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Mario Grosso · Lucia Rigamonti  
Editors


# Waste Flows Generated by the Energy Transition

Regulatory Framework, Recovery  
Technologies and Plant Infrastructures



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# Preface

The term “energy transition” refers to the global shift from reliance on fossil fuels to renewable energy sources such as solar, wind, hydro, biomass, and geothermal energy. This transition also involves advancements in energy storage technologies, widespread electrification of end-uses, improved energy efficiency, and enhanced demand management strategies. It is driven by pressing concerns over climate change, air pollution, energy security, and socio-economic sustainability. Among these, it is the climate change concern that is paving the way, with most countries committed to reducing fossil fuel emissions to meet the Paris Agreement’s ambitious goal of limiting global temperature increases to well below 2°C—and ideally to 1.5°C—above pre-industrial levels.

In the coming decades, the energy sector is poised for a profound transformation, moving from a fossil-fuel-dominated landscape (coal, oil, and natural gas) to one centred on renewable energy and cleaner technologies. The remarkable growth of solar and wind power, the adoption of electric vehicles, and other technological advancements illustrate the urgent and widely acknowledged need to mitigate greenhouse gas emissions and reduce the environmental impacts of a carbon-intensive economy.

However, the shift to cleaner energy technologies comes with a significant demand for critical minerals and metals. For instance, lithium, cobalt, manganese, phosphorus, and nickel are essential for batteries; rare earth elements are critical for permanent magnets in wind turbines and electric motors; nickel and platinum group metals are used in hydrogen electrolyzers and fuel cells; and copper and aluminum are indispensable for electricity-related technologies and distribution networks. The uneven geographic distribution of these materials and bottlenecks in their supply chains pose challenges to the expansion of renewable energy and electricity-based technologies.

From a materials perspective, the energy transition signifies a shift from a linear model—centred on single-use fossil fuels—to a circular model. Here, energy is sourced freely, while the materials required for production, transformation, and transportation infrastructures are reused, repurposed, and recycled as much as possible.

The reliance on critical minerals in the energy transition necessitates thorough investigation to ensure climate change mitigation efforts do not inadvertently cause adverse effects, such as burden-shifting to other environmental impact categories. Moreover, the lifecycle of clean technologies inevitably generates waste, including end-of-life products, mining byproducts, processing tailings, and manufacturing scraps.

Effective management of these waste streams is vital. On one hand, improper disposal must be avoided to prevent environmental harm; on the other, recycling emerges as a key strategy to meet growing material demands. Recycling reduces dependency on virgin raw materials, alleviates supply chain pressures, and enhances resource security. However, successful recycling requires not only technological solutions but also efficient systems for the collection, separation, and processing of waste materials.

This book explores four major waste streams associated with the energy transition: (i) lithium-ion batteries for electric vehicles and stationary energy storage, (ii) electric motors in electric vehicles, (iii) wind turbine blades, and (iv) photovoltaic panels. For each technology, the current options for end-of-life (EoL) management are analysed, including a detailed characterization of the components and materials in the corresponding waste stream. The legislative framework is examined to evaluate whether it fosters or hinders circular economy initiatives, and industrial practices and research efforts in repurposing and recycling are summarized.

We aspire for this book to serve as a resource for scholars, students, and practitioners in the fields of energy transition and sustainability. Our goal is to address the concerns and challenges surrounding the phase-out of fossil fuels, ensuring they are tackled comprehensively and responsibly.

The research underpinning this book was conducted by the MatER (Materials and Energy from Refuse) research centre, established in 2011 in Piacenza, Italy, within LEAP (Laboratorio Energia e Ambiente Piacenza), an external laboratory of Politecnico di Milano. MatER's mission is to identify efficient, sustainable waste management solutions and assess the best available techniques for material and energy recovery, exploring synergies between these two pillars of recovery from waste.

We would also like to thank the master's students of Politecnico di Milano who supported the initial phases of the research on the state-of-the-art: S. Bruschi, L. Ferrari, S. Ladisa, P. Salardi, I. Scigliuolo, and D. Varotto for their work on Li-ion batteries, and J. D. Chamat Torres for their contributions on waste from wind turbines.

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## About this Book

This book analyses four critical waste streams linked to the transition to cleaner energy technologies: Li-ion batteries for electric vehicles and energy storage systems, electric vehicle motors, composite waste from wind turbines, and photovoltaic panels.

Each chapter explores waste stream characteristics, including recoverable critical raw materials, legislative frameworks, waste prevention and management options, and surveys on industrial initiatives and facilities in Europe.

The text examines the state-of-art of recovery technologies for extracting valuable resources to meet the rising demand for critical materials. It reviews reuse, remanufacturing, and recycling methods, including mechanical, hydrometallurgical, pyrometallurgical, and chemical recovery processes. Each technology is discussed with its respective key features, strengths and drawbacks, also from the environmental standpoint.

A thorough evaluation of European regulatory frameworks for end-of-life management is provided.

The book also evaluates existing plant infrastructure across Europe, identifying potential gaps in facilities that may challenge waste treatment and recycling in the future.

This resource is aimed at policymakers, industry stakeholders, researchers, students, and practitioners focused on sustainable waste management in the energy transition.

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