CHAPTER

1

Recycling: A Key Factor for Resource Efficiency

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Materials form the fabric of our present society; materials are everywhere in our lives, and life as we know it would be impossible without them. In fact, terms as the "Bronze Age" and "Iron Age" demonstrate that materials have really defined our society in history. Moreover, materials will play a key role in the transition of our society toward sustainability. The challenge of sustainability is rooted in the way that we now process resources to make materials and products, which are often discarded at the end of life. This *linear* economy is now running into its limits given the large demand for materials and resources of an increasing (and increasingly affluent) global population.

Industrial society has become extremely dependent on resources, as it produces more, builds an increasingly complex society and accumulates an incredible volume of resources. Figure 1.1 depicts the global production of the key materials used in society and shows an extremely rapid growth in the past few decades, as emerging economies like China develop. Today, China produces half of all the cement, steel and other commodities in the world. Mankind now dominates the global flows of many elements of the periodic table (Howard and Klee, 2004). The materials are drawn from natural resources. However, the Earth's resources are not infinite, but until recently, they have seemed to be: the demands made on them by manufacturing throughout the industrialization of society appeared infinitesimal, the rate of new discoveries outpacing the rate of consumption. Increasingly we realize that our society may be approaching certain fundamental limits. This has made access to materials an issue of national security of many nations, especially also to ensure that emerging new "sustainable" technologies can be supplied with metals and materials.

Historically, industry has operated as an open system, transforming resources to products that are eventually discarded to the environment, as depicted in Figure 1.2. This, coupled to the massive increase in the use of resources, has led to growing impacts on the environment, as large amounts of energy, greenhouse gas emissions and other emissions to the environment are directly tied to the production and use of the resources, while also affecting land use change, the use of water and

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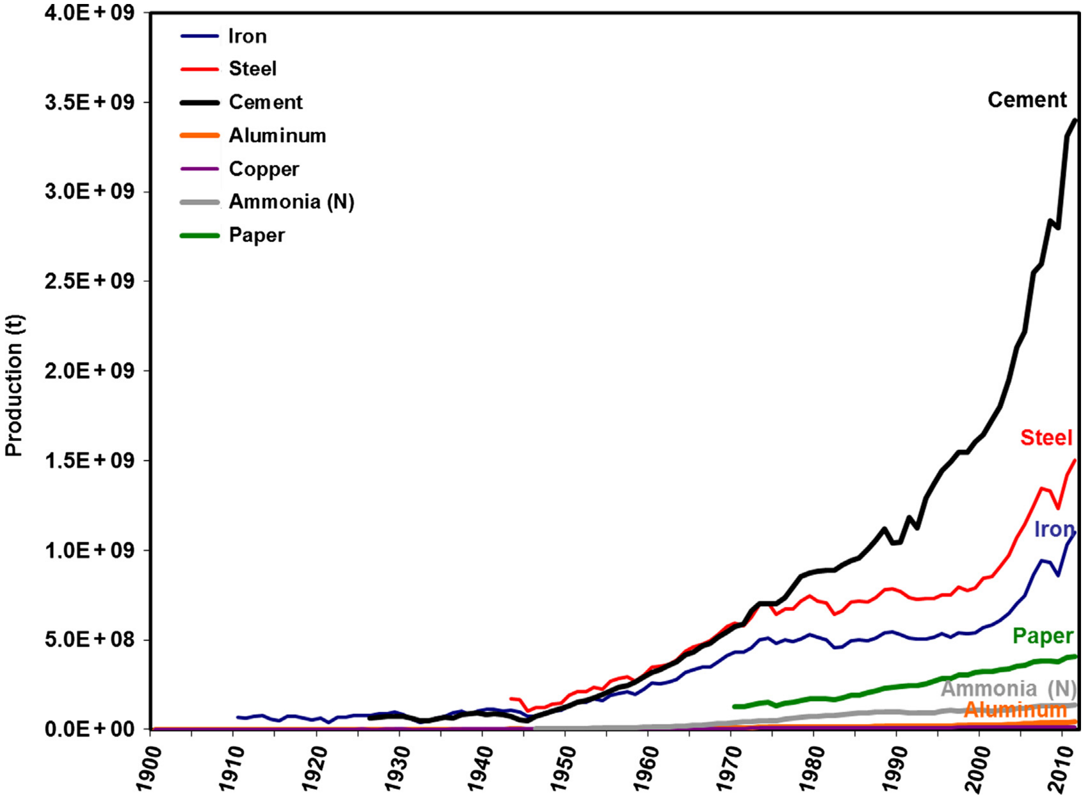

FIGURE 1.1 Global materials production of key materials since 1900 (Data: USGS).

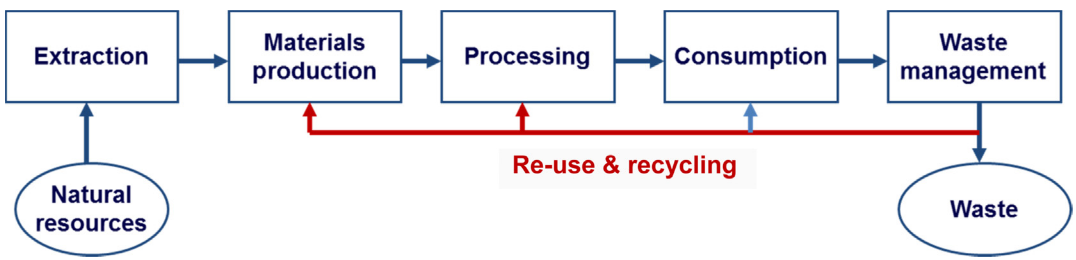

FIGURE 1.2 Closing the loops. Shifting from a linear economy (in blue) to a circular economy requires the closing of loops to ensure that products and materials are reused or recycled (in red). (For interpretation of the references to color in this figure legend, the reader is referred to the online version of this book.)

other environmental resources. Moreover, our resources use results in increasing amounts of solid wastes, which are discarded or incinerated. Waste is becoming a large problem, as we are running out of land for landfilling, and end-of-life waste treatment has negative environmental and health impacts. This is especially a problem for emerging economies, where material use (and hence discarding of it) is growing very rapidly, while limited waste management infrastructure exists.

Materials consumption in the United States now exceeds 10 t/person/year, while the global average consumption has grown to about 5 t/annum. The global average is growing rapidly, given expected population growth and developing patterns for the majority of the population living in developing countries. This makes a reevaluation of the way that we use resources necessary. To maintain our level of welfare, services by resources should be provided more efficiently using less (environmental) resources per unit of activity; i.e. we must improve the resource efficiency of our society. There are several ways that we can improve the resource efficiency of society:

- Use resources more efficiently in the provision of an activity or product (including lifetime lengthening).
- Use less resource-related services.
- Reuse product and services.
- Recycle the resources and materials in products.

Waste is only waste if it cannot be used again or if its economic value, including dumping costs, is not sufficient to make its exploitation economically feasible. Economic recycling enables waste to become a resource; however, various aspects hinder it becoming totally reusable. Recycling is the reprocessing of recovered materials at the end of product life, returning them into the supply chain.

Potentially, it could be done at a rate comparable with the rate with which we discard resources, but then the system must be carefully designed to minimize inevitable losses. Also, the energy needed for recycling is generally substantially less than the energy needed to produce the material from ores, which in the process also creates large amounts of valueless byproducts or wastes with little or no economic value, and that sometimes contains harmful compounds at the mining or processing site. While some (bulk) materials are well recycled, others can (currently) not be recycled, especially due to their complex connections because of functionality reasons in consumer products. Figure 1.3 shows that a level of sophistication in metal recovery from recyclates could exceed that of geological resources due to this depicted complexity.

For this reason, for example, despite all the policy attention to the strategic supply problems surrounding rare earth metals, less than 1% of the rare earth metals in waste are currently being recycled as these go lost owing to the aforementioned complexity. The fraction of a material that can reenter the life cycle will depend both on the material itself and on the mineralogy of the product from which it is being recovered, as (still) the quality and purity of the recovered material determine its future applicability.

The economics of recycling will depend on the degree to which the material has become dispersed, as well as the matrix (e.g. complex consumer product, building, transport, packaging) within which it is recovered. Although recycling has far-reaching environmental and social benefits, market forces determine if a material or complex products can ultimately be recycled and their contained metals, materials and compounds recovered. And market forces often fail to value externalities from environmental pollution or future scarcity, making for an “uneven” playing field. In various countries, these externalities and (other) market failures have provided the incentive to design policies to support resource efficiency in general, and recycling, specifically.

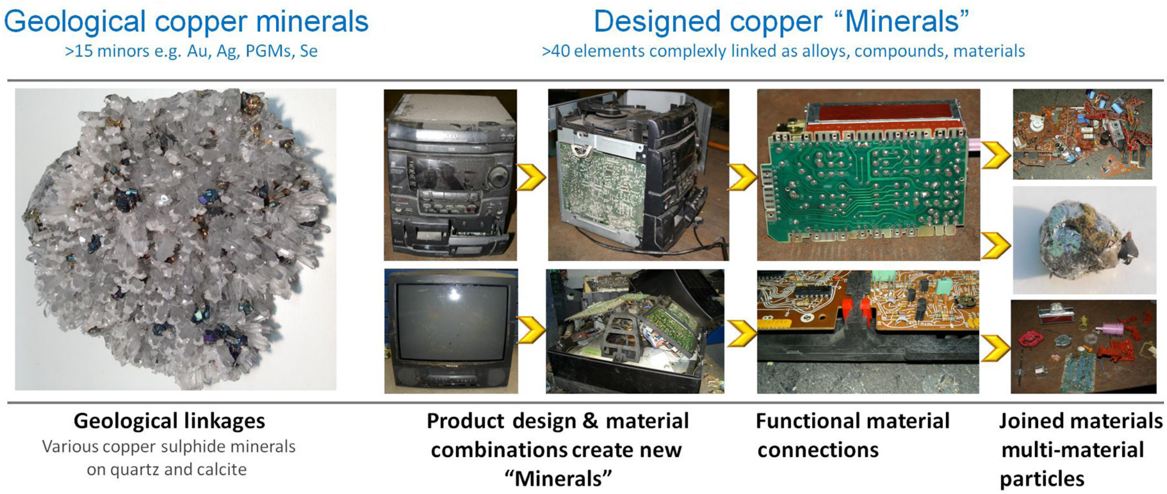

FIGURE 1.3 Conventional extraction processes can recovery various elements from geological ores economically, while much work has to be done to recover all metals from complex designer copper "minerals".

Recyclable wastes are often collected by cities and municipalities, selling them into a market of traders and secondary processors who reprocess the materials to eventually sell them to manufacturers. In the recycling market, prices fluctuate according to the balance of supply and demand, the prices of materials made from primary resources, as well as the behavior and organization of markets and its stakeholders (e.g. the role of increased market power concentration, and speculation of e.g. silver and copper). This couples the price of the recycled material to that of the primary or virgin material. This becomes more complex when minor elements associated with the ores are priced, as supply and demand are geologically linked to the extraction of the bulk base metals such as aluminum, copper, nickel, lead and zinc. The same holds for critical elements that "hitchhike" with the mining of other more common elements, as no separate mines exist for these critical or strategic elements. The markets are also affected by economic or policy interventions. Legislation setting a required level of recycling for vehicles, electronic products and packaging is now in force in most European countries, while other nations have similar programs and plans for more. A lively international trade in recycled resources has emerged, due to the local costs of separating materials from products, and the increasing resources appetite from rapidly developing nations like China and India. This has made recycling a strategic and geopolitical issue as well.

In short, recent economic and global developments have put recycling in the spotlight again, necessitating a critical assessment of the role of recycling in the context of a resource efficient society.

It is the objective to show in this book how material- and product-centric recycling can be harmonized to maximize resource efficiency (UNEP 2013). Figure 1.4 depicts this complex interplay among materials, products and different stakeholders to help maximize the recovery of all materials.

This book will provide the basis, in terms of fundamental theories of recycling, take-back

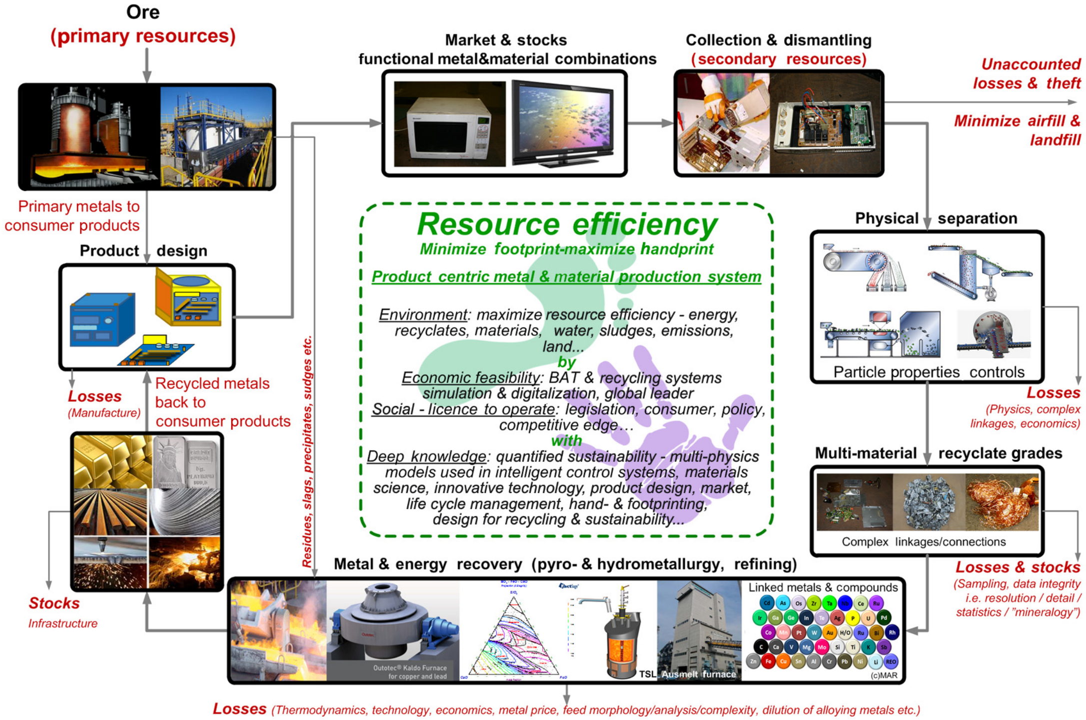

FIGURE 1.4 Recycling helps enable resource efficiency. This book will cover the various aspects detailed in this figure and figures in chapter 1.

systems and collection, used technology, economics, design-for-recycling, consumer behavior, material efficiency and policy, to understand the state of the art and the challenges of recycling in the larger context. It is intended to provide professionals, analysts and decision makers with a solid background in order to show how recycling can be used to improve resource efficiency.

The book is organized in several parts:

I. General aspects of recycling
II. Recycling technologies and applications
III. Recovery and collection
IV. Material efficiency
V. Economics of recycling
VI. Recycling and policy

Each part consists of a number of chapters. Each of the chapters is authored by key experts in the field. Experts come from academia, industry and the policymaking community, providing for a strong basis from theory to practice today, describing the lessons learned and the state of the-art in recycling of a wide variety of resources, products and waste flows.

Part I provides the background and context for recycling by discussing the basics of recycling in science and society, and putting recycling in the perspective of resource efficiency and the development toward a resource-efficient and sustainable *circular* economy.

Part II is the technical “body” of the handbook, describing the state of the art of recycling material, product and waste streams. Each chapter describes a specific material or waste stream, covering the current situation as well as technological state of the art. Starting with specific materials, this part of the book develops toward more complex waste streams that consist of a typical type of products (e.g. vehicles and electronics, as shown in Figures 1.3 and 1.4) or a difficult and varying mix of products (e.g. construction and demolition wastes, bulky household wastes).

More detailed discussions of relevant theory are also included in the Appendices.

Subsequent chapters discuss the different types of recovery schemes for key waste flows, ranging from curbside collection systems to postconsumer separation technologies.

Recovery and collection technology is an integral part of recycling. While conventional economics of a few stakeholders often determine the collection system, it is important to understand that the system will affect the material quality of the recycled materials, and hence should be considered in the full context and not stand alone.

In *Part III* the handbook will focus on the position of recycling within the total life-cycle of resources and the need to increase the efficiency of our total resources system. Hence, the role, effectiveness and efficiency of recycling should be evaluated within the context of and relative to all opportunities to improve the resource efficiency of our society. Redesigning products and reusing products are a key part of this overall strategy. Design for recycling and the fundamental link to the physics of the recycling system are key issues included in the discussions.

In the next parts of the Handbook of Recycling, attention is shifted to the economics and policy aspects of recycling. Furthermore, the economics of recycling are discussed, addressing the costs, benefits and externalities of recycling in more detail. This part also focuses on policies to stimulate reuse and recycling, bringing together knowledge on the type of policy instruments used, the experiences, effectiveness and efficiency.

A number of appendices to the Handbook of Recycling provide background data on some of the tools and data needed in evaluating recycling technology and opportunities. The appendices provide a brief introduction into topics such as physical separation and sorting, thermodynamics and extractive metallurgy, process simulation, life-cycle assessment, and simulation to guide the readers to more advanced texts on these topics. These are crucial in understanding the physics underlying resource efficiency. This knowledge provides the basis for innovation in the system, creating innovative new solutions and technologies, or also determining which systems and processes should be made redundant to ensure resource efficiency is maximized.

Combined, the parts of the handbook bring together a unique collection of material on recycling, from technology to policy, providing state-of-the-art discussions and information from a wide variety of backgrounds and experiences. This will help the reader understand the dynamics, context and opportunities for recycling, within the larger picture of shifting our economic production system to a circular system. We hope that this will contribute to the realization of a circular economy and efficient use of resources in our society.

Finally, to show the difference between material and product centric recycling, aluminium recycling was integrated into a chapter that shows the link between product design, product complexity and metal recovery. This permits the rigorous simulation based analysis of the limits of recycling by considering the effect of for example the dissolution of minor elements in (less noble) metals and other losses from the system on resource efficiency.

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