Chapter 7
Recycling Requirements and Design for Environmental Compliance

Faced with a decreasing abundance of resources, together with ravaging environmental degradation caused by mounting waste and hazardous substances, we as engineers are forced to reconsider our approach to the design and development of electronics systems. The work of the development engineer no longer ends with the finished product, but must now also include the statutory responsibility for its *recycling*. This involves dealing with product recycling—the reuse and further use of the product, and/or material recycling—the reuse and further use of its constituent materials. *Design for recycling* must be our new guiding paradigm.

We begin this chapter (Sect. 7.1) with a discussion of the importance of a *circular economy*, in which products are designed to circulate in the production system without entering the environment. We next describe the circular economy's effect on the manufacture, usage, and disposal of electronic systems in Sect. 7.2.

Section 7.3 explores the concept of *product recycling* during the disposal process, including new marketing and design strategies for a more intensive product usage.

The materials in every electronic system must be disposed of at the end of their useful life. The commercial and ecological aspects of the necessary *material recycling* (Sect. 7.4) are determined by how well the system has been designed for disassembly and by the suitability of its constituent materials for recycling. The development engineer ensures the former with his/her system layout and the latter by the selection of materials. Material recyclability is thus established at the design stage by designing for disassembly and choosing suitable materials. We will explore the applicable principles and guidelines in Sects. 7.5 (disassembly) and 7.6 (suitable materials) in detail.

Section 7.7 concludes with a review of recommendations for electronic system development that is geared for environmental compliance.

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7.1 Introduction—Motivation and the Circular Economy

For hundreds of years now technical goods have been developed and produced solely with a view to their *use*, with little or no consideration as to what will happen to them after their useful life has expired. No thought was given to their possible reuse or recycling and to their final disposal. At the end of the product's life, it was simply thrown away—or at best, was brought to the dump. This was viewed as "disposal" in those days. Those were the days—and they still are to some extent in industry today—when the throwaway mentality held sway. The term "useless" was (and still is) used to refer to a to-be-disposed-of product's value, or lack thereof, in a technical or economical sense. Other possible residual product value (i.e., "usefulness"), such as materials and energy were, and still are, ignored. High product value is increasingly being lost after ever shorter product life spans and ends up as waste in a landfill. This throwaway mentality is now an existential threat to humankind because of the following:

- The exponential growth in the consumption of finite natural resources,
- The increasing release of hazardous substances into the environment with limited absorption capacity,
- The increased depletion of raw material resources by dumping products that have become obsolete in landfill sites (this makes recovery practically impossible as low volumes of materials are distributed in a dissipative manner).

The irrevocable loss of raw materials due to their increase in *entropy* is of particular concern. Entropy is a measure of the "disorder" of a system, that is, the number of different microscopic states a system can be in.[1] (The term "microscopic states" means the exact states of all the molecules making up the system.) Hence, the more "ordered" or "organized" a system is, the lower the microscopic disorder of this system, and the lower its entropy. This means that the entropy change during a process not only represents the difference in the quantity of substances existing at the beginning and end of the process, but also the change in the order of the involved substances from beginning to end.

Figure 7.1 shows that order increases initially with the extraction of valuable materials (substances) from the raw material base. In other words, we see a reduction in entropy because the materials' microscopic disorder is reduced. (Essentially, the properties of the extracted substances are more constrained then that of the raw material "mix".) The level of disorder then rises continually with the

[1]Complex building structures are good examples to illustrate the concept of entropy. Here, for example, building blocks that have been used to construct a wall are "highly organized" (i.e. they are arranged in a complex structure) and are thus in a *low-entropy* state. This state is achieved only by the input of energy. If this structure is left unattended, it will decay after a number of years, and the disorganized, high-entropy state will return (i.e., an unorganized heap of blocks). Generally speaking then, entropy is maintained, or it increases, in all natural processes.

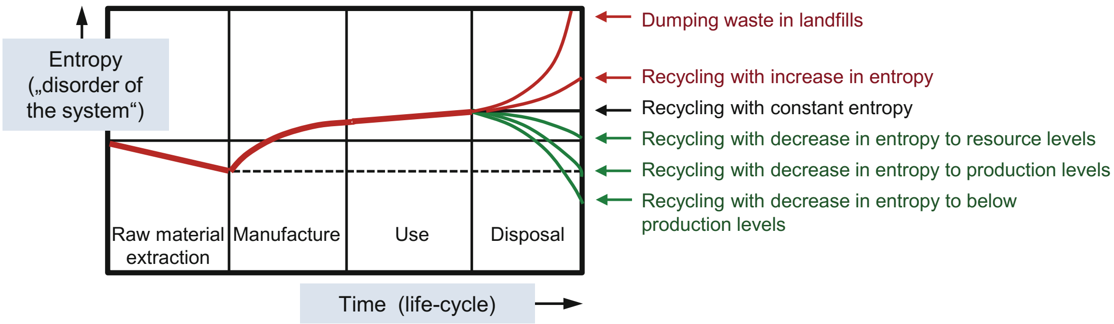

Fig. 7.1 Plot of the entropy of materials in the product life cycle where nowadays we convert low-entropy energy and materials into high-entropy waste. Product life cycles should take entropy retention into account to counter the irreversible loss of valuable raw materials due to the second law of thermodynamics

production of waste in manufacturing. The increase in disorder is further enhanced by "diluting" or "mixing" materials in the assembly of complex structures, followed by wear and tear and corrosion during the usage period. Finally, there is an exponential increase in disorder arising from the mixing of materials in landfills ("Dumping waste in landfills" in Fig. 7.1). The dissipative distribution of valuable substances renders them practically useless, they are effectively "lost forever." As a result of this directionality of the entropy law, the world's mineral resources are becoming scarcer and scarcer, increasingly limiting our economic prospects.

To counter this man-made "acceleration" of the second law of thermodynamics,[2] we must finally take into account the irreversibility of using inputs from the natural environment, thus, aiming for recycling with entropy retention as indicated in Fig. 7.1 ("Recycling with decrease in entropy").

Before proceeding, we first observe some facts and trends that will provide insight and motivation for improved recycling of electronic systems, with regard to their fabrication, usage, and disposal:

– The current widespread and large-scale use of electronic systems (e.g., there are currently about 4.5 billion cell phones in use worldwide),
– High rates of upgrading and disposal for "old" systems (e.g., the average life span of smartphones is currently about 4 years in the USA),
– The massive amount of electronic waste produced worldwide (the total amount of e-waste generated in 2018 is approximately 50 million metric tons),
– The large quantities of materials used in systems and the high concentration of materials during manufacture (one metric ton of materials must be sourced, transported, and processed to produce a "4 kg electronic system"),
– The high proportion of both hazardous materials and recyclables in the systems,
– The typically low reuse and recycling rates (30–40% in Germany),

[2]The second law of thermodynamics states that the universe evolves such that its total entropy always stays the same or increases.

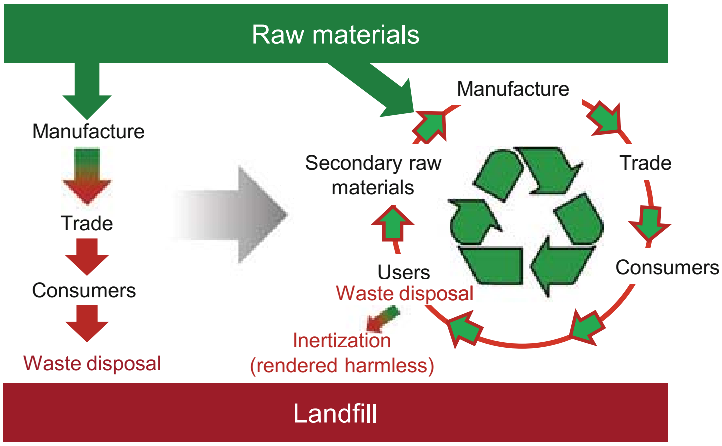

Fig. 7.2 Pivoting from a linear economy based on "take, make, dispose" material flow chain (*left*) that depletes finite raw materials and creates products that end up in landfills, to a regenerative circular economy (on the *right*). Here, products are designed to circulate with high quality in the production system, without entering the environment

– Significant energy consumption in standby mode (which represents 5–10% of all residential power used in most developed countries),
– Complex systems in particular are typically not designed for recycling.

Clearly, there needs to be a tectonic shift away from rampant throwaway consumerism to a resource-efficient and ultimately regenerative *circular economy*. We need to move from a linear "take, make, dispose" material flow (Fig. 7.2 left) to a circular economy framework by reusing or recycling products (Fig. 7.2 on the right). This will allow the deployed raw materials to be fully reintegrated in the manufacturing process beyond their so-called useful life.

The circular concept is grounded in the study of feedback-rich, nonlinear systems, particularly living systems. It considers that our products should work like organisms, processing "nutrients" that can be fed back into the cycle, whether biological or technical.

Lawmakers acknowledge the need to respond to these issues. *Closed Substance Cycle Waste Management Acts* have been enacted in most European countries to promote the circular economy model. The basis of this legal framework is the Waste Framework Directive of the European Union [1], which defines the primary waste-related terms, introduces a five-step waste hierarchy, and contains key provisions for national waste disposal laws. The purpose of this legislation is to promote the circular economy as a vehicle for conserving natural resources and to assure the environmentally compliant disposal of waste.

Section 3 of the German Closed Substance Cycle Waste Management Act entitled "Product Stewardship" stipulates that this duty of care applies to the entire life span of a product—from design and development through manufacture and deployment, and finally to disposal: "Products should be designed so that none, or a minimum of, waste is produced during their manufacture and operation, and that any waste generated at the end of their useful life is recycled or disposed of with minimum impact on the environment" [2].

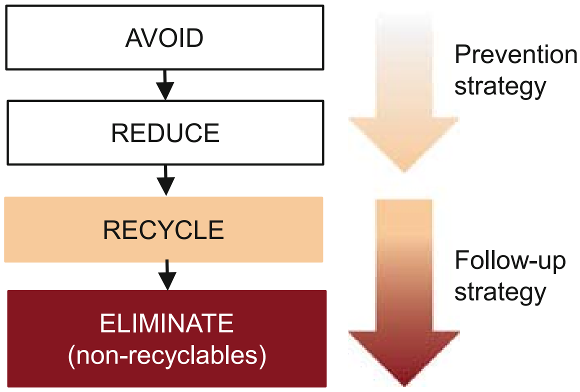

Fig. 7.3 ARRE strategy for waste management, which prioritizes waste avoidance and aims to reduce unavoidable waste

The responsibilities of the development engineer with respect to product stewardship are as follows:

1. To design, manufacture, and place products on the market that are durable and suitable for multiple reuse. It must be possible to properly and effectively reuse products in a safe and harmless manner and to disposed of them at the end of their useful lives with no negative impact on the environment.
2. To use, where possible, recyclable waste or secondary raw materials in the manufacture of products.
3. Labeling hazardous products so that any residual waste is recycled or disposed of in an environmentally safe manner at the end of their useful lives.
4. Affixing a label to the product w.r.t. return, reuse, and recovery options or responsibilities, and refund arrangements.
5. Taking back products and recovering or dispensing with any remaining waste after their recycling in an environmentally friendly manner.

Today, material recovery, in which the material is not altered, has priority over energy recovery from waste, that is, the extraction of the latent energy content. While, heretofore, non-recyclable waste was destroyed with as little impact on the environment as possible, the circular economy improves upon this with a preventative strategy for waste, rooted in *waste avoidance* and the *reduction* of *unavoidable waste*. A so-called ARRE strategy applies to waste management (Fig. 7.3).