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ESG Value Blind Spots and Sustainable Development Paths of Photovoltaic Module Recycling

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Abstract. As the world's photovoltaic (PV) industry develops at a fast speed, the abandoned amount of PV modules also increases yearly. How to recycle them has become an important issue in the environmental, social, and governance (ESG) field. However, there are many blind spots in the ESG value of the current PV module recycling process. These include environmental risks, threats to workers' health, and imperfect policies. Based on the latest industry data, this study uses literature review and case analysis to examine the current state of PV module recycling and its ESG blind spots. It also proposes suggestions for sustainable development paths. The results show several environmental problems in PV module recycling. For example, the recovery rate of high-value materials is low. There is also heavy metal pollution and secondary pollution caused by chemical treatments. At the social level, workers face high health risks, and public awareness is insufficient. At the governance level, the policy system is incomplete, and responsibility boundaries are unclear. Further analysis shows that improving policies and regulations, enhancing social awareness and corporate technological innovation are the keys to addressing ESG blind spots. This study provides theoretical support and practical guidance for the sustainable development of the PV industry.

Keywords: photovoltaic module recycling, ESG, sustainable development

1. Introduction

1.1. Research background and research topic

The transformation of global energy structures has greatly promoted the fast development of photovoltaic (PV) industry which is one of the main branches of renewable energies. According to the International Energy Agency, by 2024, the proportion of power generation from PV reaching global electricity consumption will overtake 10% for the first time. This fully shows the importance of PV industry to global energy transformation. However, the typical lifetime of PV module is 25-30 years. The first batch installed at an early date have reached the end of their lifespan and will soon enter the phase of large-scale dismantling. It is expected that more than a million tons of PV module would be scrapped worldwide each year by 2030 and that amount will increase up to over ten million tons before 2050 [1]. Such a huge amount of waste, if not handled properly, will cause serious pollution to the environment and also mean a waste of a great deal of valuable resources.

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However, the current global recycling system for PV modules is not well-developed, especially within the environmental, social and governance (ESG) framework, whose value has not been fully exploited and recognized [2]. Many enterprises have ESG value blind spots in the process of PV module recycling. These blind spots not only hinder the sustainable development of the PV industry but also pose new environmental risks.

1.2. Research purposes and implications

Although the PV industry is widely regarded as a representative of green energy, the problem of waste management at the end of its life cycle has long been neglected, casting doubt on the actual sustainability of this green industry. Improper recycling of PV modules can not only lead to a waste of resources but also cause secondary pollution, which contrasts sharply with the original intention of environmental protection [1]. Therefore, this study focuses on the ESG value blind spots of PV module recycling, aiming to reveal the environmental, social and governance issues that have been overlooked in current recycling practices, and to explore how the global PV industry can achieve a true green cycle through the three dimensions of policy, society and firm.

1.3. Research methods and research framework

This study was systematically conducted using a combination of literature research and case analysis. In terms of literature research, a comprehensive review of academic literature, policy texts and industry reports related to PV module recycling at home and abroad was conducted, aiming to clarify the overall situation and key issues of PV module recycling at present and to build the theoretical basis of this study. In terms of case studies, representative PV module recycling firm in the industry were selected as research subject to deeply analyze their specific practices at the ESG level, summarize its successful experiences and existing deficiencies, and then extract universal paths and strategies that can be promoted and reused. Through the comprehensive application of the above methods, this study aims to provide solid empirical evidence and theoretical support for identifying ESG value blind spots in PV module recycling and exploring sustainable development paths.

2. Literature review

2.1. The current state of the global photovoltaic industry

The global PV industry has seen explosive growth in recent years. By the end of 2024, global cumulative installed capacity of solar power had significantly exceeded 2.2 terawatts, compared with 1.6 terawatts in 2023, with new installed capacity of solar systems exceeding 600 gigawatts, according to the International Energy Agency. This rapid growth has brought significant environmental benefits, with PV power generation reducing carbon emissions significantly over the entire life cycle compared to traditional fossil fuels [2]. However, there is a crisis behind the industry boom, as early installed PV modules have begun to enter the decommissioning period, and China alone is expected to produce 1.4 million tons of decommissioned modules by 2030 [3]. More importantly, the early-loss scenario takes into account damage to the components during transportation, installation, or operation, as well as premature replacement due to economic incentives such as new technology iterations, which may result in the actual lifespan of the components being less than the expected 25-30 years [4]. This will further intensify the pressure of future recycling.

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2.2. ESG concepts and environmental sustainability

The ESG framework is an important tool for assessing the sustainability performance of firms. Its core concept emphasizes that enterprises should pursue economic benefits while taking into account environmental protection, social responsibility and effective governance [5]. In the environmental dimension, ESG requires firms to reduce resource consumption and promote a circular economy, which is highly consistent with the green attributes of the PV industry. However, environmental blind spots such as heavy metal pollution and resource waste in PV module recycling expose the shortcomings of current ESG practices in end-of-life management [6]. The social dimension involves labor rights and community impact, while the governance dimension needs to address issues such as policy fragmentation and ambiguous responsibility subjects. By integrating these elements, PV module recycling is expected to transform from a "green blind spot" into a model of sustainable development.

3. The current state of photovoltaic module recycling and ESG value blind spots

3.1. Recycling status in the photovoltaic industry

The core components of PV power generation systems are composed of a variety of materials, among which the main materials such as glass, metal and semiconductor have high recycling value, while certain special composite materials still face challenges in recycling treatment [1]. The current global PV recycling industry shows a polarized pattern, with significant regional differences. Developed countries such as the European Union and the United States lead in policy and technology, while developing countries represented by China still face the challenge of scaling up. Technically, existing recycling methods include mechanical recycling, chemical recycling, and thermal recycling, etc. Recovery rates are generally between 60% and 90%, but there are common problems such as low material purity and environmental pollution, and the economic feasibility is insufficient due to high energy consumption, complex processing or transportation costs [2,7]. According to industry research, the recycling and processing cost of each ton of solar panels is approximately $800 to $1,200, while the procurement cost of the same weight of raw materials is only $600 to $900, resulting in serious cost inversion.

3.2. The ESG value blind spot of photovoltaic module recycling

3.2.1. Environmental blind spots

The environmental risks of PV module recycling mainly stem from resource waste and secondary pollution. PV modules contain high-value materials such as silicon, silver, and copper, but current recycling technologies are generally less efficient in recovering these materials. For example, silver, the most expensive material, accounts for only 0.03% of the module's weight but 47% of the total value, but the existing recycling process is difficult to recover efficiently, resulting in low resource recycling efficiency [4]. Even worse, heavy metals such as lead and cadmium contained in the components may pollute the environment through soil and groundwater if not properly treated [8]. And the various acidic substances such as nitric acid and hydrofluoric acid used in the chemical recycling process, if not properly treated, will produce toxic waste liquid, causing irreversible damage to the environment [2].

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3.2.2. Social blind spots

Blind spots at the social level are mainly manifested in the health risks of practitioners and the lack of public awareness. When discarded PV modules end up in landfills, their silicon-based materials and accessory components may release chemicals that are harmful to human health. Research data show that the silicon wafer portion contributes nearly 95% to the assessment of the material's toxic impact on humans. Workers in informal recycling plants in developing countries are often directly exposed to toxic substances such as lead and cadmium and lack the necessary protective equipment, resulting in workers' direct exposure to toxic substances [2]. Moreover, the noise and dust pollution generated by component cracking devices during operation also pose a threat to workers' health. At the same time, public awareness of PV module recycling is limited, and most enterprises in developing countries are unaware of the environmental hazards of discarded modules. This cognitive gap leads to a large amount of waste modules being disposed of at will, further amplifying the health risks. Research in Ningxia shows that discarded components are often piled up at power stations or simply disposed of, exacerbating environmental risks in communities [1].

3.2.3. Governance blind spots

Governance blind spots are particularly prominent in developing countries. In developing countries, there is a general lack of specific regulations for the management of PV waste, resulting in unclear recycling responsibility subjects and low recycling rates. China, India and other major PV countries lack mandatory recycling regulations, and India only requires developers to "properly handle" waste without specific standards [4]. None of the developing countries have established mandatory recycling systems similar to the EU's Waste Electrical and Electronic Equipment Directive, nor have they fully implemented the extended Producer Responsibility system [9]. This policy gap has led to large amounts of waste components being landfilled or disposed of informally, increasing the risk of environmental leakage of toxic substances such as lead and cadmium.

4. A case study of typical firm photovoltaic module recycling

JinkoSolar Holding Co., Ltd. was among the first domestic companies to develop PV module recycling technology in China. So as a leader in the industry, JinkoSolar's recycling practices are typical.

At the technical level, a representative of JinkoSolar said that the company mainly focuses on two key tasks in the field of PV module recycling. On the one hand, it is committed to the continuous innovation of production processes and recycling technologies to enhance the processing capacity of PV modules of different specifications. On the other hand, actively build a complete recycling network system to achieve efficient utilization and value enhancement of recycled materials by leveraging the company's existing supply chain resources [3]. The company continues to explore end-of-life recycling and reuse technologies. JinkoSolar employs environmentally friendly and efficient recycling processes, such as using green solvents to separate the glass and bonding layers in PV modules, which not only avoids the high pollution risks of traditional chemical methods but also ensures the complete recycling of solar cells. At the same time, the company has significantly improved the recycling efficiency by optimizing process parameters such as temperature and cutting size and combining ultrasonic assisted technology. In addition, JinkoSolar is exploring pyrolysis technology, which decomposes residual materials at high temperatures to

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efficiently recover valuable resources such as silicon and silver while reducing energy consumption [10].

At the policy level, a person in charge of JinkoSolar has also said that a major development bottleneck for the PV module recycling industry lies in the lack of relevant policies, regulations and industry standards. The lack of such a standardized system objectively restricts the healthy and orderly development of the field [3]. As a result, JinkoSolar has been committed to promoting the establishment of recycling standards and the release of related policies and advancing the harmless and compliant treatment of retired components through recycling and reuse. As of now, JinkoSolar has been involved in drafting industry standard documents related to PV recycling, such as "Physical Method for Recycling and Treatment of Crystalline Silicon PV Modules" and "General Technical Requirements for Recycling and Reuse of Crystalline Silicon PV Modules", contributing a lot to the establishment of standards and policies for China's PV recycling system.

5. Sustainable suggestions for photovoltaic module eecycling

5.1. Policy level

At the policy level, improving the regulatory system and clarifying the responsible entities are the keys to promoting the recycling of PV modules. Developing countries can draw on the EU's Waste Electrical and Electronic Equipment Directive and the Extended Producer Responsibility system to establish mandatory recycling regulations that require PV module manufacturers, importers and users to jointly undertake recycling obligations [9]. At the same time, enterprises can be encouraged to participate in recycling through preferential policies such as financial subsidies and tax breaks to reduce operating costs [11]. It is also crucial to promote standardization and accelerate the development of unified technical standards for PV module recycling, covering material classification, processing procedures and environmental protection requirements, with reference to industry standards drafted by industry leaders such as JinkoSolar, to provide a normative basis for the global recycling system.

5.2. Social level

At the social level, raising public and industry awareness is an important step to eliminating ESG blind spots. By conducting public education campaigns to popularize the environmental risks and recycling value of discarded PV modules, the current situation of random disposal can be changed. At the same time, strengthening the training of workers to ensure that recycling workers master safety operation norms and avoid direct exposure to toxic substances such as lead and cadmium is a core link in safeguarding the health of workers. In addition, an information-based supervision platform can be built to track the entire life cycle of PV modules. Ningxia's proposal to establish a dynamic database and carbon footprint verification platform based on the advantage of the "National New Energy Comprehensive Demonstration Zone"can provide a reference management model for the world [11].

5.3. Firm level

On the company level, firm-level technological innovation and process optimization enhance recycling efficiency, firms may combine the physical and chemical means by taking apart and sorting parts so that the recycled materials will be more pure or green solvents can be used to reduce pollution during the chemical processing, and more valuable reuse paths could be found like

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converting recycled silicon wafers into new component parts, which would achieve maximized resource efficiency [12]. Finally, firms should also implement the concept of ESG, issue the company's periodic recycling reports, and release data of resource recovery rate, emission reduction etc., making recycling a transparent and safe process.

6. Conclusion

With the rapid development of the global PV industry, the issue of PV module recycling has become a key factor affecting the sustainable development of the industry. This study, through a systematic analysis of the current status of PV module recycling and ESG value blind spots, reveals the environmental risks, social challenges and governance deficiencies existing in the current recycling system. The study found that although the PV industry is regarded as a representative of green energy, there are still shortcomings in waste management at the end of its life cycle, which not only causes resource waste but may also cause secondary pollution, contrary to the industry's original intention of environmental protection.

At the environmental level, the current recycling technologies have relatively low efficiency in recovering high-value materials, and there are risks of heavy metal leakage and toxic waste liquid pollution during the chemical treatment process. At the social level, informal recycling operations in developing countries pose a serious threat to workers' health, and the public's lack of awareness of PV module recycling further exacerbates random disposal. At the governance level, policy fragmentation and ambiguous accountability are the main obstacles to increasing recycling rates, especially in regions lacking mandatory regulations and extended producer responsibility systems.

By analyzing the practice cases of leading enterprises, this study summarizes the experiences that can be drawn upon, including the continuous optimization of technology and processes, the promotion and use of green solvents, and the active attempts of enterprises to participate in standard setting, providing feasible directions for improvement for the industry.

However, there are some shortcomings of this paper: Firstly, cases in the report focus on several key businesses but do not involve many small and medium-size companies or regional differences in actual practices, which may decrease the generalizability of the conclusion. Secondly, the data for analysis is mainly taken from the industry report and secondhand information instead of the primary research information collected from field investigation and questionnaire survey.

In the future, more in-depth research can be done by expanding the sample size, conducting more on-site investigation and questionnaire surveys, while future studies might also focus on technological innovation, policy interaction, and social concerns. In addition, developing metrics that quantify ESG performance will help the industry set clear sustainability goals, as PV module recycling is not just a technical issue, but an indispensable ethical and governance topic in the global green energy transition. Only through multi-party collaboration can the PV industry make a real leap from "green power generation" to "green loop" and make greater contributions to global sustainable development.

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