Unlocking multifaceted benefits of photovoltaic recycling via global collaborative efforts

Hou Jiang,[1] Ling Yao,[1,*] Jun Qin,[1] Rui Zhu,[2] and Chenghu Zhou[1,*]

[1]Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

[2]Institute of High Performance Computing (IHPC), Agency for Science, Technology and Research (A*STAR), Singapore 138632, Republic of Singapore

*Correspondence: yaoling@lreis.ac.cn (L.Y.); zhouch@lreis.ac.cn (C.Z.)

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Since 2010, the dramatic decline in photovoltaic (PV) panel prices, coupled with robust governmental support, has propelled global deployment of solar PV systems to a cumulative capacity of 1.6 TW as of 2023. However, as the installed PV systems approach the end of their 20–25-year service life, the substantial waste generated during their decommissioning presents a critical challenge. Recycling, the "last mile" in establishing a circular PV industry (Figure 1A), becomes crucial and should be urgently prioritized as a linchpin in the transition to a sustainable, economically viable, and renewables-based future. The International Renewable Energy Agency (IRENA) underscores the urgency of PV recycling, projecting that waste from retired PV modules will surge to 8 million tons by 2030 and escalate further to 78 million tons by 2050,[1] with China, the USA, Japan, India, and Germany leading the market (Figure 1B). Recycling decommissioned PV modules is anticipated to unlock significant economic, environmental, and social benefits (Figure 1C). However, realizing the transformation from waste to wealth necessitates global collaborative efforts and substantial actions, focusing on innovative recycling technologies, supportive policies, and clear directives.

BENEFITS OF PV RECYCLING

PV recycling creates significant economic value

Recycling PV waste unlocks a substantial stock of raw materials (approximately 76% glass, 10% polymer, and 8% aluminum), along with other valuable components, including semiconductor and rare metals such as silver, indium, and gallium (Figure 1A). This represents a largely untapped opportunity for creating secondary value and exploring new economic avenues. It is estimated that reinjecting the recoverable materials into the economy could generate a global economic value of about $15 billion by 2050.[1] Recycling also reduces the costs of producing new PV modules by lessening their reliance on raw materials and sidesteps the expenses associated with end-of-life management of PV panels. Moreover, the emerging PV recycling industry extends the value chain of PV modules and enhances the overall competitiveness of the PV sector, thereby contributing to local economic growth.

PV recycling offers substantial environmental benefits

The haphazard disposal of decommissioned PV modules typically causes

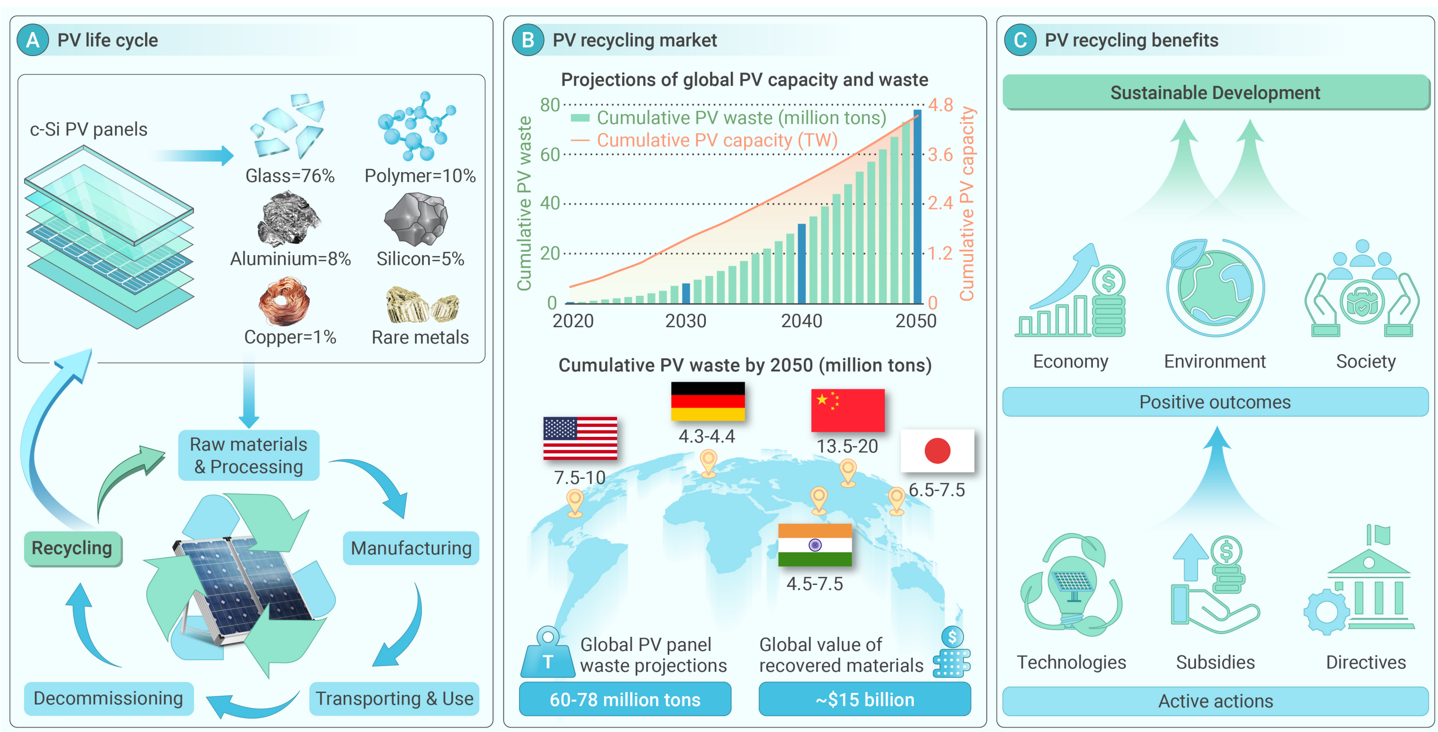

Figure 1. An overview of global PV recycling (A) Recycling facilitating a circular PV industry; (B) Projected PV recycling market by 2050;[1] (C) Initiatives to unlock multifaceted benefits of PV recycling.

environmental damage,[2] including soil and groundwater contamination by harmful chemicals like lead, chromium, and cadmium. PV recycling avoids such damages, facilitating a green and pollution-free PV industry from source to end. Recycling dramatically reduces waste volume, easing the burden on landfills and preventing visual landscape pollution from waste accumulation. The reuse of recycled materials also reduces the energy consumption and carbon emissions associated with manufacturing new panels, thereby lowering the carbon footprint of the PV industry. By decreasing the need for raw material, recycling lessens the environmental damage resulting from mining activities. Additionally, PV recycling fosters efficient resource utilization, minimizes waste, and enhances resource circularity, further safeguarding the environment.

PV recycling brings multiple social returns

Firstly, the growth of the PV recycling industry generates numerous employment opportunities[1] in recycling, processing and remanufacturing, benefiting both public institutions (e.g., resource, environmental and research institutes) and private companies (e.g., manufacturers, transporters, and waste management firms). Secondly, by reducing environmental pollution from waste, recycling mitigates public health issues and promotes a higher quality of life for residents. Thirdly, PV recycling contributes to energy and resource security by reducing dependence on imported raw materials for PV manufacturing. Fourthly, the prosperity of PV recycling industries would raise public awareness of resource circularity and sustainability, fostering a culture of environmental responsibility. More importantly, PV recycling drives a green economy and aligns with the United Nations' Sustainable Development Goals 3 (good health and well-being), 7 (clean energy), 8 (economic growth), 9 (industry, innovation and infrastructure), 12 (responsible consumption and production), and 13 (climate action).

THE WAY FOREWORD

To fully realize the profound economic, environmental, and social benefits anticipated from the upcoming wave of PV decommissioning, we believe that the global industry, governments, and other stakeholders must make substantial efforts and take coordinated actions. We emphasize three critical aspects: innovation in recycling technology, economic incentives for the industry, and clear guidance through government policies.

Technological innovation is the cornerstone of developing PV recycling industry

Currently, mainstream recycling technologies each have drawbacks:[2] physical disposal cannot fully separate components; thermal treatment emits harmful gases and causes pollution; and solvent extraction generates organic waste streams that are difficult to manage. Therefore, technological breakthroughs are urgently needed to advance PV recycling. We suggest that R&D efforts focus on designing next-generation PV modules for easier repair, reuse, or recycling, and developing cost-effective services and business models. Innovating separation techniques and material extraction processes is essential to maximize the recovery of valuable components from PV modules. Advancing waste management infrastructure is crucial to support value creation from end-of-life PV panels. Integrating emerging technologies[3] like big data and artificial intelligence to optimize recycling processes is also necessary to enhance the overall efficiency of PV recycling systems.

Encouragingly, efforts have been made, and new technologies are reaching maturity. For instance, in 2022, Yingli Energy (China) Co., Ltd. announced that they had mastered an environmentally friendly technology for recycling crystalline silicon modules and established their first demonstration line in Baoding, China. This line achieves an average recovery rate of 96% for silicon, 93% for silver, 97% for copper, and 100% for glass and aluminum. Scientists at Nanyang Technological University have invented an effective method using phosphoric acid to recover high-purity silicon from discarded solar panels, achieving a recovery rate of 98.9% and a purity of 99.2%.

Economic incentives are the catalyst for the rise of PV recycling industry

To stimulate private investment in the early stages of emerging PV recycling markets, we recommend government-funded R&D and targeted subsidies to alleviate market uncertainties associated with PV reuse and end-of-life management. Primarily, governments could establish dedicated funds to support innovation in recycling technologies, facilitating the start-up of the PV recycling industry. We also propose that the government provides subsidies or tax incentives to lower the initial investments for participating companies in technology and equipment, thereby attracting hesitant companies to enter the PV recycling field. Furthermore, establishing an effective incentive mechanism can encourage manufacturers and consumers to actively participate in PV recycling, thereby accelerating the recycling rate and reducing overall costs.

According to the U.S. National Renewable Energy Laboratory, a subsidy of $18 per module can achieve the target recycling rate of 20% six years earlier (12 vs. 18 years) than a subsidy of US$10 per module.[4] Over the entire lifecycle, optimized recycling strategies shorten energy payback time by 72.6% (to 0.09 years) and reduce greenhouse gas emissions by 71.2% (to 13.4 gCO_2 equivalent per kWh).[5] As recycling technologies progress and become more efficient, the recovery of high-value materials (e.g., silver and silicon) and direct returns from material recovery could serve as additional economic drivers for the PV recycling industry.

Policy guidance is the foundation for a sustainable PV recycling industry

Government directives ensure the safe handling, storage, treatment, transport, reuse, recycling, and disposal of PV modules. We recommend that the government lead the formulation of PV-specific collection and recycling regulations with input from various stakeholders. Recycling and treatment standards for PV modules should be clarified to ensure consistent, efficient and profitable recycling activities. Policy directives should proactively regulate the spatial layout of the PV recycling industry to ensure compatibility with current PV deployments, and manage the timeline for enterprises entering the industry to avoid a sudden influx followed by a rapid exodus. Regulatory bodies should establish robust monitoring and evaluation mechanisms to periodically assess the effectiveness of policy actions, with frameworks adapted to the needs and circumstances of each country or region.

Valuable lessons can be learned from the experiences in some countries. For instance, the revised Waste Electrical and Electronic Equipment (WEEE) Directive of 2012 mandates EU member states to achieve a 65% recycling/reuse rate for PV modules by 2016, increasing to 75% in 2018, and further to 80% thereafter. In the United States, PV waste is managed under the Resource Conservation and Recovery Act (RCRA), with states like California, Arizona, and Florida classifying decommissioned PV modules as "universal waste". In China, the China Photovoltaic Industry Association (CPIA) issued the General Technical Requirements for Recycling Crystalline Silicon PV Modules, and the Ministry of Industry and Information Technology released guidelines for building the PV industry chain and industrializing PV recycling technology.

In summary, PV recycling is becoming increasingly important for the PV industry, especially as global installations of PV systems continue to rise. In the coming years, policymakers and PV stakeholders should prepare for the increase in panel waste volume and design systems to capitalize on the resulting opportunities. Unlocking the multifaceted value of retired PV panels requires targeted efforts and actions, such as those described above. With the right conditions in place, the end-of-life industry for solar PV can flourish and become a vital pillar of sustainable energy infrastructure in the future.

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AUTHOR CONTRIBUTIONS

H. J. designed and wrote the commentary. L. Y., J. Q. participated in drafting the paper. R. Z. provided data consulting services. L. Y., C. Z. supervised the work and secured the funds.

DECLARATION OF INTERESTS

The authors declare no competing interests.

ETHICAL STATEMENT

Not applicable.

DATA AND CODE AVAILABILITY

Not applicable.