



MATERIAL RECOVERY FROM END-OF-LIFE WIND AND PHOTOVOLTAIC SYSTEMS: LINKING CIRCULAR ECONOMY AND MINERAL PROCESSING METHODS IN POST-MINING AREAS UNDER ENERGY TRANSITION

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Abstract: *The increasing deployment of renewable energy systems is expected to generate significant volumes of end-of-life wind turbine and photovoltaic waste in the coming decades, creating new challenges for material recovery and waste management. This study examines the material composition of wind and photovoltaic systems and evaluates the applicability of mineral processing methods for recovering valuable and critical raw materials. The analysis shows that wind turbines contain high shares of recyclable ferrous materials (80–94% of total mass), copper, and rare earth elements, while photovoltaic systems represent important secondary sources of glass, aluminum, silicon, silver, and thin-film critical metals. The findings indicate that integrated processing routes combining comminution, physical separation, and hydrometallurgical treatment can achieve high recovery efficiencies, particularly for bulk metals and selected high-value elements. The study also demonstrates that post-mining regions possess significant advantages for hosting renewable waste recovery activities due to existing infrastructure, industrial land availability, and a technically skilled workforce. Finally, it concludes that integrating circular economy principles with mineral processing expertise can support both critical raw material recovery and sustainable regional transition in post-mining areas.*

Keywords: *circular economy; recycling; critical raw materials; renewable energy systems; waste processing; post-mining region*

1. Introduction

The global effort to mitigate climate change has accelerated the deployment of renewable energy systems, especially wind turbines and photovoltaic (PV) installations. These technologies are considered key pillars of the global energy transition due to their ability to reduce greenhouse gas emissions and decrease dependence on fossil fuels. However, the rapid expansion of renewable energy infrastructure also raises concerns regarding the increasing demand for raw materials and the management of waste generated at the end of the systems' operational life.

Wind turbines and PV modules contain substantial quantities of steel, aluminum, silicon, copper, rare earth elements, and composite materials. While these materials are essential for clean energy generation, they also represent a future waste stream of significant economic and environmental importance. Current estimates indicate that large volumes of end-of-life renewable energy equipment will emerge over the coming decades, requiring efficient recovery strategies to avoid resource losses and environmental burdens.

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At the same time, mining regions worldwide are undergoing structural transformation due to the gradual decline of fossil-fuel extraction. Post-mining landscapes often possess extensive infrastructure, available land, grid connections, and skilled technical personnel. These characteristics create favourable conditions for the installation of renewable energy projects and the development of secondary raw material recovery facilities.

This dual challenge creates an important opportunity: post-mining regions can evolve into integrated hubs combining renewable energy production with recycling and material recovery operations. In this context, mineral processing technologies traditionally applied in ore beneficiation, such as crushing, grinding, physical separation, and hydrometallurgical treatment, can be adapted to recover valuable materials from end-of-life wind and PV systems.

In parallel with technological and industrial developments, a comprehensive legislative and regulatory framework has been progressively established, particularly within the European Union, to support the sustainable management of renewable energy systems throughout their life cycle. Policies such as the Waste Electrical and Electronic Equipment (WEEE) Directive and the Waste Framework Directive introduce structured responsibilities for collection, recycling, and recovery, while embedding the principles of extended producer responsibility and waste hierarchy into practice [1, 2, 3]. These regulatory mechanisms do not merely address end-of-life management as an isolated phase; instead, they promote a life-cycle-oriented approach that integrates design, operation, and material recovery considerations. Complementary strategies, including circular economy action plans and ecodesign requirements, further reinforce this transition by encouraging the development of products that are easier to repair, reuse, and recycle [4, 5]. As a result, the evolving policy landscape creates a coherent foundation that aligns environmental objectives with industrial practices, enabling renewable energy systems to be viewed not only as clean energy technologies but also as components of a broader resource-efficient system.

This paper investigates the potential of linking circular economy strategies with mineral processing methods to support sustainable regional development in post-mining areas. In this context, the study highlights how mining engineering expertise can contribute to resource efficiency, critical raw material recovery, and the resilience of renewable energy systems.

2. Materials Used in Wind Turbines and Photovoltaic Systems

Wind turbines and photovoltaic systems are composed of a diverse set of materials, many of which are considered critical for the energy transition due to their functional importance, supply risks, and recycling potential.

2.1 Wind Turbines

Wind turbines rely heavily on metallic materials, particularly steel and iron-based alloys, which constitute the largest share of total mass. Steel is extensively used in towers, nacelle frames, and foundation reinforcements due to its high mechanical strength, durability, and recyclability. In fact, ferrous materials can account for up to 80–94% of the total turbine mass and are almost fully recyclable through established industrial value chains [6, 7]. Cast iron is also used in key structural and mechanical components, while copper is essential for electrical systems, including generators and cabling.

A second major category includes composite materials, primarily glass fiber reinforced polymers (GFRPs), used in turbine blades. These materials combine low weight with high mechanical strength and aerodynamic flexibility. However, their heterogeneous structure makes recycling more complex, often requiring mechanical or thermochemical treatment processes [8, 9]. Carbon fiber composites (CFRPs), although less common due to higher cost, are increasingly used in larger turbines for improved performance.

Wind turbines also incorporate critical raw materials, especially in permanent magnet generators. Rare earth elements such as neodymium (Nd) and dysprosium (Dy) are used in Nd-Fe-B magnets, enabling high-efficiency direct-drive systems by eliminating gearboxes. Despite their performance advantages, these materials face supply constraints and very low recycling rates (currently below 1%), highlighting the need for improved recovery technologies [1].

2.2 Photovoltaic Systems

Photovoltaic systems are dominated by glass, aluminum, and silicon-based components. Glass represents the largest mass fraction, while aluminum is used in module frames. The core functional material is silicon, typically in monocrystalline or polycrystalline form, requiring high purity and energy-intensive production processes [10, 11].

In addition to bulk materials, PV panels contain valuable and critical metals. Silver is widely used in electrical contacts due to its high conductivity, while copper supports internal wiring. Smaller but critical quantities of tin and lead may also be present. In thin-film technologies, elements such as indium, gallium, cadmium, and tellurium are used, often as by-products of other mining processes, which limits their availability [3, 12].

Finally, polymeric and composite materials, e.g., ethylene-vinyl acetate (EVA) encapsulants and polymer back-sheets such as polyvinyl fluoride (PVF) or polyvinylidene fluoride (PVDF), ensure mechanical stability and environmental protection. However, these materials complicate end-of-life processing due to their resistance to separation and recycling [13, 14].

2.3 Implications for Material Recovery

The diversity of materials recoverable from end-of-life wind turbines and photovoltaic systems is summarized in Table 1. The presence of high-value and critical materials in both wind and PV systems makes end-of-life infrastructure an important source of secondary raw materials. Efficient recovery is essential not only to reduce dependence on primary extraction but also to enhance supply chain resilience and support circular economy strategies in post-mining regions.

Table 1. Recoverable materials from end-of-life renewable energy systems

System	Material	Category	Recovery Potential	Notes
Wind	Steel	Bulk metal	High	80–94% mass
	Copper	Metal	High	Electrical systems
	Nd, Dy	Critical raw materials	Low	Magnets
	GFRP	Composite	Low–Medium	Complicate process
PV	Glass	Bulk	Very high	>95%
	Aluminum	Metal	Very high	Almost 100%
	Silicon	Semiconductor	Medium	Energy intensive
	Silver	Critical	Medium–High	Hydrometallurgy
	In, Ga, Cd, Te	Critical	Low	Thin films

3. End-of-Life Management of Renewable Energy Systems

The end-of-life phase of renewable energy infrastructure involves a series of processes, including dismantling, transport, material separation, and recovery, all of which significantly influence the overall environmental performance of the system [12]. For wind energy installations, this phase typically includes the decommissioning of turbines after 20–25 years of operation, followed by removal and waste management procedures [15]. Metallic components such as steel towers and internal mechanical parts can be efficiently recycled through established industrial processes, contributing to high material recovery rates [16]. However, composite materials used in turbine blades, mainly fiberglass-reinforced polymers, remain a major challenge due to their heterogeneous composition, resistance to conventional recycling techniques, and potential environmental risks if improperly treated [17].

In the case of photovoltaic systems, end-of-life management begins with the dismantling of panels and the removal of external components such as aluminum frames and junction boxes, followed by the separation of glass, silicon, and metallic fractions [12]. While bulk materials like aluminum and glass can be recovered at high rates and reintroduced into production cycles, reaching recovery efficiencies close to 100% for aluminum and above 95% for glass in optimized conditions, the extraction of valuable elements such as silver and other semiconductor materials remains technically complex and economically constrained [18]. These materials are typically embedded in thin layers or composite structures, requiring advanced mechanical, thermal, or chemical treatments for efficient recovery [12].

Despite ongoing technological improvements, several barriers limit the effectiveness of recycling processes for renewable energy systems. A key challenge is the complex and heterogeneous material composition of both wind turbine components and photovoltaic panels, which complicates separation and recovery [17]. In addition, there is still insufficient large-scale, dedicated infrastructure capable of handling the growing volume of end-of-life equipment, particularly considering the expected surge in waste as installations from previous decades reach decommissioning [18]. Economic factors also play a critical role, as certain recovery processes, especially those targeting low-concentration or high-value materials, remain costly and not always profitable under current market conditions [18]. Furthermore, the lack of standardized and fully developed end-of-life management systems, along with gaps in regulatory implementation across regions, further hinders efficient material recovery [19].

These challenges underline the necessity for the development of advanced treatment technologies, improved recycling infrastructure, and more integrated policy frameworks. Emphasis is increasingly placed on circular economy approaches, including design for recyclability, material tracking, and the establishment of efficient collection and processing networks [12]. Such strategies are essential to enhance recovery efficiency, reduce environmental risks, and ensure the long-term sustainability of renewable energy systems [20].

4. From Ore Processing to Renewable Waste Recovery

The recycling of wind and photovoltaic waste shares important similarities with conventional mineral processing (Figure 1). The first step involves comminution, including crushing and grinding, to reduce the size of waste components and facilitate the release of valuable materials from complex structures. This stage is directly analogous to ore preparation in mineral beneficiation plants, where particle size reduction enhances the efficiency of subsequent processing steps. In the context of photovoltaic panels and wind turbine components, mechanical pre-treatment, such as cutting, shredding, and milling, improves handling while increasing the accessibility of embedded metals and composite materials [13, 21].

Following comminution, physical separation methods such as magnetic separation, density-based separation, and electrostatic separation can be applied to concentrate metallic fractions and remove non-metallic constituents. These techniques are effective for isolating materials such as aluminum, copper, and steel from glass, polymers, and fiber-reinforced composites. However, due to the growing complexity of renewable energy systems, particularly in thin-film photovoltaics and composite wind turbine blades, mechanical and physical processes alone are often insufficient to achieve high levels of material purity. As a result, they are typically integrated with additional treatment stages [2].

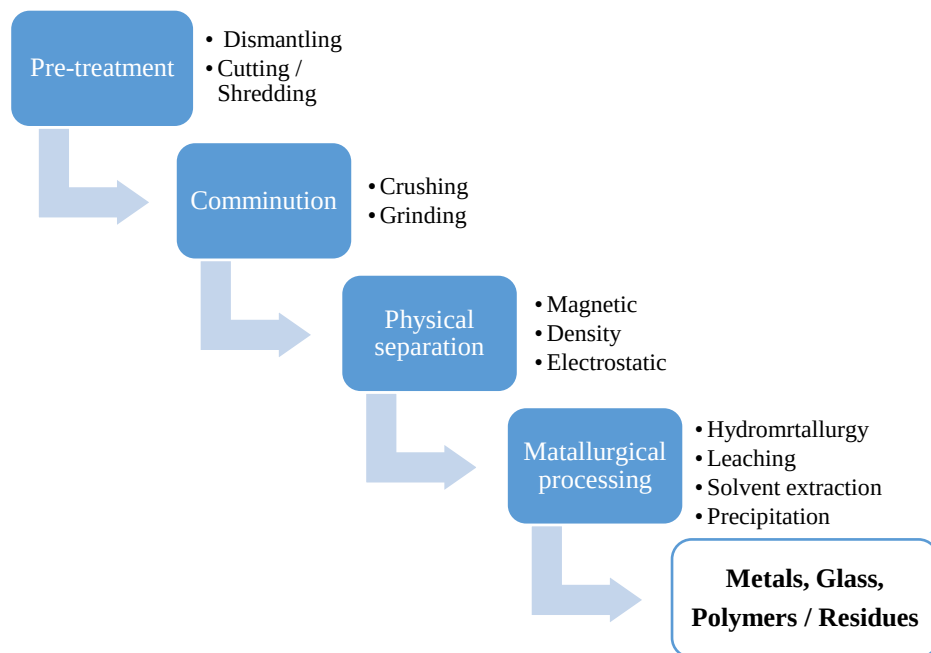


Fig. 1. Flow diagram of end-of-life renewable energy systems processing for material recovery

Subsequently, hydrometallurgical processes are employed to recover valuable metals from the concentrated material streams. Techniques such as acid leaching, solvent extraction, and chemical precipitation are particularly suitable for recovering metals like silver, copper, indium, gallium, and rare earth elements. In some cases, recovery efficiencies can exceed 99% for specific elements, such as silver, especially when electrochemical methods are applied [18]. These approaches are essential for extracting low-concentration, yet high-value materials embedded within complex matrices. At the same time, the environmental implications of chemical usage and energy demand must be carefully managed through optimized process control and waste treatment strategies [2, 18].

Moreover, hybrid processing approaches that combine mechanical, thermal, and chemical methods are increasingly being developed to improve both recovery efficiency and economic feasibility. For example, initial mechanical separation to remove bulk materials such as glass can significantly reduce the volume and cost of downstream chemical processing [2]. This reflects a multi-stage processing philosophy similar to that long established in the mining industry.

These processes demonstrate that the technical expertise of the mining sector can be directly applied to renewable energy waste management. Existing beneficiation knowledge, process equipment, and operational experience provide a strong foundation for developing recycling facilities, particularly in former mining regions. In this way, established industrial capabilities can support the transition toward a circular economy, where renewable energy waste is reintegrated into production cycles as a valuable resource rather than treated as residual waste.

5. Circular Economy Strategies for Renewable Energy Technologies

Building upon the previously discussed recovery processes, it becomes evident that such techniques (including comminution, separation, and material-specific treatment methods) do not operate in isolation but form integral components of a broader circular economy framework. Rather than being limited to end-of-life management, these processes contribute to a continuous system aimed at optimizing material use throughout the entire lifecycle of renewable energy technologies.

Circular economy principles in renewable energy systems emphasize the creation of closed-loop material flows, where outputs from decommissioned systems are reintroduced into production cycles through reuse, remanufacturing, and high-value recycling [19]. This approach supports a transition from linear resource consumption toward regenerative systems that reduce both waste generation and dependence on primary raw materials.

A fundamental aspect of this transition is the reduction of waste generation across all lifecycle stages. Beyond recovery at the end of life, this includes improved design strategies, accurate material specification, and enhanced coordination between stakeholders. For example, minimizing installation losses (e.g., excess cabling) and adopting modular system architectures can significantly reduce material inefficiencies [9]. Additionally, extending product lifetimes through maintenance and repair strategies helps prevent premature replacement, which is often driven by economic considerations such as Net Present Value calculations rather than technical necessity [22].

Reuse and remanufacturing represent key strategies for retaining material value at higher levels within the circular hierarchy. In renewable energy systems, components such as wind turbine blades can be repurposed in structural or architectural applications, avoiding energy-intensive processes like comminution and preserving their functional integrity [6]. Where direct reuse is not feasible, partial disassembly enables the recovery of valuable subcomponents for reintegration into new products [19].

High-value recycling complements these strategies, particularly in photovoltaic systems where critical materials such as silicon (Si), silver (Ag), and copper (Cu) must be recovered with high purity to maintain their economic and functional value [13]. In this context, comminution remains an important preparatory step, facilitating downstream separation and refining processes. However, the overall efficiency of such recycling pathways depends strongly on design-for-disassembly principles and material selection during the initial production phase [14]. Regulatory frameworks, such as the WEEE Directive, further reinforce this direction by setting ambitious recovery and recycling targets [13].

The integration of these strategies is further strengthened through industrial symbiosis, where material and energy flows are exchanged between different industrial sectors. For instance, recycled materials from photovoltaic panels or wind turbine components can serve as inputs for construction or electronics industries, reducing the need for virgin resources [23]. Such cross-sectoral linkages are particularly relevant given the projected increase in demand for materials like silicon in Europe [11]. Digital technologies, including IoT and data-driven platforms, can support this coordination by enabling real-time tracking and forecasting of material availability [12].

In parallel, the valorization of by-products plays a crucial role in enhancing resource efficiency. Materials that cannot be directly reused or recycled at high value can still be utilized in secondary applications or energy recovery processes, contributing to a cascading use of resources [15]. This approach aligns with circular economy principles by ensuring that the concept of “waste” is progressively minimized and replaced by that of continuous resource flows.

Ultimately, the combination of advanced recovery technologies, circular design principles, and industrial symbiosis leads to the development of integrated industrial ecosystems. These systems not only reduce environmental impacts and waste generation but also enhance resource security and economic resilience within the renewable energy sector.

6. Opportunities for Mining Regions

Post-mining regions can become key hubs for implementing circular economy models linked to renewable energy systems. These areas often already possess important assets such as available industrial land, developed transport networks, electricity infrastructure, and a workforce with experience in industrial and material-handling operations. Such conditions significantly reduce the initial investment barriers for establishing recycling and renewable energy facilities.

In particular, the co-location of renewable energy infrastructure with end-of-life material processing facilities (e.g., photovoltaic and wind turbine recycling plants) can improve logistical efficiency and reduce overall system costs. Since the cost of material management is strongly influenced by geographical, infrastructural, and operational factors, the reuse of former mining sites offers a strategic advantage by minimizing transport distances and leveraging existing industrial ecosystems.

From an economic perspective, mining regions can diversify their activity base by shifting from extractive industries to secondary raw material recovery. The recovery of valuable materials such as aluminium, copper, silicon, and glass from renewable energy technologies can generate new revenue streams and support local industrial value chains. In this way, waste materials are transformed into secondary resources, reducing dependence on primary raw material extraction and improving resilience to market fluctuations.

A key dimension of this transition concerns employment. Former mining regions already host workers with relevant technical skills, which can be adapted through targeted retraining programs for roles in dismantling, sorting, and recycling operations. This facilitates a “just transition” by mitigating job losses associated with mine closures while simultaneously creating new employment opportunities in circular economy sectors. However, continuous training and skill upgrading are essential to align the workforce with evolving technological requirements.

Social acceptance is another critical factor. Mining regions often have prior exposure to large-scale industrial activity, which may ease the integration of new infrastructure if local communities perceive tangible benefits. Transparent communication, equitable distribution of benefits, and active stakeholder participation are essential for building trust and reducing resistance. In addition, education and awareness initiatives can strengthen public understanding of circular economy practices and their long-term benefits.

Policy frameworks also play a decisive role. Instruments such as Extended Producer Responsibility (EPR), financial incentives for recycling, and restrictions on landfill disposal can significantly improve the economic feasibility of recycling investments. Stable and predictable regulatory environments are particularly important for attracting private investment and reducing uncertainty in long-term planning.

Finally, from a sustainability perspective, decentralized recycling facilities located in post-mining regions can reduce transport-related emissions and improve the overall energy efficiency of material recovery systems. The integration of renewable energy production with recycling activities further enhances environmental performance and supports broader decarbonization goals.

Overall, the transformation of post-mining regions into circular economy hubs represents not only a technical solution but a comprehensive socio-economic strategy that combines economic diversification, job creation, environmental protection, and social cohesion.

7. Conclusions

This study confirms that end-of-life wind turbines and photovoltaic systems represent an increasingly important secondary source of valuable and critical raw materials, including steel, aluminum, glass, silicon, copper, silver, and rare earth elements. The analysis shows that recovery efficiency is strongly influenced by material heterogeneity and component design: metallic fractions exhibit high recyclability, whereas composite materials and embedded critical elements remain significant technical challenges.

The review further demonstrates that the recovery of these materials can effectively rely on mineral processing principles. Comminution, physical separation, and hydrometallurgical treatment were identified as the dominant technological pathways, offering recovery efficiencies that can exceed 95% for bulk materials and approach near-complete recovery for selected high-value metals under optimized conditions.

A key finding is that post-mining regions possess the infrastructure and technical prerequisites for deploying integrated recycling and renewable energy systems. Existing industrial assets, skilled workforce, and established logistical networks provide strong advantages for the development of circular economy hubs.

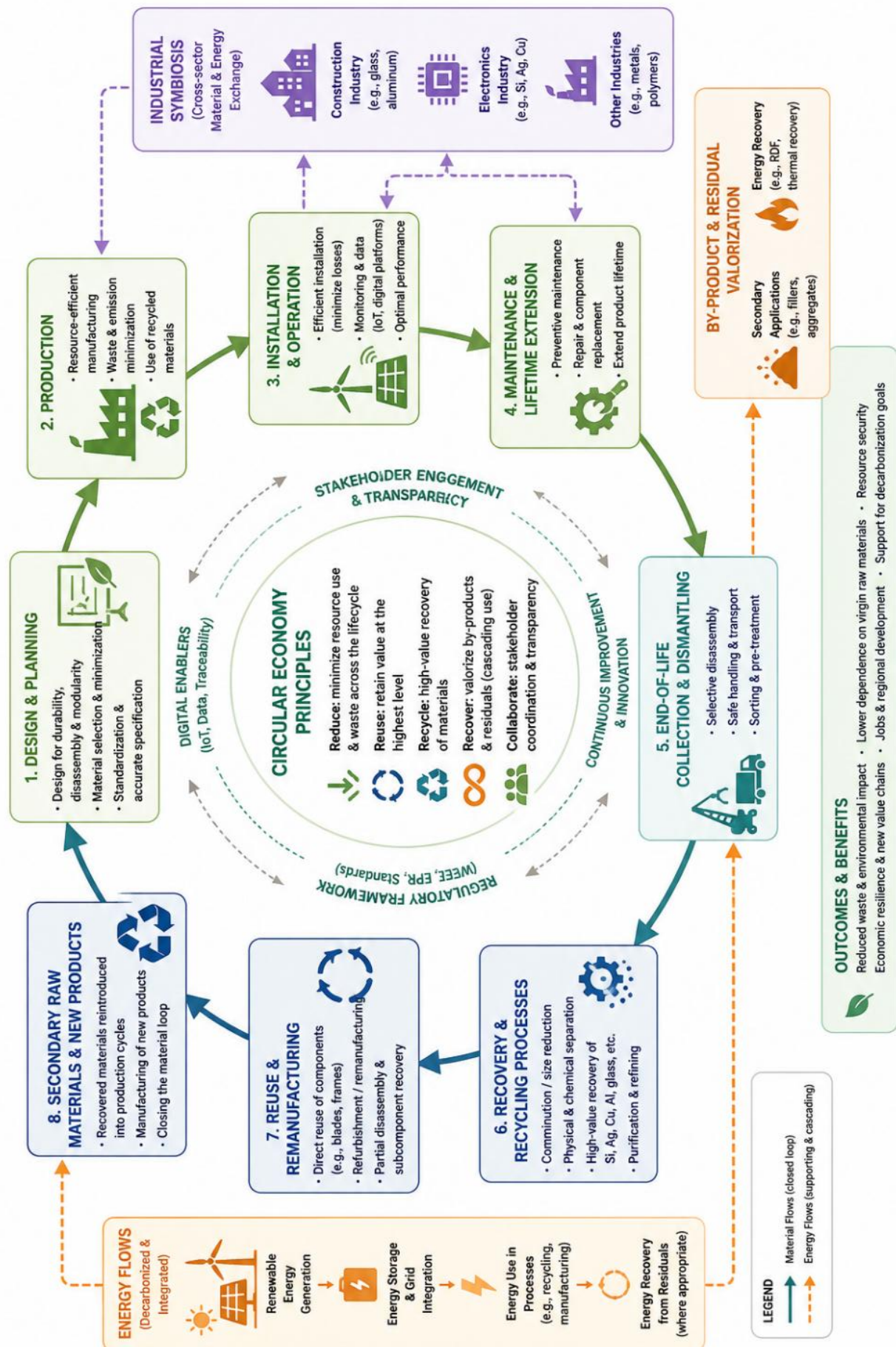


Fig. 2. Materials and energy circularities throughout the entire lifecycle of wind turbines and photovoltaic systems

Overall, the literature indicates that linking renewable energy waste management with mineral processing expertise offers a technically feasible and strategically valuable pathway for supporting resource security, reducing dependence on virgin raw materials, and facilitating the socio-economic transition of former mining regions. Future research should focus on process optimization, economic feasibility assessment, and design-for-recycling approaches to improve large-scale implementation.

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