	Select appropriate chemical processes to recover silver, silicon, aluminum, copper, and lead/tin step by step.	Recovered metals hold considerable economic value.	Typically, strong acidic or alkaline corrosive reagents are used, requiring careful control of the process to manage "three wastes" emissions and prevent secondary pollution.	Recycled metals can be utilized in various fields depending on their specific grades and specifications.
Final Disposal: Primarily targets non-recyclable components and solid waste generated during the disposal process.	Landfilling	Disposed of as solid waste in landfills.	Simple operation and low energy consumption.	Release of harmful gases, significant land usage, and resource wastage.	
	Incineration	Direct combustion or co-processing in cement kilns	Mature technology and the recovery of thermal energy	Generates secondary pollution; low thermal energy utilization value; limited co-combustion ratio; inconsistent elemental content, requiring consideration of cement quality stability.	Thermal energy recovery and the production of cement-based materials.

Table 8-1 Advantages and Disadvantages of Current Disposal Methods for Decommissioned PV Equipment.

8.2 Existing Issues in the Industry

Currently, photovoltaic (PV) equipment recycling technology faces several bottlenecks. Reducing recycling and processing costs while improving economic viability remains a critical challenge for the PV equipment recycling industry. Unlike wind power equipment, PV power stations do not encounter significant dismantling challenges. However, the industry shares similar issues with wind power equipment regarding policy and technological advancement.

First, there is a lack of comprehensive top-level planning and design. Many standards and regulations related to electricity, energy, and environmental protection in various countries do not adequately address PV power generation, let alone the retirement of PV systems. Consequently, existing policies are often not applicable to the recycling and reuse of decommissioned PV modules. While some countries and regions have introduced supportive policies to foster the development of the PV equipment recycling industry, a unified and comprehensive global policy framework has yet to be established.

Second, obtaining decommissioned PV modules poses significant challenges. PV power stations are typically dispersed, particularly distributed systems, and there is a lack of systematic information platforms. This creates information asymmetry between waste generators and recycling enterprises, leading to substantial obstacles in securing sources for recycling.

Third, the recycling technology for decommissioned PV modules remains underdeveloped and costly. Recycling enterprises vary greatly in quality; some employ rudimentary processes without adequately addressing the collection and treatment of "three wastes", resulting in secondary pollution.

Fourth, the economic benefits of the PV equipment recycling industry need significant improvement. On one hand, the low recovery price of decommissioned PV modules often fails to cover recycling and processing costs. On the other hand, the reutilization value of recovered materials remains limited. This lack of profitability diminishes the enthusiasm of many enterprises to engage in PV equipment recycling.

Lastly, the insufficient maturity of the market, coupled with high research and development costs, has resulted in some large-scale production lines operating below full capacity. This underutilization hampers economic benefits and impedes the overall progress and advancement of the industry.

The theoretical scale of decommissioned PV modules and their actual circulation scale currently show a weak correlation. Further research on circulation ratios is needed to clarify the actual supply of decommissioned modules. When examining circulation ratios, attention should be focused on the following influencing factors:

The reuse of decommissioned PV modules is generally influenced by specific conditions. Modules suitable for reuse are typically those with relatively intact appearances, shorter operational lifespans, and relatively stable power generation performance. These modules mainly originate from sources such as power station deconstruction (policy-driven deconstruction, replacement of distributed rooftop photovoltaics), proactive technological renovation pilot projects, and non-critical natural disasters (e.g., water-damaged modules). However, standards and regulations for the reuse of photovoltaic modules are not yet fully developed, and there is currently no precise data on the supply scale of modules available for reuse.

The lifespan and decommissioning of PV modules are influenced by numerous factors, many of which are unpredictable, making it challenging to accurately assess the quantity of decommissioned modules. One key issue is the volume of non-standard decommissioned modules, which often arises in several situations. During production, a certain percentage of modules, estimated at about 0.5% of total output based on industry experience, is scrapped due to manufacturing defects. Additionally, climatic disasters such as sandstorms, typhoons, floods, and earthquakes can cause significant damage to PV modules, leading to unexpected retirements. Furthermore, policy-driven dismantling or proactive decommissioning of power stations may result in modules being decommissioned earlier than expected. These scenarios contribute substantially to the overall volume of decommissioned PV modules. Variability in manufacturing quality among different types of modules and the unpredictable nature of natural disasters and policy shifts further complicate the task of gathering accurate data. As a result, precise statistics for these categories remain difficult to ascertain due to their inherent fluctuations.

Photovoltaic Equipment Recycling Industry

From a technical perspective, the diverse materials and manufacturing methods used in PV modules create significant challenges in developing a universal recycling solution. While the external components, such as aluminum frames and glass, are relatively straightforward to recycle, the internal components containing valuable metals pose greater difficulty. The robust design of PV modules, intended for long-term operation, also complicates their disassembly and recycling. Thermal delamination, widely used industrially, is effective for separating layers but often damages the cells, reducing the market value of recovered silicon. In contrast, chemical or solvent-based delamination methods avoid cell damage but require closed-loop systems that are not scalable for industrial applications. Mechanical delamination, involving processes such as crushing, cutting, peeling, laser irradiation, and eddy-current separation, is commonly used as a preprocessing method. However, these processes often yield materials with low purity, necessitating additional treatment for reuse. This subsequent processing demands specialized, high-energy, and costly equipment, further complicating the economic viability of module recycling.

The economic challenges lie in the direct relationship between the profitability of the recycling process and the quantity and quality of the materials recovered. At a commercial level, recycling can only generate significant revenue if conducted on a large scale. However, even under such circumstances, the revenue often struggles to offset the costs involved. For PV panel recycling to become commercially viable, the cost of recycling per ton of panels must be reduced to approximately $400–500.

The environmental challenges of PV recycling arise from the goal of minimizing the environmental impact of solar panels, while certain recycling processes themselves can have adverse effects. PV recycling may release pollutants into the air, soil, and groundwater. To achieve sustainable recycling, environmentally friendly technologies are essential. However, current methods, particularly during delamination and chemical processing, result in harmful emissions that significantly impact the environment. For example, the decomposition of EVA releases pyrolysis products such as acetic acid, ethane, and propane, which pose serious environmental threats.

Chapter 9
Technologies for the Photovoltaic Equipment Recycling Industry

9.1 Industry Layout and Strategic Planning

The PV equipment recycling industry chain is gradually taking shape and improving. From the recovery and disassembly of PV equipment to the recycling of materials and the manufacture of new products, some companies have already begun to invest in and establish positions within the related industry chain. However, the entire chain remains relatively fragmented and incomplete, requiring further cooperation and coordination. With a significant wave of PV equipment retirements on the horizon and the accelerated development of the renewable energy industry, the challenge of managing large-scale equipment retirements is becoming increasingly urgent. In this context, the key lies in effective industry planning and layout to achieve a green closed-loop development of the renewable energy supply chain. Accelerating the establishment of a comprehensive system for the recycling and reuse of decommissioned equipment is critical to meeting the demands of sustainable development in the renewable energy sector.

The PV industry has established a comprehensive supply chain, encompassing high-purity silicon materials, silicon ingots/rods/wafers, solar cells/modules, PV auxiliary materials, PV production equipment, system integration, and PV product applications. Governments worldwide are actively promoting renewable energy development. For instance, China's Smart PV Industry Innovation Development Action Plan (2021–2025), jointly issued by five ministries, aims to guide the intelligent upgrading of the industry and foster the healthy development of the PV sector.

First, the development of new environmentally friendly materials and components is crucial. PV cell modules form the core of PV systems, with PV cells classified into three main categories: crystalline silicon cells, thin-film cells, and new-concept cells. Crystalline silicon cells, comprising multicrystalline and monocrystalline silicon cells, dominate the market, with monocrystalline silicon cells being the mainstream choice. Thin-film cells, which represent a significant direction in solar cell development, include silicon-based types (such as amorphous silicon, microcrystalline silicon, and low-temperature polycrystalline silicon), compound-based types (such as cadmium sulfide, cadmium telluride, gallium arsenide, copper indium gallium selenide, Group III-V materials, and perovskites), and organic material-based cells. New-concept cells, such as multi-bandgap photovoltaic cells, hot carrier photovoltaic cells, and tandem PV cells, are largely still in the research and development stage.

The diverse and complex materials in PV cell modules present significant environmental risks if decommissioned equipment is not properly managed. To ensure the PV industry continues to thrive while advancing toward sustainable, innovative, and circular development, new materials and technologies are essential drivers. Governments, research institutions, and enterprises must focus on fostering research and innovation, boldly exploring areas such as materials with longer lifespans, improved recyclability, and advanced control systems. Efforts should include reducing or optimizing the heavy metal content in modules and embedding the concept of lifecycle-oriented recycling into the design process from the very beginning.

Secondly, selecting pollution-reducing and carbon-reducing green recycling processes is essential.
To ensure the proper disposal and recycling of decommissioned photovoltaic (PV) modules while maximizing resource recovery efficiency and minimizing environmental pollution, the type and structure of PV modules must be carefully analyzed. This targeted approach allows for the selection of the most appropriate recycling processes, effectively reducing the generation of secondary pollutants and lowering carbon emissions.

Thirdly, distributed PV construction requires comprehensive coordination.
In the distributed PV sector, project developers must thoroughly understand project compliance requirements and contract execution processes. This includes mastering relevant regulations and assessing associated risks, such as reviewing key documents like project filings, environmental impact assessments, grid connection approvals, and construction-related permits. Ensuring the completion and proper operation of projects depends on meticulous attention to these critical aspects.

9.2 Environmental Requirements

Firstly, it is essential to define recycling responsibilities. In line with international practices and national laws and regulations, manufacturers, sellers, or users of photovoltaic (PV) modules must bear certain recycling obligations. This requires relevant companies to take responsibility for the collection and processing of PV modules at the end of their lifecycle.

Secondly, it is crucial to establish a comprehensive PV module recycling network. This network should enable consumers and businesses to return used PV modules to professional recycling facilities. Such a system will enhance recycling efficiency and help mitigate the environmental impact of discarded PV modules.

Thirdly, green production and operation are essential across all stages of the PV recycling industry chain. This involves reducing energy consumption and environmental pollution by using clean energy in manufacturing, optimizing production processes, and enhancing waste management practices.

Lastly, improving recycling technical standards is crucial. The recycling of PV modules must adhere to established technical guidelines to ensure safety and environmental protection throughout the process. This involves employing recycling methods that are harmless, resource-efficient, and minimize waste, thereby avoiding harm to the environment and human health.

In summary, the environmental requirements of the global PV recycling industry encompass various aspects, including the recycling and processing of PV modules, material reuse, environmentally sustainable industrial development, and policy and legal support. These requirements aim to advance the eco-friendly growth of the PV recycling industry, promote resource conservation and circular utilization, and protect the ecological environment.

Chapter 10
Case Studies and Emerging Technologies

European Union

In 2007, the European Union established PV CYCLE, a dedicated organization for the recycling and reuse of crystalline silicon PV modules. This organization provides comprehensive end-of-life PV module recycling and reuse services to businesses. It collaborates with logistics and transportation companies, as well as other partners, to build a robust recycling network. PV CYCLE operates on a membership basis, allowing global industry organizations, associations, and enterprises to apply for membership. Upon paying membership fees and processing costs, PV CYCLE assists member organizations in recycling and processing end-of-life PV modules. It also offers recycling and reuse services to members and their end customers, supporting members in fulfilling their corporate responsibilities. The fees charged to member organizations depend on the specific policy and regulatory requirements of each country and the market scale. Typically, larger market shares incur higher fees. Currently, PV CYCLE's membership covers over 90% of the European market, with hundreds of collection points for end-of-life PV modules across Europe. Since its official launch in 2010, PV CYCLE has processed over 60,000 tons of end-of-life crystalline silicon PV modules, including approximately 17,000 tons in 2021 alone.

China

Nantong Riyixin Environmental Protection Technology Co., Ltd. has developed a comprehensive recycling production line for disassembling and utilizing discarded crystalline silicon PV modules. The process is designed based on a combination of physical methods and two stages of wet chemical methods (Wet Method 1 and Wet Method 2). The physical method involves removing junction boxes and aluminum frames, separating glass from the laminate, and crushing the laminate into block materials suitable for Wet Method 1. This step recovers aluminum, copper, backsheet materials, glass, and silicone from the PV modules. Wet Method 1 focuses on separating EVA films from the laminate and extracting the solar cells, enabling the recovery of EVA and the intact cells. Wet Method 2 is dedicated to further refining and purifying valuable components like silver, aluminum, and silicon from the solar cells. Starting in 2023, the company has been upgrading the initial production line as part of a phase-one enhancement project. Upon completion, the production line is expected to achieve an annual capacity of 80,000 tons. The optimized and upgraded process aims to improve the overall recovery rate to over 95%.

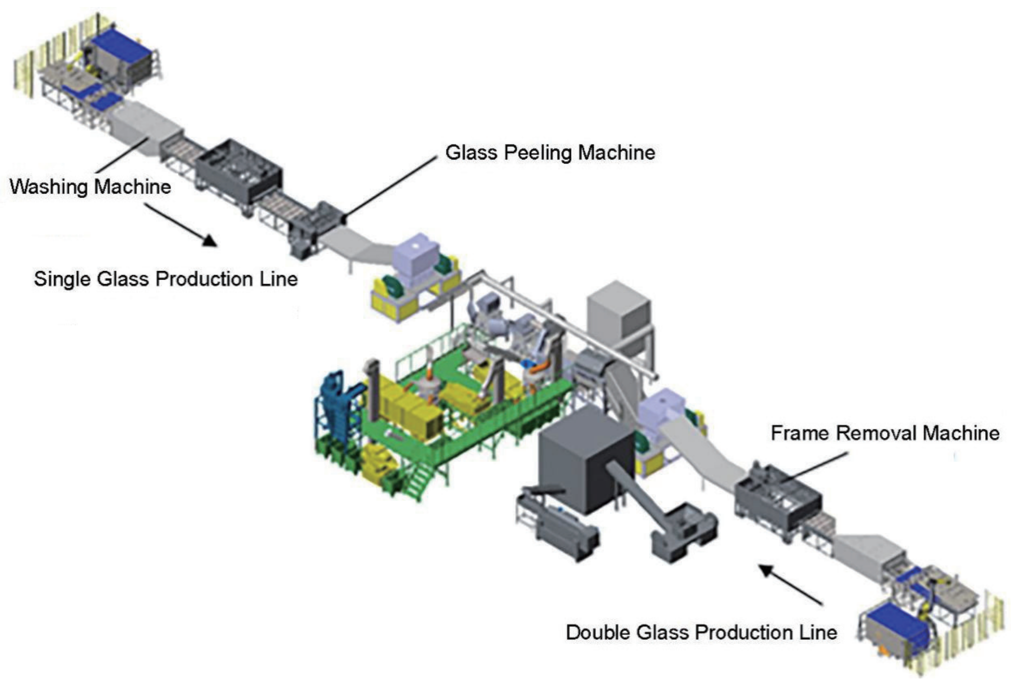


Figure 10-1: Photovoltaic Recycling Production Line

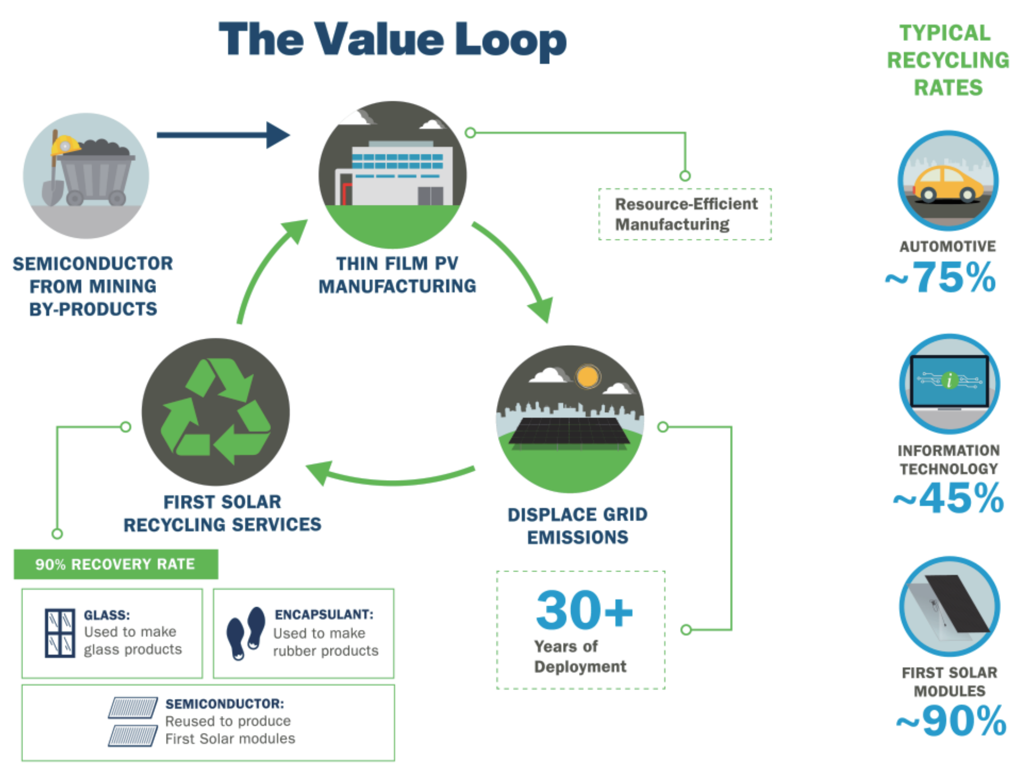
RESOLAR Energy Technology (Shanghai)Co., Ltd. has developed proprietary technology combining "physical disassembly, chemical separation, thermal separation, and wet impurity removal" to recycle decommissioned or production-defective PV modules. This innovative process extracts high-purity regenerated silicon materials, including 6N-grade silicon suitable for direct use in PV wafer production, achieving true green closed-loop recycling. The company has completed the construction of a large-scale production line in Fengyang, Anhui Province, capable of recycling over 10,000 tons of PV modules annually. The facility recovers approximately 5,000 tons of factory-grade solar cells, producing 3,500 tons of silicon ingots and manufacturing 200–300 million wafers and solar cells each year.

To address the issue of low-purity glass powder from traditional PV recycling methods—often contaminated with silicon powder, EVA film, and other impurities—the production line applies self-adaptive frame disassembly and initial crushing of PV glass. Using a proprietary wet separation solvent developed by the team, the EVA film is efficiently separated, achieving PV glass with a purity exceeding 99.9%. For silver recovery, traditional techniques often yield silver powder mixed with silicon, glass, and other metal powders, resulting in low purity. The company has developed an integrated heat treatment and annealing furnace with atmospheric control to thermally separate solar cells from busbars. This is followed by a chemical silver recovery process that produces high-purity silver ingots. The recovered pure silver has significant value, and the process is characterized by maturity, low losses, and high efficiency.

United States

One of North America's largest photovoltaic and wind power developers, EDF Renewables North America, has announced a partnership with solar recycling company Solarcycle to recycle damaged or broken solar panels. EDF Renewables North America specializes in the development and construction of onshore and offshore wind and solar photovoltaic systems. As a clean energy company, it is committed to advancing the recycling of clean energy assets, starting with photovoltaics. Solarcycle's proprietary technology can recover 95% of the value from recycled panels, including silver, silicon, copper, aluminum, and glass.

In the United States, the scale and experience of recycling crystalline silicon and thin-film PV modules differ. First Solar, the world's largest PV recycler, has seen continuous growth in its performance over recent years. The company has a recycling capacity of 150 metric tons per day for its thin-film CdTe PV modules in the U.S., achieving a recovery rate of 90% for bulk and specialty materials from decommissioned CdTe photovoltaic modules.



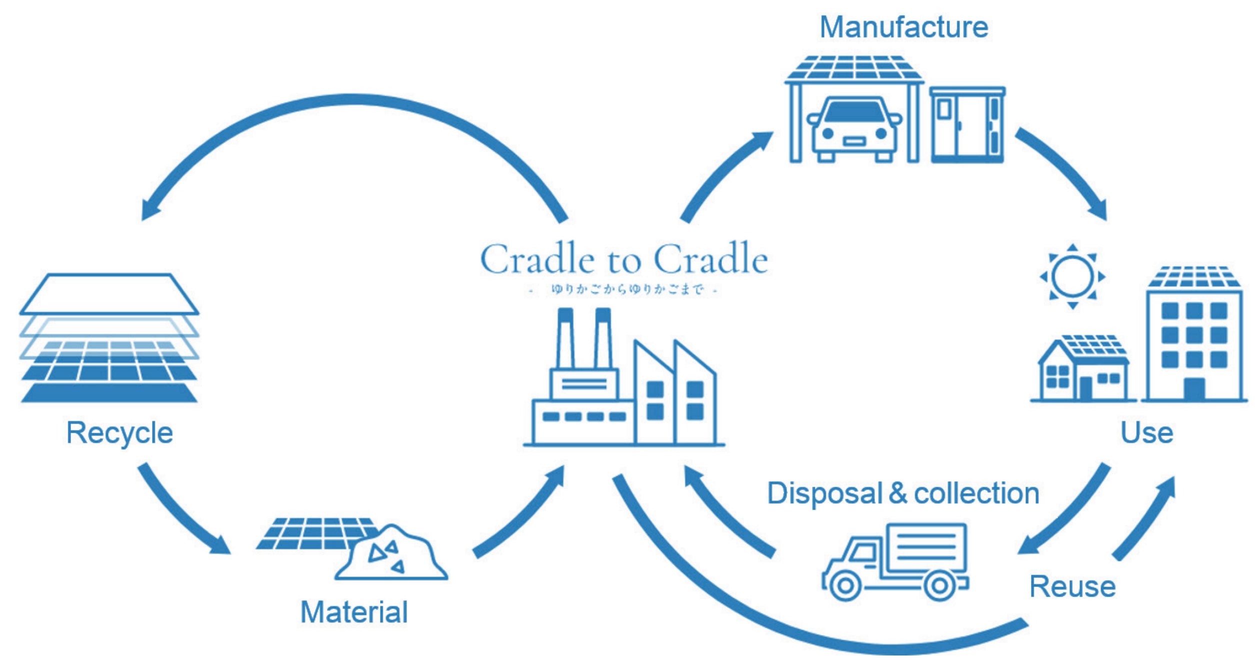
For every product sold, First Solar allocates a specific percentage of its sales revenue into a recycling fund, which is managed by an independent third-party organization. When any customer owning First Solar PV modules requests recycling services at the end of the product's life, the recycling company established by this third-party fund undertakes the collection and bears the cost of recycling and reusing the products.

Because the recycling fund operates independently of First Solar's financial status, it ensures that all PV modules are fully recycled and not discarded irresponsibly after their service life ends. Furthermore, the recycling company established by the fund refines the collected PV modules and resells certain rare materials, such as tellurium, back to First Solar for reuse in manufacturing.

Japan

The PV REBORN Association (Nishiawakura Village, Okayama Prefecture) and Niimi Solar Company (Niimi City, Okayama Prefecture) have announced the successful development of a pyrolysis system capable of recycling approximately 95% of solar panels into new panels. This innovation is poised to become a powerful measure to reduce waste, especially in anticipation of a significant increase in discarded panels during the latter half of this century. The PV REBORN Association aims to achieve "circular regeneration" of solar panels by restoring discarded panels into their original materials and using advanced technologies to fabricate more efficient panels for long-term use. The association plans to achieve practical implementation and mass production by 2027 and will continue research and development efforts. The system's first unit is scheduled for delivery in June, with expectations of handling the influx of end-of-life solar panels from the 2030s. The pyrolysis unit is an environmentally friendly system that does not emit carbon dioxide, making it a viable solution for industrial waste processing companies and others

seeking effective waste management solutions. Operating continuously 24 hours a day, the system can process 200 discarded panels per day (each panel measuring up to 2.5×1.5 meters) or over 50,000 panels annually. This capacity is equivalent to recycling waste from about 10 large-scale solar power plants. Moreover, recycling one ton of discarded solar panels can reduce greenhouse gas emissions by 1.2 tons.



Marubeni Corporation and Next Energy are collaborating to leverage blockchain technology for recycling discarded solar panels. Blockchain technology enables the inspection of solar panels while providing data on traceability and the components used. This system also verifies whether the data has been altered or tampered with, facilitating the reuse trade of solar panels, panel recycling, and the circular utilization of raw materials, while reducing the amount of waste sent to landfills. Since 2005, Next Energy has been engaged in the solar PV recycling sector. The company's inspection of over 40,000 discarded solar panels revealed that, even after 25 years of use, these panels retained 80% of their performance. Additionally, the company contributed to drafting resale guidelines for solar panels under development by the New Energy and Industrial Technology Development Organization (NEDO).

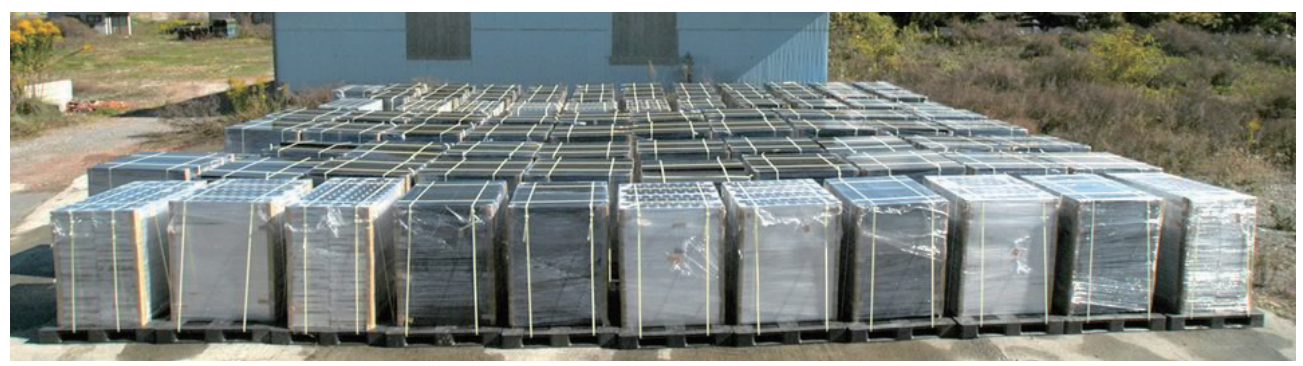


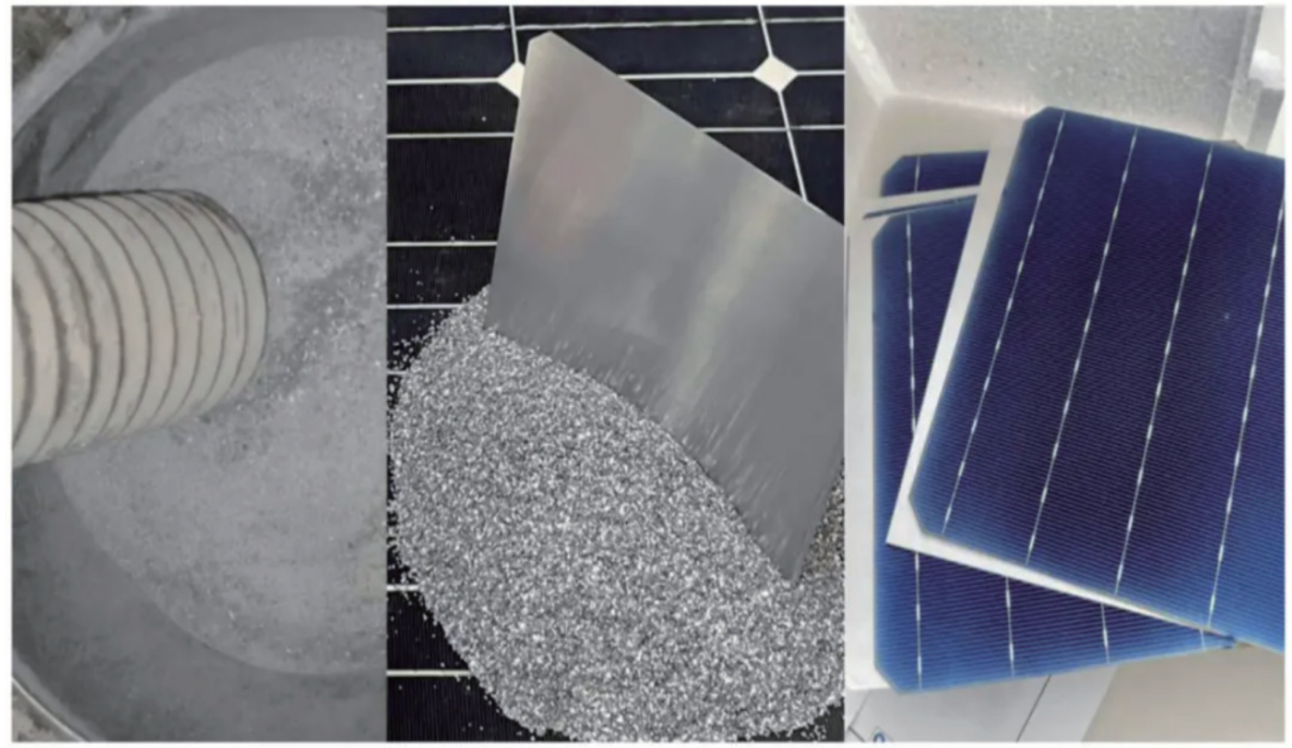
Figure 10-3: PV Recycling Center

Germany

In Germany, the recycling, regeneration, and reuse of decommissioned photovoltaic modules are managed by specialized service providers. The recycling of crystalline silicon photovoltaic modules is predominantly carried out by glass recycling companies, such as Reiling Unternehmensgruppe. The recycling of cadmium telluride PV modules is handled by First Solar at its facility in Frankfurt.

Figure 10-5: Geltz Umwelt-Technologie Equipment

Geltz Umwelt-Technologie has developed a pyrolysis-based solar recycling system, successfully creating a testing unit for solar module recovery. Given the close integration of PV modules with polymers, separating individual panel components for recycling presents significant challenges. The company identifies breaking down the polymer layer as the critical step in the recycling process. Through a controlled pyrolysis process, unwanted polymer layers are melted away, enabling the separation of glass from the panel structure. Fine materials are further segregated using sieves and air classifiers. This approach allows for the effective recovery of aluminum, glass, silver, copper, tin, and silicon. To address the issue of exhaust gases generated during the process, the team employs a thermal afterburner equipped with a gas scrubber cooling system, ensuring that the entire solar lifecycle, from power generation to recycling, adheres to green technology principles. Geltz reports that these recycled materials hold the potential to become valuable sources for future metal raw materials. The innovative system is estimated to process 50,000 PV modules annually, achieving a 95% material recovery rate. Research indicates that each pyrolysis cycle can handle 1 ton of discarded photovoltaic modules, effectively addressing the challenges associated with difficult-to-recycle solar components.



The Fraunhofer Institute for Solar Energy Systems (ISE) in Germany has developed an innovative process to produce PERC solar cells using 100% recycled silicon from discarded PV modules. This advanced recycling method is capable of handling all types of crystalline silicon solar PV modules, regardless of the manufacturer. The process begins by separating solar cell fragments from the byproducts of mechanical recycling. Silicon cell fragments are then liberated from the surrounding glass and plastic materials. Through a series of wet chemical etching steps, the process removes back contacts, silver contacts, and anti-reflective layers from the silicon. The purified silicon is subsequently processed into monocrystalline or quasi-monocrystalline ingots, which are then sliced into wafers. The resulting PERC solar cells achieve a conversion efficiency of 19.7%. While this efficiency is lower than the 22.2% typical of premium modern PERC solar cells, it is notably higher than the efficiency of cells found in older, discarded PV modules. According to Fraunhofer ISE, approximately 10,000 tons of silicon from decommissioned solar PV modules enter the German recycling market annually. This figure is projected to rise significantly, reaching hundreds of thousands of tons per year by the end of the century. This breakthrough contributes to the sustainable lifecycle of solar technology by effectively integrating recycled silicon into high-performance solar cells.

In September 2021, Siemens Gamesa officially launched the "RecyclableBlade," a fully recyclable wind turbine blade. This innovative blade design was first utilized at the Kaskasi offshore wind farm in Germany, developed by RWE, and equipped 8 MW turbines with 81-meter-long blades. By May 2023, Siemens Gamesa confirmed that the RecyclableBlade would be deployed on a larger scale at the Sofia offshore wind project in the United Kingdom. Of the 100 SG 14-222 DD turbines planned for the project, 44 will feature 108-meter-long fully recyclable blades, amounting to 132 sets in total. This represents a significant step forward for the wind energy industry in achieving sustainability and circularity in turbine blade production and usage.

Spain

In March 2022, LM Wind Power, a subsidiary of GE Renewable Energy, successfully designed and manufactured the first 100% recyclable thermoplastic blade at its Ponferrada facility in Spain. This achievement followed nearly a year of material development and testing, supported by sub-component level process trials conducted with alliance partners. Unlike conventional blades, blades made from thermoplastic resin can be easily recycled by heating them to high temperatures or through depolymerization reactions, which liquefy the solid resin. This process enables complete separation of glass fibers from the resin, significantly reducing recycling costs and facilitating material circularity.

With the support of GE Renewable Energy, Endesa and PreZero Spain plan to establish the first wind turbine blade recycling plant on the Iberian Peninsula.

Figure 10-6: Wind Turbine Blade Storage at As Pontes Warehouse (A Coruña).

The new recycling plant will be located in Cubillos del Sil (León province) and is part of Endesa's Compostilla industrial complex redevelopment plan. This initiative, recently approved by the Ministry for Ecological Transition and the regional government of Castile and León, addresses the challenge of recycling over 6,000 tons of fiberglass and carbon annually from wind turbine blades. By adhering to circular economy principles, the project aims to give a second life to blade materials. The project is being implemented by Endesa and PreZero Spain, with GE Renewable Energy and its subsidiary LM Wind Power participating as suppliers of blades and fiberglass.

The project is led by Endesa and PreZero Spain, with GE Renewable Energy and its subsidiary LM Wind Power participating as suppliers of blades and fiberglass.

South Korea

In 2021, the Korea Institute of Energy Research (KIER) developed a cost-effective method for processing decommissioned crystalline silicon PV modules, aiming to recover intact crystalline silicon solar cells and metallic materials. The method involves first placing the module's aluminum frame in a furnace and heating it to 500–550°C with air. At this temperature, the EVA layer within the module oxidizes and decomposes, allowing the separation of the glass sheet from the crystalline silicon solar cells, enabling glass recovery. Subsequently, acid washing with nitric acid retrieves the intact crystalline silicon solar cells. The solution resulting from the acid wash contains copper and silver ions, which can be further processed to recover various metals. This technology has successfully refined 72 decommissioned solar panels into 6-inch monocrystalline ingots and wafers, which are then used to manufacture solar cells with a power conversion efficiency of 20.05%, outperforming conventional commercial solar cells. Currently, the research project by KIER has received support from Korea's Ministry of Trade, Industry, and Energy (MOTIE) and the Korea Institute of Industrial Technology (KITECH).

Promoting the recycling of decommissioned wind and PV equipment is of significant importance. Effective utilization of recycled materials such as scrap steel, non-ferrous metals, and waste glass not only conserves resources and reduces dependence on virgin raw materials but also mitigates land use and environmental risks associated with improper disposal. This approach can yield considerable economic returns. With the accelerating global energy transition and widespread adoption of renewable energy, the market demand for wind and PV equipment recycling is expected to grow steadily. The field offers vast opportunities for technological innovation, attracting numerous enterprises and research institutions to invest in development and innovation. Governments worldwide are increasingly supporting policies that encourage the recycling of wind and PV equipment, creating a favorable environment for business growth and sustainable industry development.

In conclusion, the global wind and PV equipment recycling industry holds immense market potential and promising development prospects. Facing shared challenges and opportunities, it is essential for governments, enterprises, and research institutions across the globe to strengthen collaboration and innovation. Together, they can drive the healthy and sustainable development of the wind and PV equipment recycling industry.

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