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# Introduction

The subject of this book is mechanical recycling, also known as physical recycling or materials recovery. Its goal is to separate solid waste into valuable and residual fractions. The valuable fractions are returned to industrial material cycles, while the residual fractions are either further processed in subsequent recycling steps or finally disposed of.

The history of recycling dates back to ancient times. Early civilizations practiced reusing materials to conserve resources and minimize waste. In ancient Mesopotamia and Egypt, metals such as bronze and copper were remelted to make new tools and weapons. Recycling also played an important role in the Roman world: glass was collected, re-melted, and formed into new objects, and even ceramics and construction debris were reused.

In the Middle Ages, recycling was driven primarily by economic considerations: the revenue from recycled products covered the cost of collection and reprocessing. Metals, especially tin, copper, and iron, were remelted and reshaped. Rag collectors roamed the cities, collecting old textiles that were turned into paper. Wood was scarce, so in some regions waste paper was already being reused to make new paper products. Glass bottles were also often collected and refilled.

With industrialization in the 19th century, global consumption of raw materials increased rapidly, posing new challenges for waste management. Municipal waste became a serious problem, and structured waste management systems began to emerge in which valuable fractions were recycled while residual fractions were disposed of, usually in landfills.

Scrap yards were set up in many European countries to recover metals such as copper, tin, and iron. Even bones were collected and turned into glue or fertilizer. In England, building materials were made from ash and coke residue. During the world wars, recycling became even more important: raw materials were scarce, and metals, rubber, textiles, and even paper were actively collected and reused. People were encouraged to collect scrap materials to support the war economy.

In the second half of the 20th century, growing environmental awareness combined with regulatory frameworks and technological innovation led to the development of modern recycling technologies. Waste separation programs and the broader concept of a circular economy began to take shape.

## 1.1 Paradigm Shift: From Waste Management to a Circular Economy

### 1.1.1 From a Linear to a Circular Economy

Traditionally, waste management has followed a linear model: raw materials are extracted, used, and eventually disposed of. In this "take-make-dispose" system, the use of resources and the generation of waste are directly linked: one ton of raw material results in one ton of waste. In the long run, this has two consequences: a depletion of resources and an increase in waste.

For many decades, landfills and incinerators dominated waste management. The rapidly increasing diversity of materials used during the 20th century led to an increasingly complex composition of waste streams and produced large quantities of toxicologically relevant hazardous waste. As a result, protection of the environment from harmful substances became a major driver for modernizing waste management, along with resource conservation.

Fortunately, the world's population is becoming more affluent, which is reflected in rising gross domestic product. However, in a linear waste management system, GDP growth is directly correlated with resource consumption, which in turn leads to a proportional increase in waste generation.

Greater prosperity leads to higher levels of consumption, which in turn leads to greater resource use and more waste (Figure 1.1). This is where the circular economy comes in. Its central idea is to keep raw materials in the economic cycle

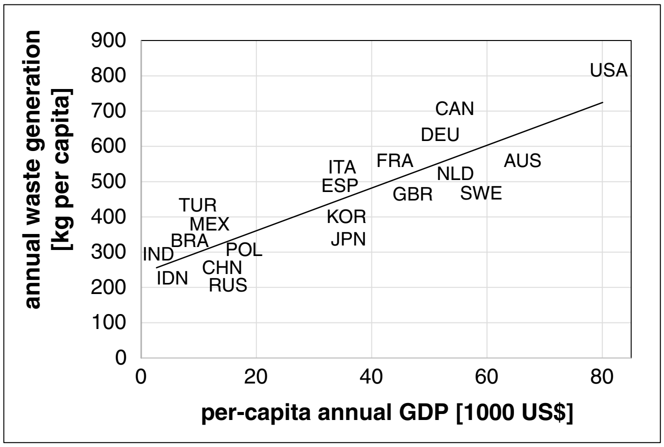


**Figure 1.1** Data from 20 industrialized and emerging economies. Waste generation increases with gross domestic product (base year 2024).

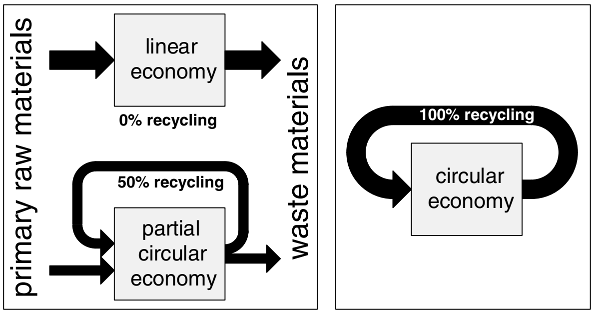


**Figure 1.2** (Left) Linear economy and partial circular economy. (Right) Full circular economy.

for as long as possible through reuse, repair, and recycling (Figure 1.2). Achieving this requires technological innovation, new business models, and a fundamental shift in societal thinking.

Another key driver in the transition from waste management to a circular economy is technological progress, particularly in recycling, materials science, and digitalization. Innovative sorting technologies and new approaches to material design are enabling increasingly efficient recovery of raw materials. Digital solutions such as traceability systems and intelligent recycling centers help optimize recycling processes. Legislation also plays an important role. In the EU, the Green Deal and the Circular Economy Action Plan have established binding requirements to promote the circular economy.

The transition to a circular economy has far-reaching economic implications. Businesses can reduce costs by using resources more efficiently and enter new markets. At the same time, new business models are emerging, such as “product as a service,” in which companies no longer sell products physically but offer their use as a service (for example, rental models for electronic equipment). As a point of reference, the recycling industry in developed countries accounts for about one percent of gross domestic product.

Transforming society into a circular economy requires a change in mindset among both enterprises and consumers. Education and awareness-raising play a central role in this process. However, a circular economy imposed by legislation alone runs counter to the principles of a market economy and can therefore be highly inefficient (see Section 1.3). This challenge is compounded by the fact that the circular economy debate is often ideologically charged in political discourse. This can lead to the implementation of measures that are not economically sound. There are many examples of environmentally motivated policies that have spent large sums of money on measures that seemed intuitively beneficial but were questionable from an objective point of view. A balanced circular economy should therefore always consider all three dimensions of sustainability equally: environmental, economic, and social. The paradigm shift from a linear waste management system to closed material cycles is essential, but it must be implemented with a sense of proportion. Technological innovation, regulatory measures, and societal engagement—while recognizing financial constraints—are key factors for the success of this transition. Only under these conditions can the circular economy deliver sustainable economic growth while protecting resources and the environment.

### 1.1.2 Recycling and Environmental Impact

In most cases, the supply of industrial raw materials (e.g., metals) through recycling is environmentally much better than processing primary raw materials. Compared to recycling, primary materials typically go through a much longer processing chain. As a result, they consume more energy and water and release greater amounts of $CO_2$ and other pollutants into the environment. The environmental impacts of recycling processes are typically only about 5–20% of those associated with the production of primary raw materials. The difference in environmental impact between primary production (e.g., from crude oil) and recycling (e.g., from PET bottles) is credited to recycling as an environmental benefit in *Life Cycle Assessments*, LCA. The terminology used in the recycling industry is inconsistent and often confusing. For the purposes of this book, the following definitions are used:

- A *raw material* is the starting material used for the production of *industrial raw materials*. It may be a *natural primary resource* (crude oil, ore, wood) or a *secondary resource* with waste characteristics (electronic scrap, mixed demolition waste).
- The process that converts a raw material into an industrial raw material is either *primary material processing* or a *recycling process*. Example of primary material processing: converting a natural raw material into an industrial raw material (e.g., ore into pig iron, crude oil into naphtha).
- In a subsequent processing step, industrial raw materials are refined into sector-specific base materials. Examples:
  - Pig iron (industrial raw material) is converted into steel (a base material used, for example, in mechanical engineering).
  - Naphtha (industrial raw material) is converted into polyethylene pellets (a base material for the plastics-processing industry).

  In recycling processes, secondary raw materials are often converted into base materials in a single step. For this process, a homogeneous and well-sorted waste collection is advantageous. For example, high grade steel scrap can be processed directly into reinforcing steel.
- Industrial raw materials and base materials produced from primary or secondary resources are referred to as *primary products* and *secondary products* (recycled products), respectively.

In Table 1.1, several examples of the production chains from primary and secondary raw materials to the corresponding products are shown.

**Table 1.1** Examples of production chains for base-material supply.

| | **Primary raw material** | **Secondary raw material** |
|---|---|---|
| **Raw material** | Crude oil<br>Iron ore<br>Gravel | PET bottles<br>Iron scrap<br>Mixed demolition waste |
| | | |
| **Industrial raw material** | Naphtha<br>Pig iron<br>Washed gravel size fractions | PET flakes<br>Shredded scrap<br>Concrete granulate, brick granulate, ... |
| | | |
| **Base material** | Polyethylene pellets<br>Steel<br>Certified RC-concrete aggregate | PET regranulate<br>Recycled steel<br>Certified recycled construction material |

## 1.2 Importance of Recycling for Waste Management

Recycling processes convert plastics, metals, minerals, and other valuable materials into reusable resources and return them to the production cycle. As a result, the amount of waste that must be incinerated or landfilled is reduced, and the environmental impact is minimized. The relationship between recycling and other areas of waste management can be illustrated using the waste hierarchy. This hierarchy serves as a rule of thumb for setting priorities in waste management. The order of priorities is based on environmental benefits, with waste prevention at the top and landfilling at the bottom (Figure 1.3). Recycling is ranked second and therefore takes precedence over all other disposal methods for waste that cannot be avoided.

- Upcycling is the process of adding value to the original material. Examples include the use of used coffee grounds to make coffee cups or the design of high-quality fashion accessories from textile waste. In practice, however, successful upcycling is mostly limited to creative curiosities, and its material flows are negligible compared to those of downcycling.
- Downcycling refers to the transformation of materials into inferior products through recycling. This is common for plastics and paper, whose components (macromolecules, fibers) lose quality with repeated recycling cycles. The same is true for mineral wastes, whose recycled products usually still contain residual levels of contaminants. In summary, recycling is, in practice, downcycling.

Another important argument for the relevance of recycling is its economic importance. In many countries, the recycling industry is an important economic sector, creating jobs and driving technological innovation. Modern recycling facilities are

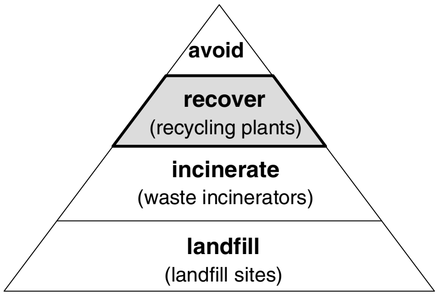


**Figure 1.3** Position of recycling in the waste hierarchy. For unavoidable waste, recycling has the highest priority.

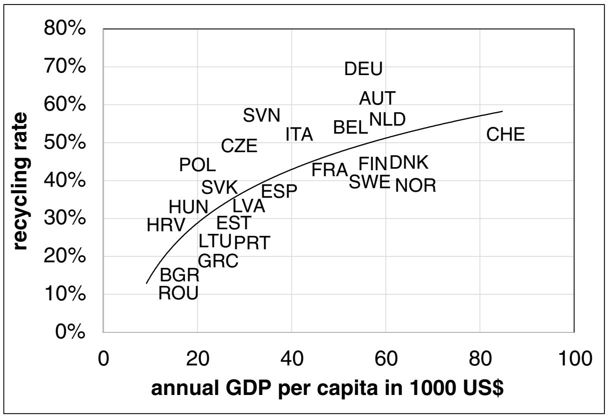


**Figure 1.4** Data from selected countries in Europe. As GDP rises, not only does waste generation increase, but so does the recycling rate. Only wealthy countries can afford a circular economy (base year 2024).

constantly optimizing their processes to improve the quality of recycled products and develop new applications.

At the same time, the circular economy supports sustainable development by encouraging enterprises and consumers to use resources more efficiently. Figure 1.4 shows that the recycling rate increases as GDP increases. This puts into perspective the statement in Figure 1.1 that waste generation increases with GDP. Wealthy countries may generate more waste, but they dispose of it in a much more environmentally responsible way than poorer countries, primarily through recycling and incineration rather than landfilling. The environmental impact of the significantly higher waste generation in developed countries is more than offset by extensive recycling and regulated incineration with energy recovery. On balance, countries with a high gross domestic product have a lower environmental impact than countries with a low gross domestic product, even though they generate more waste.[1]

1 Important note: This statement applies only to **the environmental impacts of waste disposal**. On the *consumption side*—including the **environmental impacts caused by producing the goods consumed**—wealthier countries place a far greater burden on the environment than poorer countries.

Market prices for recycled products allow an approximate assessment of the economic viability of recycling for different material groups. For an approximate indication of order of magnitude, the following list is used, in which the revenue from recycled aluminum is normalized to 100%:

| | |
|---|---|
| Copper: | 500% |
| Aluminum: | 100% |
| Stainless steel: | 100% |
| Plastic pellets: | 100% |
| Steel: | 10% |
| Recycled paper: | 10% |
| Gravel and sand: | 1% |

It goes without saying that high-value materials (e.g., precious metals) are recycled with particular care. Effective recycling, however, also requires an appropriate infrastructure. Industrial metals such as iron, copper, and aluminum are purchased at current market prices at virtually every scrap yard in the world and returned to the established process chains of metal production. The higher the turnover in the regional scrap trade, the better the recycling infrastructure and the higher the recycling rate (Figure 1.5). Interestingly, paper as a raw material follows roughly the same trend as metals.

In contrast, recycling rates for glass and plastic bottles are surprisingly low, despite their high global sales volumes. This is due to a variety of factors. A key difference with metals (and paper) is that recycling glass and plastics, while environmentally beneficial, is significantly more expensive than recycling metals. A major cost driver is that for glass and plastics, color is an essential quality attribute (especially high transparency), and even minute impurities severely limit the usability of the recycled granules. Plastic recycling is also costly because the low density of plastic

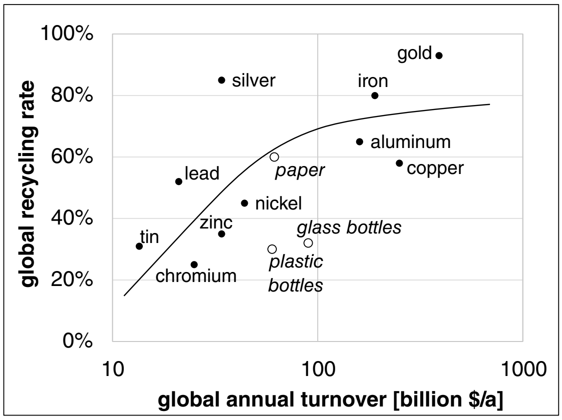


**Figure 1.5** Turnover versus recycling rate. Materials traded globally in large quantities and/or at high prices exhibit high recycling rates (base year 2024).

bottles makes transportation about five times more expensive than for much heavier materials such as metals, paper, and glass. As a result, the recycling of glass and plastic bottles is generally not market-driven and instead requires legal enforcement. Non-market-driven recycling can therefore, in practice, only be implemented in wealthy, industrialized countries (see Subsection 1.3.2). This is particularly true for the collection and recycling of plastics.

A major economic driver for recycling today is the increasing scarcity of landfill space, particularly in densely populated regions. This issue is usually not primarily an environmental or geological one but a social one. While the public generally recognizes the need for landfills, there is strong opposition to their construction near residential areas—a phenomenon known as "Not in My Backyard" (NIMBY). This opposition is making it increasingly difficult to build new landfills, while existing sites are beginning to reach their capacity limits.

Where landfill space is a scarce resource—for example, in the immediate vicinity of cities—the costs of landfilling rise. This increase in price improves the economic competitiveness of alternative waste-management pathways: recycling becomes economically more attractive. This aspect is particularly relevant for the treatment of construction and demolition waste. Although C&D waste recycling is generally low-tech and comparatively inexpensive, product revenues are low compared with those generated from metals recycling. In regions where NIMBY-driven opposition leads to high landfill costs, high-tech processing plants are therefore installed even for C&D wastes to minimize the amount of residual waste requiring disposal.

## 1.3 Limits of Recycling

Recycling reduces raw material consumption, saves energy, reduces environmental pollution, and offers economically attractive prospects. However, political discussions often overlook the fact that recycling also has its limits.

### 1.3.1 Economic Boundaries

Although recycling ranks above incineration and landfill in the waste pyramid, very high recycling rates lead to unacceptable costs. As shown in Figure 1.6, the revenues from the sale of recyclable materials increase proportionally with the recycling rate. However, the costs of material recycling increase disproportionately—the closer the recycling rate approaches 100%, the more expensive the treatment per ton of recyclable material becomes and the higher the specific costs ("increasing marginal costs"). Profit is calculated as revenue minus costs. It initially rises, reaches an optimum, and then falls again at high recycling rates. It is important to note that once a certain recycling rate is exceeded, the accumulated profit is depleted and becomes negative (i.e., a loss). If recycling were left to the market economy, the recycling rate would level off at the economic optimum.

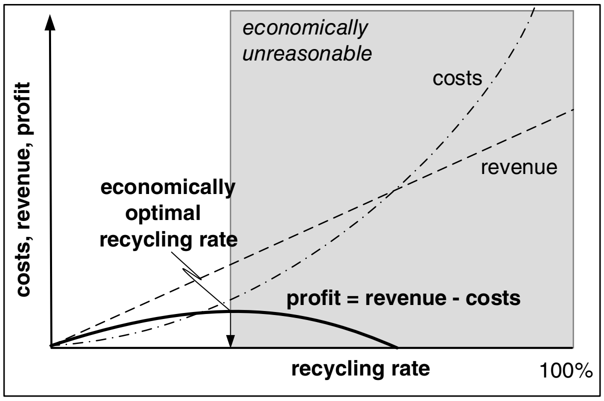


**Figure 1.6** With rising recycling rates, the "economic profit" reaches a maximum (economic optimum) before declining and eventually becoming negative. 100% recycling is not economically viable.

Where the costs of recycling are lower than the costs of primary raw material processing, recycling even works with very high recovery rates solely due to market economy mechanisms.

### 1.3.2 Ecological Limits

The extraction of primary raw materials involves not only internal production costs, but also external costs resulting from the environmental damage caused (e.g., $CO_2$ emissions, pollution of soil, air, and water, etc.). These external costs are usually passed on to the general public, meaning that the economic profits of companies are partly achieved at the expense of society. To prevent this, the state—quite rightly—uses environmental legislation to "artificially" increase internal production costs so that at least part of the external costs are shifted to the polluters and thus "internalized" by the companies. Companies pass on the higher production costs resulting from additional environmental regulations to consumers via product prices, which leads to problems when competing (foreign) companies are not required to comply with the same environmental regulations.

Eager environmental politicians should not forget that the separate collection of selected waste fractions and their recycling are industrial processes that consume resources and release pollutants (e.g., $CO_2$ emissions from transport, electrical energy, chemical use, water consumption, etc.). This can lead to an ecological dilemma, quite apart from the enormous costs of ambitious recycling targets. With excessively high recycling rates, the specific ecological cost of providing recycled products exceeds the ecological cost of primary raw material products. The ecological balance then tips into negative territory (Figure 1.7).

Conclusion: Recycling is good, more recycling is better, but excessive recycling is counterproductive! A 100% circular economy is neither affordable nor ecologically sensible.

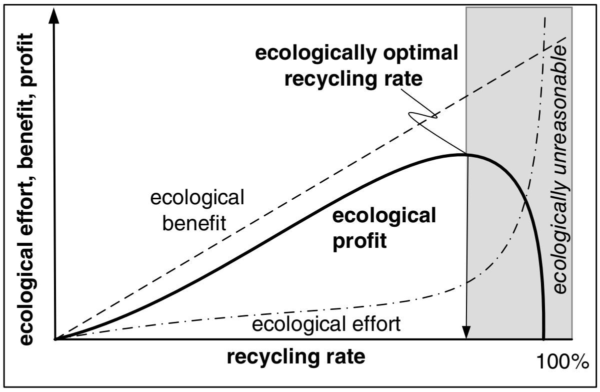


**Figure 1.7** The "ecological gain" also peaks (ecological optimum) as the recycling rate increases and then falls into negative territory. Recycling rates exceeding the ecological optimum are therefore ecologically nonsensical.

In order to obtain an overview of the position of individual recycling measures within the overall recycling landscape, a selection of recycling measures has been listed in Table 1.2 and presented in Figure 1.8. The horizontal axis of Figure 1.8 shows the additional costs of the environmental measures considered in comparison to the baseline scenario. The vertical axis shows the environmental benefits compared to the baseline scenario.[2] The following examples from Table 1.2 serve to illustrate this:

- **Plastic recycling vs. incineration or landfill** (measure 1 in Table 1.2): Plastic recycling is more environmentally friendly than incineration or landfill, but it is also more expensive. It is therefore classified in the lower right quadrant ("legally mandated recycling") in Figure 1.8. The same applies to measures 2–7.
- **Politically motivated, excessive recycling rates** (measure 9, upper right quadrant in Figure 1.8: "irrational recycling"): As already discussed, excessive recycling rates can paradoxically lead to additional environmental pollution. One example is the recycling of indium, which occurs in tiny traces as indium tin oxide in the plastic-glass sandwich of computer monitors. Depending on the process, recovering this highly dispersed indium from monitors can be more ecologically costly than extracting it from primary raw materials or recovering it from mining waste, which is also a recycling measure. A similar problem can arise with biomass: If it is separately collected with great emphasis (for fermentation or composting) instead of being sent to waste incineration, this can be ecologically disadvantageous. Studies show that forced recycling rates for biomass can lead to significant amounts of plastics entering the recycled secondary raw material product (e.g., compost) and being released into the environment as microplastics.

2 The benefits or harms of an environmental measure compared to a baseline scenario can be quantified using life cycle assessments LCA. One example is the conversion of avoided methane emissions into $CO_2$ equivalents. Depending on the method and period under consideration, the emission of 1 ton of methane is roughly as harmful to the climate as the emission of 60 tons of $CO_2$.

**Table 1.2** Evaluation of environmental measures compared to baseline scenarios.

| | Recycling measure vs. | Baseline scenario | Increases environmental impact | Increases costs |
|---|---|---|---|---|
| 1 | Plastic recycling | Incineration/Landfilling | – | + |
| 2 | Household battery recycling | Incineration/Landfilling | – | + |
| 3 | Paper recycling | Incineration | – | + |
| 4 | Biomass recycling | Landfilling | – | + |
| 5 | Glass recycling | Landfilling | – | + |
| 6 | Construction and demolition waste recycling | Landfilling | – | + |
| 7 | Aluminum can recycling | Incineration/Landfilling | – | + |
| 8 | Indium recovery from monitors | Indium Extraction from Ore | + | + |
| 9 | Recycling with an excessive target rate | Standard recycling | + | + |
| 10 | Private burning of used tires | Incineration | + | – |
| 11 | Export of electronic scrap to an emerging economy | Incineration | + | – |
| 12 | Gold recycling | Incineration/Landfilling | – | – |
| 13 | Platinum/palladium catalyst recycling | Landfilling | – | – |
| 14 | 40% NF-metal recovery from MWI ash | Landfilling | – | – |
| 15 | 70% NF-metal recovery from MWI ash | Landfilling | – | + |
| 16 | 95% NF-metal recovery from MWI ash | Landfilling | + | + |

*NF = nonferrous metals; MWI = municipal waste incinerator*

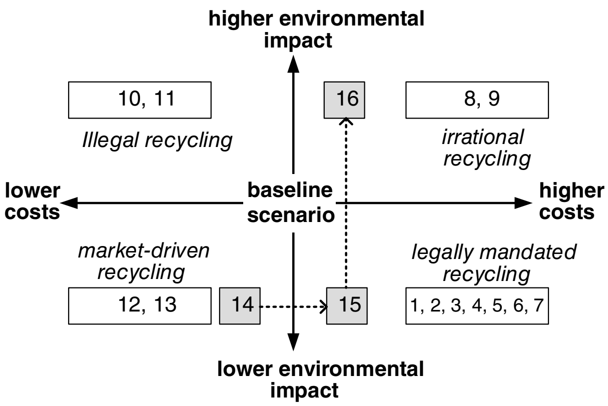


**Figure 1.8** Classification of recycling measures in terms of "costs" and "environmental impact." The baseline scenario positioned in the middle serves as a reference.

- **Lucrative business models at the expense of the environment** (measures 10 and 11): These are practices in which financial interests are pursued at the expense of the environment. A drastic example would be burning old tires in one's own garden instead of disposing of them properly at a cost—a significant environmental burden that is rightly prohibited. Another variant is the export of electronic waste to emerging countries, where it is "recycled" at financial gain, but with the release of massive pollutant emissions. As a rule, the environmental impact of improper recycling, as often observed in developing countries, far exceeds the ecological benefits of the recovered metals.
- **Market-driven recycling** (measures 12 and 13): Certain recycling processes do not require legal enforcement because the economic value of the recovered materials is sufficient to cover the associated costs. This applies, for example, to the recycling of gold and platinum, which is financed solely by the revenues. It is estimated that 90% of the gold and 65% of the copper ever mined are still in circulation.
- **Overlaps between recycling categories:** Not all recycling measures can be clearly assigned to one of the quadrants in Figure 1.8. One example is the recovery of nonferrous metals (aluminum, copper, brass) from the bottom ash of waste incineration plants. In the EU, this recovery is market-driven at a rate of approximately 40% and therefore falls into the lower left quadrant (measure 14). In Switzerland, on the other hand, a statutory minimum rate of 70% is required (measure 15), which means that the measure falls into the "legally enforced recycling" quadrant (lower right quadrant). However, if unrealistically high recycling rates of, for example, 95% were mandated, the measure may fall into the "irrational recycling" category (measure 16).

### 1.3.3 Design for Recycling

The idea of considering subsequent recycling during product development is obvious. Recycling-friendly product design is a frequently mentioned element of modern waste management to facilitate the recycling of products at the end of their useful life. The aim is to enable better separability of materials, more efficient recycling, and ultimately more sustainable use of resources.

However, this additional ecological benefit does not usually come "free of charge." In practice, products are primarily optimized for maximum customer benefit, so that recycling-friendly design often represents a compromise with other factors, and conflicts of interest arise, e.g., in the areas of technology, costs, and aesthetics.

A physical contradiction makes the problem particularly clear: during its useful life, a product should be as solid and durable as possible, but at the end of its life, it should ideally "spontaneously" disintegrate into its individual parts for easy recycling. Technically favored high-strength connections—such as gluing, welding, or riveting—are, by definition, difficult to dissolve. Alternatively, detachable screw connections can be used, but these require manual disassembly. Especially with miniaturized products, such as electronic components, disassembly becomes extremely time-consuming and expensive. In such cases, the ecological advantage of recycling comes at the price of increased technical and financial effort.

Designing products for recyclability can even lead to environmental trade-offs. For example, to meet the requirements of "low weight, high stability, and long service life," many products are made from composite materials—e.g., shoes, car bodies, or the rotors of wind turbines. A typical example is the beverage carton, which consists of plastic, cardboard, and aluminum. Compared to glass packaging, its low weight gives it a better ecological balance during transport than glass bottles, for example. At the same time, recycling the three material components is not economically feasible (as of 2025).

Design for recycling therefore always requires a compromise between technical, economic, and ecological requirements. The optimal solution depends on the product in question, market conditions, and legal requirements. Currently, recycling-friendly product design plays a minor role in practice and is largely limited to larger, easily dismantled assemblies—particularly in the automotive industry, large electrical appliances, and construction materials (e.g., doors, railings). However, future developments in the areas of circular economy, digitalization, robotics, and materials science could help to further mitigate these conflicting goals.

## 1.4 Mechanical Recycling: Process-engineering Context

Mechanical, biological, thermal, and chemical recycling are the four basic process engineering approaches to waste recycling (Figure 1.9). Of these, mechanical recycling is by far the most important for waste management. When people talk about "recycling" without further specification, they usually mean mechanical recycling.

In **biological recycling**, organic waste is converted into new products with the help of microorganisms or enzymes. A typical example is fermentation to produce biogas, a renewable energy source that can replace fossil fuels.

In **thermal recycling**, waste is processed using heat, with temperatures generally exceeding the melting point of the recyclable materials contained therein. Examples

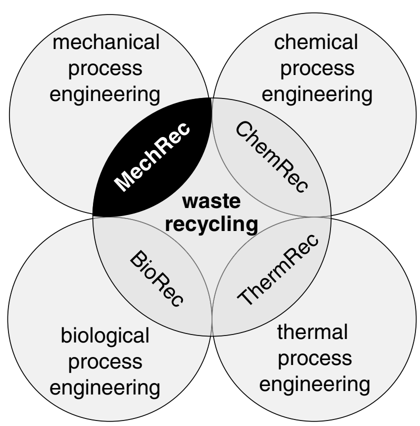


**Figure 1.9** Mechanical recycling as an overlap of mechanical process engineering and waste recycling.

include pyrometallurgy, distillation processes, and the pyrolysis of plastics—the latter is sometimes misleadingly referred to as "chemical recycling."

In **chemical recycling**, waste is dissolved and further processed through specific chemical reactions, such as leaching, electrolytic processes, precipitation, or ion exchange. Typical examples are:

- Hydrometallurgy: Leaching metals with acids, alkalis, or complexing agents
- Solvolysis: Dissolving plastics in organic solvents.
- Hydrolysis: Conversion of wood into sugar using strong acids or bases.

Since many of these processes are accelerated by elevated temperatures, there is a broad gray area between chemical and thermal recycling.

**Mechanical recycling**, on the other hand, aims to process materials without changing their chemical structure. A classic example is the recycling of PET bottles: these are crushed, freed of impurities, and returned to bottle production as purified PET granulate. The focus here is on physical separation processes for bulk particles. In this book, the term "(mechanical) processing" is used as a synonym for "material recycling," provided that it is clear that these are basic operations of mechanical process engineering and there is no risk of confusion with other recycling processes.

## 1.5 Fundamentals of Mechanical Recycling

In process engineering literature, many technical terms are used inconsistently. In this book, we adhere to the terminology introduced in this chapter. An overview is provided in the glossary in the appendix. A single grain of material is referred to as a particle. A collective of particles that can move relative to each other is referred to as bulk material. A processing plant consists of several unit operations in which the basic process engineering operations are carried out, e.g., comminution, magnetic separation, or filtration. These units are connected to each other by conveyor systems—usually conveyor belts or pipelines.

### 1.5.1 Basic Technical Operations

The technical objective of processing is to separate a solid target material from a feed material consisting of the target material and the matrix material (Figure 1.10).

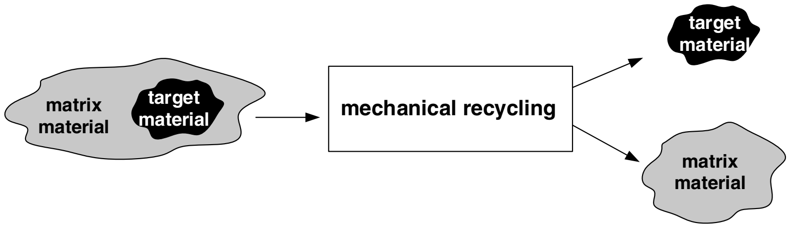


**Figure 1.10** The technical objective of mechanical processing is to separate the target-material from the matrix material.

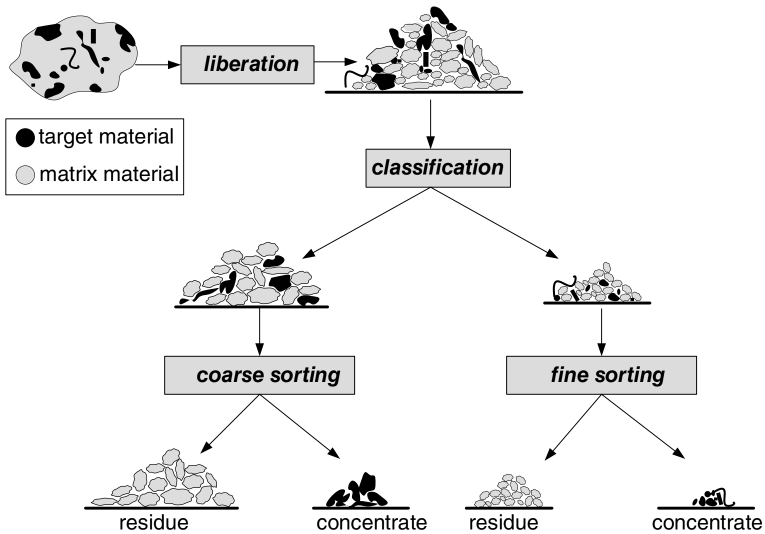


**Figure 1.11** Typical structure of a recycling plant. The prerequisite for perfect separation of target material and matrix material is complete liberation of the target material and classification of the material streams into narrow size fractions.

The target material is usually a single substance (e.g., PVC) and, in some cases, a clearly defined class of substances (e.g., all nonferrous metals). The matrix material, by contrast, comprises all solid constituents of the material stream other than the target material.

Since the matrix material often consists of many different solids, the term "material" is deliberately used here in a broader technical sense rather than in the narrower chemical sense. This makes it possible to represent the feed material as a binary mixture of target material and matrix material, which greatly simplifies the description of technical separation processes with two product streams.

Mechanical processing methods essentially comprise the following three steps (Figure 1.11):

1. Liberation by comminution: releasing the valuable materials from their composite with other materials. After this step, the valuable materials exist as pure particles within a bulk solid, which is then processed further.
2. Classification by particle size.
3. Sorting of each size fraction according to material properties.

**Liberation:** In waste materials, target and matrix materials are usually present in some form of composite. Important types of recycling-relevant composites are illustrated in Figure 1.12. Coatings may include, for example, surface-applied paints. Pressure-impregnated wood also behaves like a coating system: the outer 25 mm may be impregnated with a fungicide, while the wooden core remains uncontaminated (e.g., railway sleepers). A typical example of a laminate is safety glass (e.g., automotive windshields), where a "sandwich" structure of glass and polymer films is present.

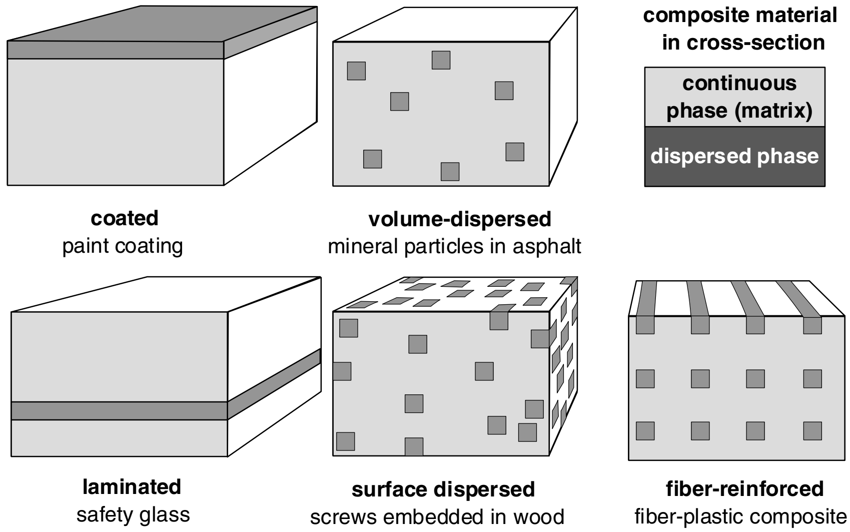


**Figure 1.12** Composite structures relevant to recycling. In practice, these are often hybrid forms of the five types shown, e.g., 4-layer printed circuit boards.

Volume-dispersed composites are characterized by one material occurring as particles (dispersed phase) embedded within a continuous phase (matrix). Examples include asphalt and concrete, in which mineral particles are bound within a continuous binder phase (bitumen, cement paste). Another example is metallurgical slags or sintered mineral residues from waste incineration in which metal pieces are embedded.

Surface-dispersed composites are similar to coatings, but the dispersed phase is not continuous; instead, it appears as discrete “patches” on the surface. An example is nails driven into wooden boards. Unlike volumetrically dispersed composites, the surface-dispersed particles are located on the surface, which may facilitate subsequent sorting, for instance by optical color detection. In contrast, volumetrically dispersed particles are completely enclosed by the continuous phase.

Fiber-reinforced composites are commonly encountered in polymer systems (e.g., GFRP, CFRP), where a reinforcement made of flexible, tear-resistant fibers is embedded in a brittle continuous matrix. By analogy, reinforced concrete or fiber-reinforced shotcrete can also be regarded as fiber composites.

In processing, the dispersed phase is usually the target material and the continuous phase the matrix material. Unless otherwise specified, these terms are used synonymously throughout this book (“dispersed phase” = target material; “continuous phase” = matrix material). In processing, a distinction is made between “liberated” particles—consisting either of pure target material or pure matrix material—and composite particles (Figure 1.13).

- A particle consisting entirely of target material is a target-material particle.
- A particle consisting entirely of matrix material is a matrix-material particle.
- A particle consisting partly of target material and partly of matrix material is a composite particle.

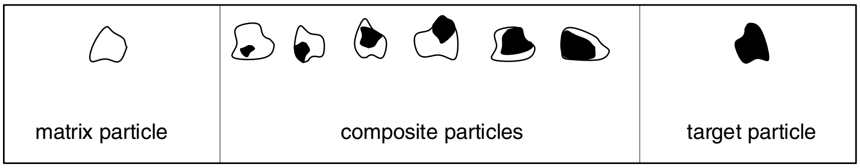


**Figure 1.13** Composites and liberation.

The liberation of the target material depends on the type of composite and on the physical properties of the materials involved. Coatings and laminates can sometimes be removed by peeling and/or by an abrasion treatment (attrition). In most cases, however, substantial comminution of the composite material is required to expose the dispersed phase. Other possible liberation mechanisms include dissolving the matrix material in acids or organic solvents. For example, industrial diamonds can be recovered from worn diamond-cutting tools by dissolving the surrounding matrix of sintered cobalt in acid.

Another example is the thermal liberation of metals in waste incineration. Metals with high melting points, such as copper and iron, remain in the form of nails or wires in large quantities in the ash of waste-to-energy plants after the surrounding organic matrix (wood, textiles, plastics) has been combusted.[3] If the continuous phase is organic, it can first be embrittled by pyrolysis, after which the resulting pyrolysis coke can be selectively comminuted to expose a ductile dispersed phase (e.g., a piece of metal) embedded within it.

**Classification:** Classification is the separation of particles by size or shape (Figure 1.14). The following terminology is used: material larger than a specified particle size is referred to as the *coarse fraction*, and material smaller than the specified particle size is referred to as the *fine fraction*. By convention, the coarse fraction is the *target material* of a classification step. Consequently, the fine fraction represents the *matrix material* of a classification step. The same logic applies to particle shape: on a long particle separator, the long particles represent the target material.

The product enriched with the target material is called the *coarse product*, while the residue is called the *fine product*. Unlike the primary aggregates industry (gravel, crushed stone, etc.), the production of classified products is not the primary goal of processing, but merely a means to enable more effective sorting. In general, the result of screening is strongly dependent on the width of the particle size spectrum in the feed. Liberation comminution produces a very broad particle size distribution, typically spanning one to two orders of magnitude. From a process-engineering perspective, it is essential to classify the total material stream into substreams with narrow particle-size ranges. These streams are subsequently processed through parallel sorting lines (Figure 1.11).

3 The bottom ash from municipal solid-waste incineration contains approximately 10% metal pieces.

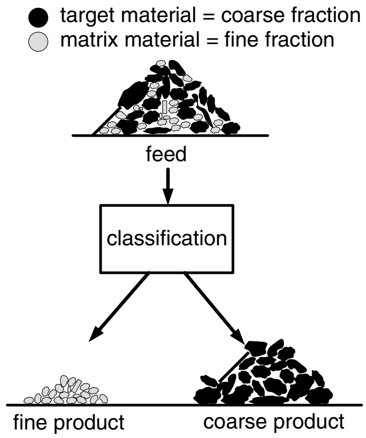


**Figure 1.14** "Perfect" classification: the fine product consists exclusively of fine particles, and the coarse product exclusively of coarse particles.

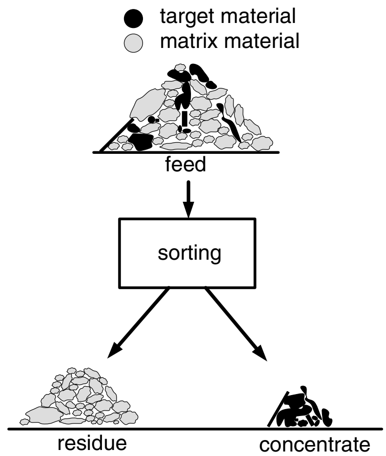


**Figure 1.15** "Perfect" sorting: the concentrate consists only of target-material, and the residue only of matrix material.

**Sorting:** Sorting processes are the core of mechanical processing, as this is where value creation takes place. The upstream operations (comminution, classification) merely prepare the material for sorting. Table 1.3 lists several examples of sorting processes.

Sorting methods use physical material properties as *separation characteristics* (Figure 1.15). The separation characteristic is the qualitative property on which the separation is based (e.g., density, electrical conductivity, magnetic susceptibility). The quantitative expression of this property is the *separation-characteristic value*. For density separation, the separation characteristic is the material density $\rho$; an example of a separation-characteristic value would be $\rho = 2600\ \mathrm{kg/m^3}$. The material with the stronger expression of the separation characteristic is, by definition, the target material in the separation process, and all other constituents form the matrix-material. Sorting enriches the target material in the concentrate and the matrix-material in the residue.

To separate target-material particles from matrix-material particles, the material stream is exposed to a physical field (e.g., a magnetic field). This field generates separation forces whose magnitude depends on the particles' separation-characteristic value. By definition, these forces act more strongly on the target material than on the matrix material. As a result, target-material particles are deflected more strongly from the original transport direction than matrix-material particles. This enables their selective removal as the concentrate (Figure 1.16).

**Auxiliary Processes:** Important auxiliary processes in mechanical processing include phase separation, which separates solids from fluids (Figure 1.17). They play an important role where very fine solid particles must be separated from large fluid streams, such as in the filtration of slurries (wet) or dusts (dry).

**Table 1.3** Examples of sorting processes.

| target material | matrix material | separation criterion/sector | separation principle |
|---|---|---|---|
| blueberries | leaves | density /household | Float-sink sorting: the leaves float in water; the berries sink to the bottom |
| Reinforcing bars | concrete | magnetizability /construction waste processing | Magnetic separation: Iron sticks to the magnet; concrete does not |
| aluminum screw cap | glass | electrical conductivity /glass processing | Eddy current sorting: eddy currents form in aluminum, but not in glass |
| bad apples | good apples | color /food processing | Visual sorting: the rotten apples are blackened |
| printing ink | paper fibers | wettability with water /waste paper recycling | Flotation: the paper fibers are water-wettable; the printing ink is water-repellent (Subsection 2.1.5) |
| wheat | chaff | sedimentation rate /food processing | Cross-flow separation: the wheat grains fall down and the chaff is carried away by the wind |

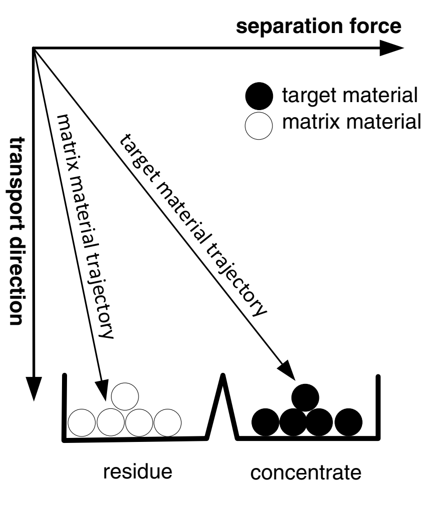


**Figure 1.16** Perpendicular to the general direction of transport, a field force acts which determines the trajectories of the particles. The target-material particles are deflected more strongly from the direction of transport by the field force than the matrix-material particles.

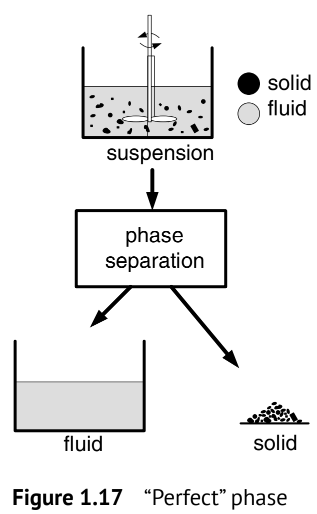


**Figure 1.17** "Perfect" phase separation: The fluid contains no solids and the solids contain no fluid. These processes are particularly relevant in the separation of fine particles by a fluid phase, which must then be cleaned again (dedusting, desliming).

### 1.5.2 Economic Perspective

The economic objective of recycling is to recover a solid valuable material from a binary raw material consisting of the valuable material itself and other solids that collectively form the residual material. In solid–solid separation, one outlet of the processing unit discharges a valuable-material product enriched in the valuable material. The other outlet correspondingly discharges a residual-material product depleted in valuable material (Figure 1.18).

In positive separation, the valuable material is actively separated from the raw material stream (the feed) by the action of the separation force. In this case, the valuable material is the target material. Negative separation, on the other hand, actively removes the residual material; in this case, the residual material is the target material (Figure 1.19). For clarity, the outlets of a separator through which the target material exits are sometimes marked with a "+."

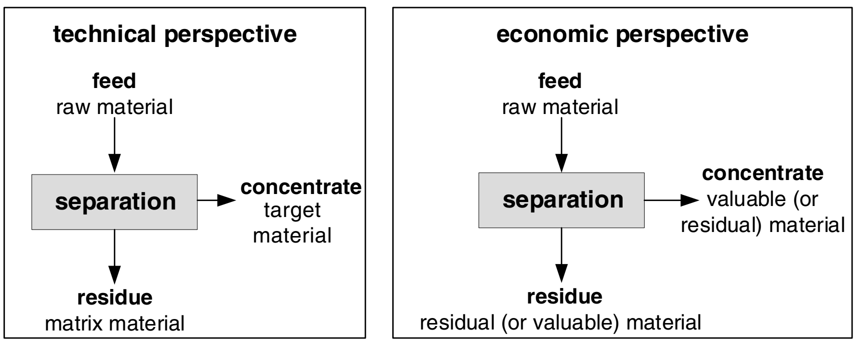


**Figure 1.18** Schematic representation of solids separation based on technical (left) and economic (right) perspectives.

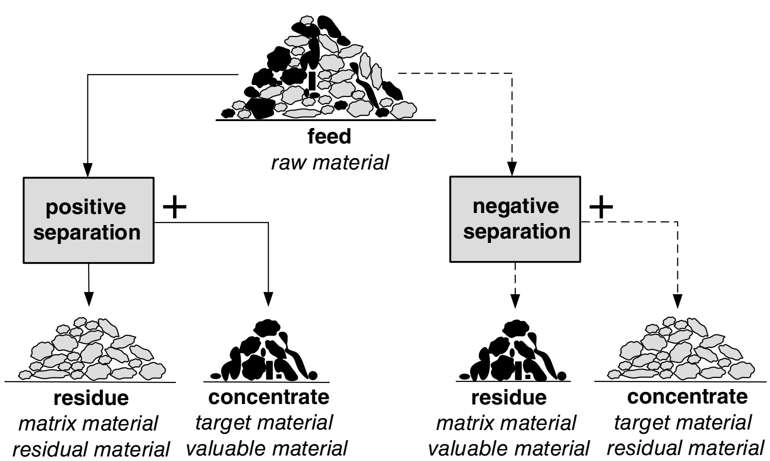


**Figure 1.19** In positive separation, the target material is the valuable material, which is enriched in the concentrate. In negative separation, the target material is the residual material. In this case, the residue of the negative separation is depleted in residual material.

Because the matrix material is typically a mixture of several constituents with differing properties, whereas the target material usually has narrowly defined properties, positive separation is the standard case. Consequently, discussions of separation processes implicitly assume positive separation unless explicitly stated otherwise.

**Example 1.1: Extraction of iron from waste incineration ash (positive separation)**

In this case, the valuable material is the iron, and the residual material is the predominantly mineral fraction of the ash. Magnetic sorting exploits *magnetizability* as the separation characteristic, thereby separating ferromagnetic iron from the nonmagnetic mineral ash. The target material of this separation is therefore iron. Because the valuable material (iron) is simultaneously the target material of the technical separation, this is a *positive solid–solid separation*.

**Example 1.2: Processing of concrete rubble by removing reinforcing bars (negative separation)**

The primary economic objective of concrete demolition waste processing is the production of recycled concrete aggregate. The valuable material is therefore concrete, while the reinforcing steel embedded in the concrete waste is an undesired component and is therefore classified as a residual material.[4] After liberation of the concrete debris, the rebar appears mixed with the concrete fragments. This rebar is the target material of the subsequent magnetic separation, which transfers it to the concentrate. The valuable material, recycled concrete aggregate, is the matrix material and is indirectly concentrated by *negative separation* where the tramp material (iron) is removed by magnetic separation. Negative separation is particularly common when the valuable material is already present as a pre-concentrate and needs to be further purified by removing the few remaining residual material particles.

### 1.5.3 Plant Engineering: Dry and Wet Processing

Separation of solids is generally much more efficient in aqueous suspension than in dry conditions. In suspension, interfering adhesive forces between the target and matrix materials are suppressed, especially capillary adhesive forces in moist materials. In addition, the flow conditions of the particles in water are often laminar, which promotes orderly separation. This contrasts with the typical turbulent movement of particles in an air stream.

The operating costs of wet mechanical processes are generally much higher than those of dry mechanical processes—typically about twice as high. One reason for

4 This applies even if the reinforcing steel can be sold.

this is the considerable effort required for water treatment. For environmental reasons, wet-processing plants must operate with largely closed water loops. Sludge and dissolved solids accumulate in these loops and must be removed through extensive wastewater treatment. Wet processes also often require specialized personnel, preferably with expertise in aqueous chemistry. In addition, many processed products can only be marketed in a dry state, requiring at least dewatering—and in some cases complete drying—after wet processing.

These challenges have led to a strong preference for dry separation processes in recycling. Dry processes such as eddy current separation and sensor-based sorting are often used instead of classic wet density separation. However, for demanding separation tasks involving fine particles (<4 mm) and stringent product specifications, wet mechanical processes are often indispensable. In Switzerland, this trend is particularly evident in the processing of construction and demolition waste, where more and more plants are being converted from dry to wet processing. This trend is further reinforced by the emerging PFAS issue, with efforts focusing on transferring PFAS either to the process water or to the fine fraction (sludge).

Combinations of wet and dry processing are also widely used. The feed material is first processed in a dry stage, and then the resulting fine particle fractions (e.g., all material <8 mm) are transferred to the wet stage.