CHAPTER

2

Definitions and Terminology

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2.1 INTRODUCTION

Recycling is not a goal in itself, but rather an essential tool out of a whole toolbox to better manage natural resources. 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 rapidly increasing demand for resources has initiated various initiatives, such as "Factor 4, 5 or 10" to reduce the total amount of resources needed, while still fulfilling the needed services provided by materials and resources in today's society (e.g. Von Weizsäcker et al., 2009).

Historically, industry producing the materials has operated as an open system, transforming resources to products that are eventually discarded to the environment. This, coupled with the massive increase in the use of resources, has led to growing impacts on the environment. The massive use of materials results in increasing amounts of solid wastes, which are discarded or incinerated. This results not only in a loss of valuable materials, but also in negative environmental and health effects.

Our massive use of resources also contributes to a potential depletion of economically (or environmentally) recoverable reserves of materials. In fact, one could say that natural stocks (i.e. geologic reserves) are transferred to anthropogenic stocks (i.e. capital goods in our society). This makes recycling an important source of material, and this importance will only increase in the future. This is reflected in terms as the "urban mine" (i.e. minerals and metals contained in the urban infrastructure and buildings) and "urban forest" (i.e. wood fibers and paper).

A distinction needs to be made between non-renewable materials, such as minerals (including oil) and metals, and renewable materials (e.g. wood and biomass). Note that the two are interrelated because of the need for nutrients (e.g. nitrogen, phosphorus and potassium) and micronutrients (e.g. selenium and many others). Recycling of renewable materials contributes to a more efficient supply of resources, since primary resources (e.g. forest, land, water, energy) are saved and emissions such as greenhouse gases are reduced (Laurijssen et al., 2010). The success of paper recycling in many countries

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illustrates the need for recycling of renewable resources.

To maintain our level of welfare, services by resources should be provided more efficiently using less (environmental) resources per unit of activity, i.e. improve the resource efficiency of our society. This means that we need to move from a linear economy, which extracts resources from the environment and discharges the wastes to the environment, to a circular economy, one that reuses and recycles products and materials in a material-efficient system, extracting and wasting as little as possible (see Chapter 1). There are several ways that we can improve the resource efficiency of society, of which recycling is one. 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. In historical societies, recycling was much more prevalent. The Industrial Revolution allowed for a massive reduction in the cost of materials, resulting in a reduced emphasis on reuse and recycling in today's society. However, with increasing costs for primary materials, recycling has enabled waste to become a resource. While some materials are well recycled, others can (currently) not be recycled. In this chapter, recycling is put in context of a resource-efficient economy, and critical issues are defined that will contribute to understanding and positioning recycling. This is illustrated by applying the concepts to the case of metals.

2.2 DEFINING RECYCLING

Recycling is the reprocessing of recovered materials at the end of product life, returning them into the supply chain. Recycled material may also be called "secondary" in contrast to "primary" material that is extracted from the environment. Hence, primary and secondary in the context of recycling do not express a difference in quality.

Recycling has a key role to play in a resource-efficient economy. In past decades, recycling was mainly considered a waste management issue, whereas today the vision is slowly moving toward resource efficiency as a driver for recycling. This places recycling in a wider context. In various countries a variation on the "waste management hierarchy" (for example, also known as the 3 Rs in the United States, which stands for reduce, reuse and recycle) was introduced, which still forms the basis for waste management in most countries:

1. Reduce or avoid waste
2. Reuse the product
3. Recycle
4. Energy recovery
5. Treatment and landfilling

Figure 2.1 provides an overview of the typical waste management chain, including the treatment options of the hierarchy.

Reduction (or avoidance) describes the impact of material efficiency and demand reduction to minimize the amount of material that is needed

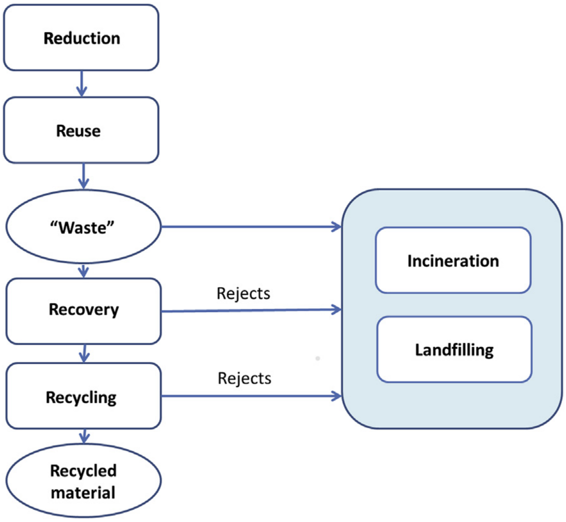

FIGURE 2.1 Simplified depiction of the typical waste management chain.

to satisfy a material service (Worrell et al., 1995). This may also include reducing the need for the service in the first place. Other options are lengthening the service lifetime of a product (either by design or through repair), or increasing the yield in the supply chain of a product (i.e. reducing material or off-spec product losses in the different production steps of a product) (Allwood et al., 2011). Note that this may reduce the amount of material available for recycling, as e.g. less "home" or "new" scrap may be generated (see below). Material efficiency is increasingly getting attention again, as resource efficiency is slowly gaining traction.

Reuse allows for the reuse of the product in which the material is contained, by (re-) designing a product for multiple uses (e.g. refillable bottle versus single-use bottles) or setting up a market for reusable goods (of which many can be found, both in industry and households). Exchange systems can be very effective means to reuse products, as, for example, evidenced by the success of online auction systems such as eBay and others in many countries.

Recycling aims at recycling the materials contained in the products that are recovered from the waste stream. Potentially, recycling can 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. The fraction of a material that can reenter the life cycle will depend both on the material itself and on the product it was part of, as (still) the quality and purity of the recovered material determine its future applicability. Recycling rates are defined in various ways, affecting the figures dramatically (UNEP, 2011). First of all, the recycling rate is determined by the volume of material that is recovered or actually recycled. This volume can also include material that is generated during the production of the material, manufacturing of products, or at end-of-life. For example, in metals, the following categories of recovered material are discerned (Graedel et al., 2011):

- *Home scrap*: scrap material arising internally in production sites or mills as rejects, e.g. from melting, casting, rolling or other processing steps.
- *New (pre-consumer) scrap*: scrap from fabrication of the material into finished products.
- *Old (post-consumer) scrap*: scrap from obsolete products that is recovered, traded and sold to plants for recycling.

Furthermore, the rate is affected by the basis on which it is calculated, e.g. the volume of material sold in the market, produced in a country or region, or the total amount of the material available in the waste.

Energy Recovery generally applies to the recovery of (part of the) embodied energy in the materials in the products, using a number of techniques, including the production of refuse-derived fuel for industrial processes (e.g. in cement making) or specialized boilers, incineration with energy recovery in waste-to-energy (WTE) facilities, or through anaerobic digestion of biologic/organic materials in the waste. Note that the latter process may also take place in a landfill, and the landfill gas may be recovered for energy production. The efficiency of energy recovery of these systems may vary largely, and could be very low (e.g. 12–15% for older WTE facilities).

Treatment and landfilling are waste management techniques to reduce the environmental and health impacts (if properly controlled) of waste, and do generally not result in recycling or recovery from resource. In many developing countries, but also the United States, landfilling is still the main waste management option, while in developing countries this is often done in uncontrolled and non-sanitary landfills, resulting in negative impacts on the local environment, water and air quality, as well as human health. In some specific cases, old landfills have been mined to recover some of the materials contained in the landfill. In practice, this has only been economically interesting for selected metals and is determined by local economic conditions.

Figure 2.1 also distinguishes various indicators to measure the success of a recycling program, i.e. recovery and recycling rates. These terms are often used, but also often not clearly defined. Hence, caution is needed when interpreting reported rates.

Recovery rate refers to the volume of material recovered from a waste stream. However, different definitions are found in the literature. Typically, it can be defined as the volume of material recovered from a waste stream divided by the amount of material in the generated waste.

Recycling rate often refers to the volume of material collected for recycling—generally including any material rejected during processing—divided by the volume (weight) of waste generated. However, more correctly, the rejected material should be subtracted, and only material marketed for recycling after processing should be included. Differences may hence be found in where the volume of recycled material is counted, and how the volume of material in the waste is estimated. The most rigorous way would be to dynamically simulate the material cycles in all its complexity, but data are often lacking.

Recycling efficiency. The total amount of material available for reuse will be affected by any material losses (due to e.g. quality, color or processing) during the recycling process itself. This can be defined as the recycling efficiency, or output of the recycling process divided by the input. For metal recycling, the recycling efficiency would be defined as the amount of scrap melted (output)/amount of scrap recovered (input).

The relation between the three indicators can be given as:

$$\text{Recycling Rate} = \text{Recovery Rate} * \text{Recycling Efficiency} \qquad (2.1)$$

Recycled content. This is the fraction of recycled or secondary material in the total input into a production process.

2.3 MATERIALS AND PRODUCTS

Typically, recycling focuses on materials, while the first two steps in the waste management hierarchy focus on products. An integrated view on recycling in the waste management hierarchy also puts a central focus on the product (Allwood et al., 2011), which will enable reduction, reuse and also the efficient recovery of recyclable materials from a product. In other words, an efficient waste management system should be centered on the product, and less on the material, or what is called a product-centric approach. A *mineral-centric approach* or in other words a *product (mineralogy) centric* view (UNEP, 2013) is required to maximize resource efficiency rather than a simpler material-centric view that considers things material by material. It is this depth that lies at the heart of the recycling, recycling simulation models for optimization of resource efficiency and design for recycling/resource efficiency. It is the application of this depth that will enhance closing of the loop because it will permit a much deeper understanding between all actors than the current understanding.

This will help us to better understand, sample, quantify products and recycling on element/compound/alloy level, and simulate the performance of recycling systems, also in relation to product design. This rigor in the recycling will also help to increase the general level of sophistication in the field and bring it to a similar level of detail and sophistication as common in the producing industry, something which is very important when discussing such initiatives as design for recycling, resource efficiency and eco-design, and labeling for recycling/environmentally optimized products.

A *product-centric* approach considers how to increase the recycling of a product (e.g. an LCD screen, mobile phone, car, solar panel) in its entirety and therefore considers the complex thermodynamic and physics aspects and interactions that affect their recovery. This necessarily involves consideration of what will happen to the many different materials within the product, and enables decision makers to more easily look at how the products are collected and how design affects outcomes. However, it is to be noted that design for recycling is not the golden bullet it is made to be, as functionality often determines the material connections, overriding their incompatibility for recycling. However, some companies have used similar approaches to design equipment (or components thereof) for reuse, allowing the use of remanufactured parts in e.g. new copiers (e.g. Xerox) or machinery (e.g. Caterpillar).

Also, note that the order of the steps goes (generally) hand in hand with a decreasing amount of energy recovered in the processing of the material. Reduction will obviously save the largest amount of energy, while reuse recovers more from the energy embodied in the product/materials than recycling. However, after a certain degree of reuse, inevitably the product will land in the recycling chain and its materials will be recovered. The energy needed for recycling is generally substantially less than the energy needed to produce the material from ores. Landfilling will recover only the smallest part of the embodied energy, in fact, only from the organic fraction if landfill gas would be recovered.

While the hierarchy forms the theoretical basis for a waste management strategy, in practice in many countries some of the steps in the hierarchy may be lacking for specific waste or product streams. This failure is one of the reasons why there is still a very large potential for improving resource efficiency in today's economy.

2.4 APPLYING THE PRODUCT-CENTRIC APPROACH—METALS

Metals, their compounds and alloys have unique properties that enable sustainability in innovative modern infrastructures and through modern products. Through mindful product design and high (end-of-life) collection rates, metals and their compounds can enabling sustainability, and other products can be recovered as well; thus recovery and therefore recycling of metals can be high. However, limitations on the recycling rate can be imposed by the (functionality driven) linkages and combinations of metals and materials in products (UNEP, 2013).

Figure 1.3, Figure 1.4 and Figure 2.2 shows various factors that can affect the resource efficiency of metal processing and recycling. The interaction therefore of primary and secondary recovery of metals not only drives the sustainable recovery of elements from minerals but also provides the recycling loop that recovers metals from complex products and therefore enables the maximum recovery of all elements from designer minerals. It is self-evident that "classical" minerals processing and metallurgy play a key role in maximizing resource efficiency and ensuring that metals are true enablers of sustainability. Thus key to recycling of complex consumer goods is:

- Mineral processing and metallurgy — foundation
  - The link of minerals to metal has been optimized through the years by economics and a deep physics understanding.
  - There is a good understanding between all actors from rock to metal.
- Product-centric vis-à-vis metal-centric recycling
  - Designer minerals (e.g. cars) as shown in Figure 1.3, Figure 1.4 and Figure 2.2 are far more complex than geological minerals, complicating recovery.

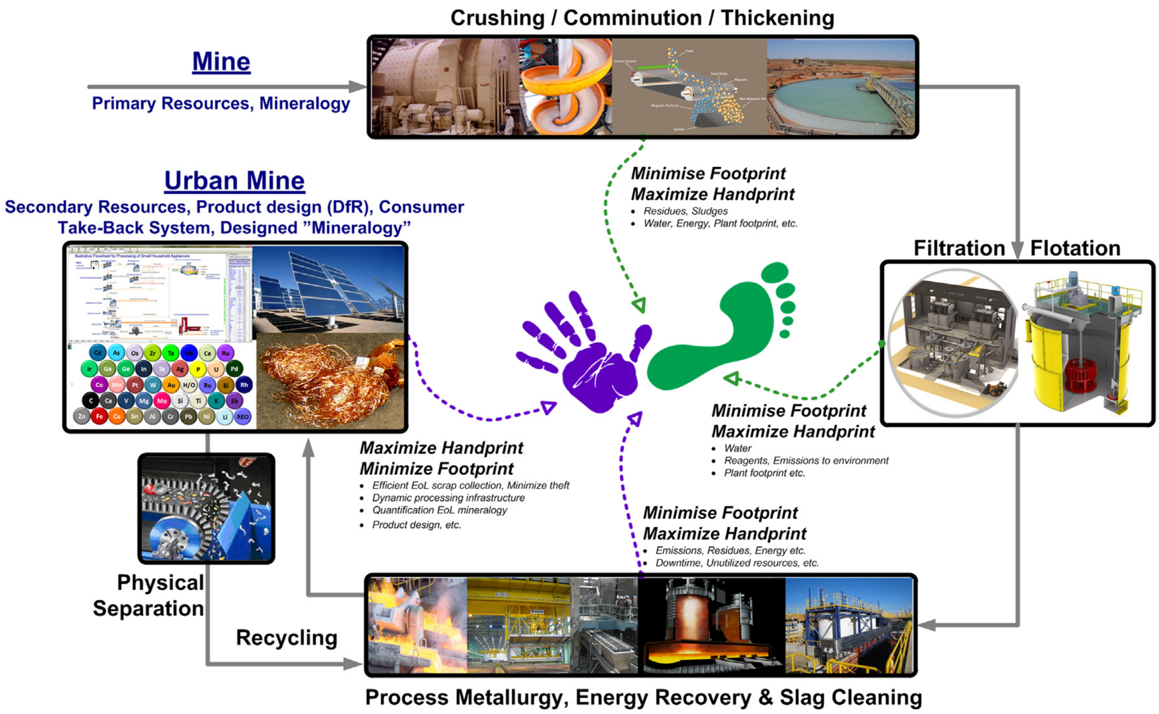

FIGURE 2.2 Design for resource efficiency. Optimally linking mining, minerals processing, (BAT) Best Available Technique(s) for primary and secondary extractive metallurgy, energy recovery, original equipment manufacturers and product design, end-of-life products, recyclates, residues and wastes, while minimizing resource losses.

- To "close" the loop requires a much deeper understanding between all actors of the system than is the case currently. Resource efficiency will improve if this is achieved.
- Metal/material-centric recycling is a subset of product-centric recycling
  – Various definitions exist for material-centric recycling of metals as documented in a report by UNEP (2011), for example, how much of the end-of-life (EoL) metal is collected and enters the recycling chain (old scrap collection rate), the recycling process efficiency rate and the EoL-recycling rate (EoL-RR).
- This deeper understanding of recycling will help to develop sensible, physics-based policies.

The use of available minerals processing and process metallurgical theoretical depth to describe the system shown in Figure 2.2 is required to understand the resource efficiency of the complete system. A fundamental description of the system also shows what theory and methods still have to be developed to innovate the primary and recycling fields further. It is evident from Figure 2.2 that the rigorous theory developed in the classical minerals and metallurgical processing industry over the years and more recently adapted for recycling is very useful to quantify the various losses shown in Figure 2.2. "Classical" minerals processing and process metallurgy therefore both have a significant role to play in a modern resource-constrained society. Identifying the detailed metal, compound, and other contents in all flows will help in optimizing the recycling system, as is already the case for the maximum recovery of metals in concentrates from known ore and product streams, giving a rather precise mass balance for all total, compound and elemental flows (see Figure 1.3).

The recycling and waste processing industry has much to gain to implement and adapt techniques and thinking of our industry rather than following the conventional bulk flow approaches of a material-centric mindset of waste management and derived legislation, which are often colored by this thinking.

Three major factors determine the outcomes of recycling expressed as a recyclability index (RI): (1) the way waste streams are mixed or pre-sorted during collection; (2) the physical properties and (3) design of the end-of-life products in those waste streams. These factors all affect the final recovery and subsequent production of high quality metal, material and alloy products. These factors interrelate in ways that make it impossible to optimize one without taking into account the others. To get the best results out of recycling, the stakeholders of the recycling system (e.g. in design, collection, processing) need to take into account what is happening in the other parts of the system. They also need to consider how to optimize along the chain the recycling of several metals found within one product, rather than only focusing on one or two major metals (and their alloys and alloying elements) and ignoring the rest of the periodic table.

Figure 1.3, Figure 1.4 and Figure 2.2 provides an overview of all the actors and aspects that have to be understood in a *product-centric* systemic and physics-based manner in order to optimize resource efficiency. Also a clear understanding of the various losses that occur is imperative (many governed by physics, chosen technology and linked economics), which also requires a deep compositional understanding of all residues, but also the understanding of unaccounted flows (poor statistics, data as well as collection) and the economics of the complete system are critical. Especially also understanding and controlling the dubious and illegal flows as well as theft, etc. will help much to maximize recovery, but this is a relatively simple task organized by leveling the playing field by suitable policy. Maximizing resource efficiency, and therefore design for resource efficiency, considers and embraces Figure 2.2 in its totality. This requires rigorous modeling techniques to pin-point, understand and minimize all losses. It also requires a detailed understanding of the technology of recycling, both physical and metallurgical, as discussed in detail by Reuter and Van Schaik (2012) and Van Schaik and Reuter (2012).

In summary, it is extremely important for resource efficiency to step away from the material perspective to the product perspective. A particular focus will be the recycling of the high-value, lower-volume metals that are essential elements of today's and tomorrow's high tech products, as applied in complex multimaterial design such as electronics and vehicles (also aircraft) or generation and storage of renewable energy. These metals, such as gallium, rare earth elements, platinum group elements and indium, are often scarce, essential to sustainable growth and yet typically lost in current recycling processes.

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